NASA'S RPS DESIGN REFERENCE MISSION SET FOR SOLAR SYSTEM EXPLORATION

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Abstract. NASA's 2006 Solar System Exploration (SSE) Strategic Roadmap identified a set of proposed large Flagship, medium New Frontiers and small Discovery class missions, addressing key exploration objectives. These objectives respond to the recommendations by the National Research Council (NRC), reported in the SSE Decadal Survey. The SSE Roadmap is down-selected from an over-subscribed set of missions, called the SSE Design Reference Mission (DRM) set. Missions in the Flagship and New Frontiers classes can consider Radioisotope Power Systems (RPSs), while small Discovery class missions are not permitted to use them, due to cost constraints. In line with the SSE DRM set and the SSE Roadmap missions, the RPS DRM set represents a set of missions, which can be enabled or enhanced by RPS technologies. At present, NASA has proposed the development of two new types of RPSs. These are the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), with static power conversion; and the Stirling Radioisotope Generator (SRG), with dynamic conversion. Advanced RPSs, under consideration for possible development, aim to increase specific power levels. In effect, this would either increase electric power generation for the same amount of fuel, or reduce fuel requirements for the same power output, compared to the proposed MMRTG or SRG. Operating environments could also influence the design, such that an RPS on the proposed Titan Explorer would use smaller fins to minimize heat rejection in the extreme cold environment; while the Venus Mobile Explorer long-lived in-situ mission would require the development of a new RPS, in order to tolerate the extreme hot environment, and to simultaneously provide active cooling to the payload and other electric components. This paper discusses NASA's SSE RPS DRM set, in line with the SSE DRM set. It gives a qualitative assessment regarding the impact of various RPS technology and configuration options on potential mission architectures, which could support NASA's RPS technology development planning, and provide an understanding of fuel need trades over the next three decades.

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INTRODUCTION

In the Solar System Exploration (SSE) Decadal Survey [NRC, 2003], the National Research Council (NRC) of the National Academies provided an overview of our current knowledge of the universe, summarized science goals and objectives, and prioritized future exploration plans. The Vision for Space Exploration [Bush, 2004] responded to these recommendations by the NRC, and identified pathways for the exploration of the Moon, Mars, Solar System, and beyond. In that document Outer Planets exploration consisted of one large flagship class mission, which eventually was cancelled in 2005 and was replaced by a set of missions, as documented in NASA's 2006 Solar System Exploration Roadmap [NASA, 2006]. Both the Lunar and Mars pathways were leading to eventual manned missions around the middle of the third decade. Further science input to NASA in developing and maintaining these pathways and priorities is provided by the NASA Advisory Council (NAC) and by other science advisory groups, namely the Outer Planets Assessment Group (OPAG) [OPAG, 2006], the Venus Exploration Analysis Group (VEXAG) [VEXAG, 2006], the Mars Exploration Program Analysis Group (MEPAG) [MEPAG, 2006], and the Lunar Exploration Analysis Group (LEAG) [LEAG, 2006].

NASA's Science Mission Directorate (SMD) supports an ongoing effort to review technologies currently under development at NASA, DoE, industry, and academia. In the 2006 SSE Roadmap [NASA, 2006] a number of missions are proposed, which could be enabled by Radioisotope Power Systems (RPS). In this SSE Roadmap RPSs are identified as one of the highest priority technologies, which are necessary to enable future missions. RPS power technologies and related mission concepts are described in a number of NASA reports, including missions enabled or enhanced by small-RPSs [Abelson, Balint, et al., 2004], standard RPSs [Abelson, Balint, et al., 2004a], and advanced RPSs [Abelson, Balint, et al., 2005]. Potential RPS enabled Mars missions are addressed in [Balint, Sturm, et al., 2006]. This paper provides a general overview of potential future NASA missions, which could be enabled by RPS technologies. However, it should be noted that no decision has been made by NASA on any power source selection for future missions, and the discussions in this paper only represent possible power system configurations.

SCIENCE DRIVERS

The scientific foundation of NASA's Solar System Exploration Roadmap is set to answer fundamental questions, based on five objectives in response to the NRC's Decadal Survey [NRC, 2003], and to the exploration goals of the Vision for Space Exploration [Bush, 2004]. These are:

1. How did the Sun's family of planets and minor bodies originate?
2. How did the Solar System evolve to its current diverse state?
3. What are the characteristics of the Solar System that led to the origin of life?
4. How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?
5. What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?

Among these goals, a unifying theme for Solar System exploration is habitability – the ability of worlds to support life. Each goal addresses a different aspect of habitability; and together they encompass all of its characteristics addressable with SSE.

In line with these objectives, the Mars Exploration Program is governed by four goals, established by the Mars Exploration Program Analysis Group (MEPAG) [MEPAG, 2006]. These goals are:

1. Determining if life ever arose on Mars;
2. Understanding the process and history of climate on Mars;
3. Determining the evolution of the surface and interior of Mars; and
4. Preparing for human exploration.

The first three goals are science driven, while the fourth is primarily technology focused. All of these can be translated into a number of robotic and human precursor missions, leading to a possible human landed Mars mission by around 2035.

PROGRAMMATIC CONSIDERATIONS

Whereas science drivers can help with the selection of target bodies and with measurement objectives, programmatic considerations play a significant role in selecting future missions. Based on the scope, these missions can fit into a number of cost cap driven mission classes. For Solar System exploration, there are three mission classes, namely Discovery (small), New Frontiers (NF) (medium), and Flagship (large). For Mars exploration, Scout missions are the smallest, followed by medium and large missions, which roughly correspond to the New Frontiers and Flagship classes under SSE.

Smaller missions are more affordable, but they can provide limited science return. Conversely, some of the larger or more complex scientific problems can be answered by large Flagship class missions, but due to budgetary constraints the number of these missions per decade is limited to about one or two.

Competitive Discovery class missions for SSE and Scout missions for Mars exploration have the smallest cost caps (~$425M FY06). These missions are not allowed to use RPSs, and therefore, will not be discussed further. Medium class New Frontiers and large Flagship class missions, however, can consider RPSs, when they are enabling to the mission. When adjusted for inflation, New Frontiers missions have a cost cap of $767M FY06. Flagship missions can be either Small or Large, with cost caps of ~$750M to $1.5B, and $1.5B to $3B, respectively [NASA, 2006]. Cost caps for the Mars program are not defined this specifically, but they are expected to be similar to those within the SSE program. Consequently, NASA's Roadmaps are set up in a way that can provide a balanced exploration program, including missions from all of these classes, with the challenge of staying within the allocated annual budgets. These Roadmaps should be also flexible to respond efficiently to scientific discoveries and budgetary constraints, while maintaining continuity to the Agency's long term goals.

NASA's 2006 SSE Roadmap [NASA, 2006] identified a set of missions for Solar System exploration over the next three decades. Timelines for Flagship class and New Frontiers class missions are shown in Figures 1 and 2, respectively. In the directed Flagship lineup all of the missions require RPS technologies. Since mission architectures influence technology approaches, the actual power system configuration may vary for any given mission. For example, the Titan Explorer mission could be conceived with an in-situ element only, or with an in-situ element supported by an orbiter, thus influencing the number and type of RPSs. These variations are addressed through multiple mission entries in the Design Reference Mission set, from which the final architecture could be chosen based on programmatic considerations. The Roadmap also identified competed New Frontiers class missions up to the next (3rd NF) opportunity. The first NF mission, the Pluto Kuiper Belt Explorer – New Horizons mission, was launched in January 2006. It used the last General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) [Surampudi, 2001]. GPHS-RTGs have been successfully used on the Galileo, Ulysses and Cassini missions. This technology is now discontinued and would be replaced with the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which is currently under development and is baselined for the 2009 Mars Science Laboratory (MSL) mission. The second NF mission, the Jupiter Polar Orbiter (Juno), is designed with Low Intensity Low Temperature (LILT) solar panels [Cutts & Prusha, 2003]. Missions competing for the 3rd NF opportunity, and proposed for a 2015 launch, are the Saturn Flyby with Probes; the Comet Surface Sample Return; the Venus In-Situ Explorer; and the Lunar South Pole – Aitken Basin Sample Return missions. All of these four mission concepts can be achieved with the support of solar power generation; therefore, they are not included among the proposed New Frontiers missions in the RPS DRM set, which is discussed in the next section.

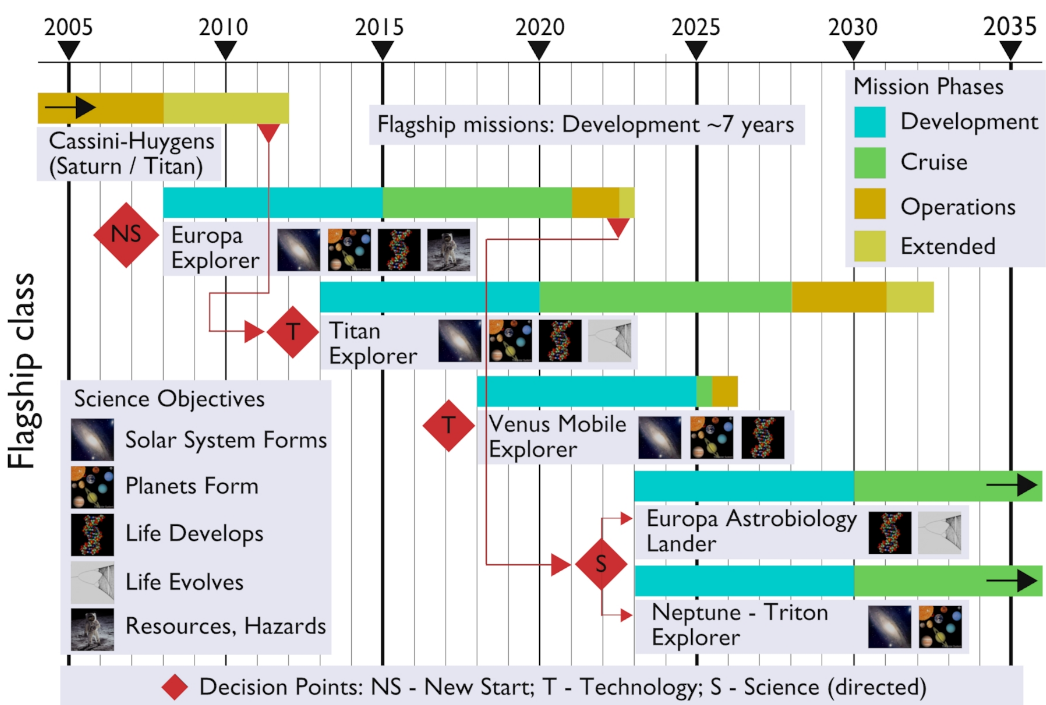

FIGURE 1. Recommended sequence of Flagship missions established by the SSE Roadmap Team [NASA, 2006].

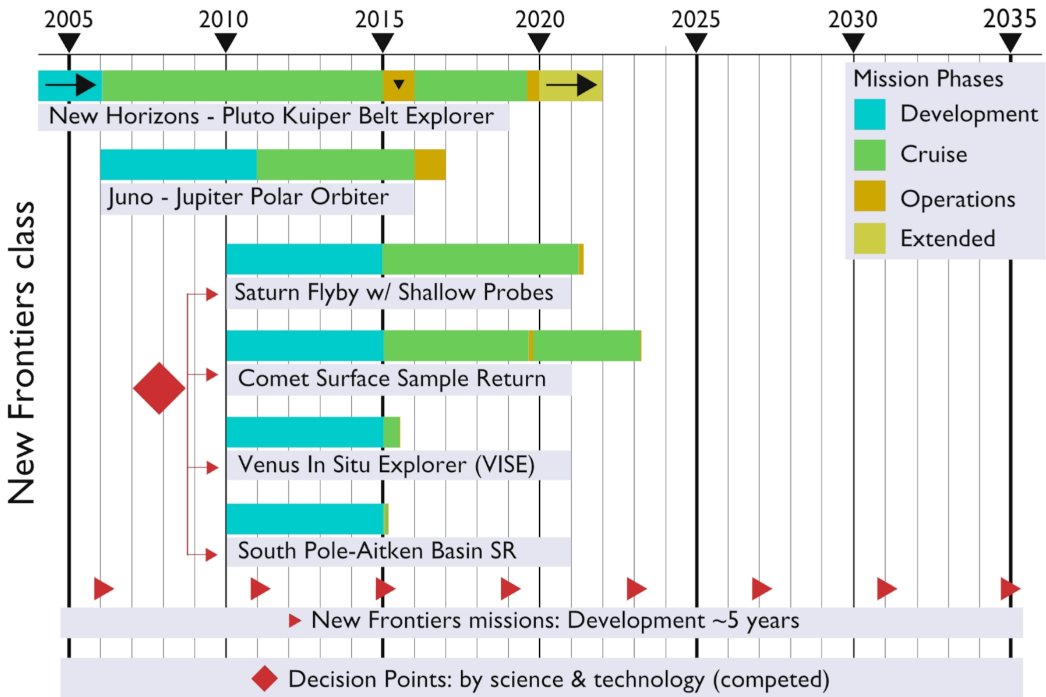

FIGURE 2. Sequence of New Frontiers missions established by the SSE Roadmap Team. [NASA, 2006]

RPS DESIGN REFERENCE MISSION SET

The SSE Design Reference Mission set, and consequently the Radioisotope Power System DRM set, was set up according to a systematic exploration strategy, that includes missions with increasing complexity. According to this methodology the simplest mission architectures are flybys, followed by orbiters, then in-situ missions, and finally sample returns. Typically, Design Reference Missions represent an over-subscribed mission set, from which the actual Roadmap missions can be down-selected, based on science objectives, programmatics, mission architectures and technology readiness. This section includes the list of RPS DRMs, followed by a discussion on possible mission impacts by RPS technology, and potential RPS development targets.

List of Conceptual RPS Design Reference Missions

The RPS DRM set is a subset of NASA's Solar System Exploration Design Reference Mission set. Although there is a large number of additional missions which could be either enabled or enhanced by RPS technology (e.g., small-RPS enabled mission concepts listed in [Abelson, Balint et al., 2004]), this RPS DRM set only lists programmatically relevant missions. The list, shown in Table 1, includes 24 mission concepts; some of them represent variations on a given architecture. For example, the SSE Roadmap identified the Flagship class Neptune / Triton Explorer as a proposed third decade mission. The RPS DRM set addressed this mission through three entries, such as the Neptune Triton Orbital Tour, the Neptune Orbiter with Probes, and the Neptune / Triton Explorer. The first architecture could include an orbiting spacecraft without in-situ elements. The second architecture would focus on Neptune alone with a Galileo mission like orbiter / probes configuration. The third and likely most complex architecture would not only study Neptune, but would include a Triton lander, in order to study this retrograde orbiting moon of Neptune, which is theorized to be a captured Kuiper Belt Object (KBO). A fourth, New Frontiers class mission concept, would represent the simplest and most affordable architecture with a Neptune flyby, however, the science return of that mission would be severely limited compared to the other three Flagship class mission concepts.

TABLE 1. Radioisotope Power System Design Reference Missions (RPS DRM). (Note: the missions listed in this table represent missions, which could be enabled by RPSs, however, no pre-decision has been made by NASA on the use of RPSs for these missions.)

DRM Mission Name	Mission Class	Earliest Launch	Comments
Europa Explorer	Flagship	2015	MMRTGs, high radiation
Titan Explorer (no Orbiter)	Flagship	2020	RPS excess heat for balloon heating
Titan Explorer (with Titan Orbiter)	Flagship	2020	Aerocapture, RPSs for orbiter/in-situ
Venus Mobile Explorer	Flagship	2025	Special Stirling with active cooling
Europa Astrobiology Lander	Flagship	2030	EE follow on, high radiation
Neptune Triton Orbital Tour	Flagship	2030	RPS excess heat for Triton lander
Neptune Orbiter with Probes	Flagship	2030	Neptune Aerocapture
Neptune Orbiter/Triton Explorer	Flagship	2030	RPS excess heat for Triton lander
Uranus Orbiter with Probes	Flagship	2035	RPS required, Galileo like config.
Saturn Ring Observer	Flagship	2035	NRC DS recommended
Neptune Flyby	New Frontiers	2020	RPS required, New Horizons like
Uranus Flyby	New Frontiers	2020	RPS required, New Horizons like
Neptune Flyby with Probes	New Frontiers	2020	Jupiter or Saturn Entry Probes like
Uranus Flyby with Probes	New Frontiers	2020	Jupiter or Saturn Entry Probes like
Io Observer	New Frontiers	2020	Higher radiation than at Europa
Ganymede Observer	New Frontiers	2020	Lower radiation than at Europa
Enceladus Explorer	New Frontiers	2020	New mission, based on new finding
Trojan/Centaur Recon Flyby	New Frontiers	2020	REP – requires over 8W/kg
Venus Geophysical Network	New Frontiers	2020	Special Venus RPS
Mercury Geophysical Network	New Frontiers	2020	RPS required at dark Polar Regions
Mars Science Laboratory	Large	2009	Baselined with one MMRTG
Mars Astrobiology Field Laboratory	Large	2016	Possibly MMRTG heritage
Mars Multi-Lander Network	Large	2020	Small-RPS (baselined solar power)
Mars Mid-Rovers	Medium	2016	Small-RPS (baselined solar power)

Pre-Decisional: For Discussion and Planning Purposes Only

Mission Impact of Radioisotope Power Systems

RPS technologies require environmental documentation and safety analysis before approved for use and launch, special accommodation, impacting mission architectures, and mission designs. These issues are briefly discussed below.

Mission phases

RPSs must be designed for all mission phases, namely Earth storage; launch; cruise; entry, descent and landing (EDL); and in-situ operations. Conditions between these mission phases vary and so as the heat transfer mechanisms to reject the excess heat generated by the radioisotopic decay of the plutonium fuel. While operating in planetary environments with atmospheres – such as on Earth, Mars, Titan, and Venus – heat is rejected through convection, conduction and radiation. For these in-situ missions, during the cruise phase the RPS(s) would be encapsulated inside an aeroshell, while the excess heat would be removed by a fluid loop and rejected to space through external radiators. Sizing of the fluid loop and the radiators for Venus missions would be different than similar in-situ missions to Titan for example, because of the extreme environmental conditions at the destinations (480°C at Venus versus -178°C at Titan). RPS and thermal management sizing should also account for the atmospheric entry phase, when the probe or lander would be still inside an aeroshell, but forced circulation would be no longer available [Balint, 2006]. For orbiting missions – e.g., Europa Explorer – the RPSs would be exposed to the space environments, and heat would be rejected through radiation directly to space. For these missions the system must still address the pre-launch and launch environments on Earth.

Radiation Environment

Missions to the Jovian system encounter extreme radiation. The Galileo mission and the Juno mission design minimized radiation exposure by having highly elliptic orbits, and thus minimizing the time spent in the high radiation environments. Orbiters and landers at and around Galilean moons, such as on the proposed Europa Explorer, Europa Astrobiology Lander, Io Observer and Ganymede Observer missions, are continuously exposed to high radiation, which must be mitigated. RPSs with static conversion, such as the MMRTGs, employ hundreds of thermocouples, which provide built in redundancy. That is, failure of a few thermocouples would have a minimal impact on the overall power system performance. MMRTGs could tolerate radiation at the multi-MRad level, reducing shielding requirements, and thus the mass impact on the mission. Conversely, SRGs are more sensitive to radiation. The controller electronics require significant shielding. EMI radiation from the SRG could interfere with science measurements, while EMI shielding to reduce it would impact system mass. Failure modes of SRGs do not allow for graceful degradation the same way as that for MMRTGs.

Hybrid Power System

RPSs provide continuous power, which translates to high energy output, but low average power. At high power operating modes, such as telecom or traversing on the surface, the RPS alone may not provide sufficient power. This could be solved by the use of a hybrid power system, where the RPS power would be augmented by secondary batteries. At low power modes the batteries would be recharged by the RPS.

Power System Trades for Smaller Mission

The Titan balloon mission is conceived with 1 or 2 MMRTGs, where beside the power generation the excess heat would be used to heat the Montgolfiere. This mission would not benefit from the use of SRGs, since the reduced fuel would not provide sufficient excess heat for the balloon. In-situ missions to Mars – for example the proposed MSL and AFL rover missions – are designed with a single MMRTG. Alternative architectures could consider an SRG, however, design principles for dynamic conversion based RPSs require system level redundancy. This translates to an additional unit for the mission. While two SRGs would provide twice as much power as a single MMRTG, the power system mass would be also impacted. Having a second SRG unit would double the fuel requirement (from two to four GPHS modules), which is only half of the fuel required for an MMRTG. Therefore, while on one hand dynamic systems on smaller Mars missions would reduce the fuel requirements by 50% and would increase power output; on the other hand they would almost double power system mass, cost and complexity, due to a not yet space qualified power system. Other smaller missions, such as network missions to Mars and Mercury, could be designed with single GPHS module based small-RPSs. The development of small-RPSs is currently under consideration, and if made available they could enable a number of smaller missions or adjunct elements on Flagship class missions.

Outer Planets Missions

Solar flux decreases with the inverse square of the distance from the Sun. Since the solar panel mass and power scales linearly, and the power output reduces with the increasing distance from the Sun, at around 4 AU RPSs become more mass efficient than solar panels at comparable power outputs. Although most missions to the outer planets are baselined with RPSs, there are possible mission architectures even at Saturn, where solar power generation could be a suitable solution. For example, the proposed Saturn Flyby with Probes mission would have an approximately 5-hours operational lifetime, and would return a total of 10-15 Mbits of data. This could be supported with the combination of LILT technology and batteries, using Juno design heritage. Missions operating longer at these distances would require an internal power source, not only for power generation, but also for thermal management by utilizing excess heat from the power system (e.g., on a potential Triton Lander mission). In addition, the cruise phase of these outer planets missions could take 6 to 15 years, which would likely impact the selection between static conversion based heritage RPSs, and dynamic conversion based systems, which are not yet lifetime tested or flight qualified for these mission durations.

G-load Tolerance Requirements

MMRTGs and SRGs are designed to tolerate launch conditions, up to 40 g and 30 g, respectively. This is suitable for orbiter and soft landed in-situ missions. The proposed Mars Multi-Lander Network mission is currently baselined with solar panels, but concepts with small-RPSs were also evaluated. Each of the 4 to 10 small landers would land, using crushable materials. This would result in deceleration loads over 2000 g, which would require significant technology development for these small-RPSs.

Radioisotope Power Systems for Long Lived Venus In-Situ Missions

Driven by science requirements, longer missions provide greater science return than short ones. Short lived missions could be designed with power storage systems (e.g., batteries [Mondt, Burke et al., 2004]), but long lived in-situ missions require external or internal power sources (not storage), such as solar panels or radioisotope power systems (RPS). For high-altitude Venus balloon missions, solar power generation is a suitable option. However, for long lived surface or low altitude aerial missions a specially designed RPS would be required. These RPS enabled missions could operate continuously for many months, granted that other issues related to the extreme environment mitigation (e.g., pressure and temperature) are addressed. The RPS, and the rest of the spacecraft, would also need to tolerate the highly corrosive supercritical carbon dioxide atmosphere. For Venus conditions dynamic power conversion (e.g., Stirling converters) may provide an advantage over static conversion systems, due to the strong coupling between the power conversion performance and the temperature difference between the hot and cold sides of the thermocouples. High ambient temperatures would result in a very low static conversion efficiency, higher mass and volume, and higher fuel requirements. Dynamic conversion systems have significantly higher conversion efficiencies, and due to the lower fuel requirements less excess heat to reject. In addition to power generation, an RPS for Venus would also require to power an active cooling system, in order to maintain a quasi steady state thermal environment for the payload inside the pressure vessel. Current Stirling Radioisotope Generator (SRG) development work does not include a requirement to operate at 480°C. Therefore, future development work should include work on a special dynamic conversion system that includes a power generator and an active cooler to support continuous operation near or at the surface of Venus. The power system should also utilize a suitable coating to minimize the impact of the corrosive environment, while maintaining or if possible improving heat rejection performance. Furthermore, the aerial platform of the proposed Venus Mobile Explorer mission would impose mass and volume constraints on the RPS design, which should be balanced against the power requirement of the mission. [Balint, 2006]

Potential RPS Development Targets

DoE and other industry partners is currently developing two new types Radioisotope Power Systems for NASA. The MMRTG utilizes static thermoelectric conversion, while the SRG uses Stirling power conversion technology, producing power at the 100 W_e level. Both of these systems are multi-mission capable, that is, they can operate in vacuum and in planetary atmospheres. The MMRTG is the proposed baseline power source for the Mars Science Laboratory rover mission with a planned launch of 2009. To date, the SRG does not have a programmatic mission slot.

Following MSL, the next missions under the Science Mission Directorate that could utilize RPSs are the proposed Europa Explorer (2015) and Mars Astrobiology Field Laboratory rover (2016) missions. Both of these concepts are conceived with existing technologies. Conceptually, EE would use up to 8 MMRTGs, while AFL would utilize MSL heritage with one MMRTG.

An alternative to the MSL class AFL rover in 2016 could be Mars Exploration Rover (MER) class mid-rovers, using either solar power generation or, if developed, small-RPSs. It is expected that these small-RPSs would be designed with a single GPHS module then stacked unit-by-unit as needed, or build in a modular configuration, similar to that of a mod-RTG. In both cases power could be provided in the sub-100 W_e level. Note that the MER solar panels generated ~1000 Wh/sol at BOL (beginning of life). This corresponds to ~40 W_e average power, which could be achieved with two stacked single GPHS module base small-RPSs with 8% conversion efficiency on the system level. Other missions, such as the Mars Network Lander and Geophysical Network missions to Mercury and Venus could also benefit from small-RPSs, although Venus in-situ missions would require special considerations due to the extreme environment. However, it is strongly recommended to continue development work on these small-RPS systems.

The extreme environments at Venus are unique to that planet. Therefore, RPS developed for long lived Venus in-situ missions would not provide feed forward to other SSE missions. Nevertheless, this technology is considered potentially enabling for the Venus Mobile Explorer mission concept, and should be studied and developed in time to make it available for the proposed 2025 launch date.

A proposed Titan in-situ mission in 2020 could also use multi-mission capable MMRTGs, but with modifications for the extremely cold environment by reducing the size of the radiator fins, in order to maintain the temperature drop across the thermoelectrics at an optimal level.

The Trojan/Centaur Reconnaissance Flyby mission could benefit from Radioisotope Electric Propulsion. However, this would require power levels above 750-1000 W_e, and an RPS specific power above 8 W_e/kg. Today's RPSs are designed at a specific power level of about 3-3.5 W_e/kg, while advanced RPSs target about twice as that. Although RPS development aims at increasing specific power levels, the development for REP is currently not in the main focus. However, once the specific power level reaches 8 W_e/kg and above through a natural developmental evolution, these advanced RPSs then could be considered for REP enabled missions, if those missions become programmatically important.

Advanced RPSs at higher specific powers and conversion efficiencies would enhance SSE missions. The mass saving from ARPSs could be traded against additional payload, or design margin. The reduced overall system mass could also allow for a smaller launch vehicle, possibly resulting in significant mission cost savings.

In summary, near future solar system exploration missions from now until the middle of the next decade could be enabled with existing RPS technologies. For example, MMRTGs would be well suited for future Mars and Titan in-situ missions. RPSs for Venus exploration would require a special development, where a Stirling Radioisotope Generator would not only provide power to the payload, but also active cooling to the components inside a pressure vessel. Other missions identified in the Roadmap and in the DRM sets do not require multi-mission capability and the performance penalty that is associated with it. Therefore, advanced RPSs could be developed for in-vacuum operations, which would immediately increase system performance. Further improvement in conversion efficiencies could bring us closer to performance goals initially in the 6 to 8 W_e/kg specific power range.

CONCLUSIONS

NASA's Solar System Exploration program is formulated to answer questions about solar system formation and habitability. Proposed missions must address four key interrelated areas: they have to be scientifically interesting; programmatically affordable; and enabled by appropriate mission architectures; and technologies to achieve mission success. The Radioisotope Power System Design Reference Mission set, documented here, was derived as a subset of NASA's SSE DRM set and planned Mars Exploration missions. It reflects a set of missions which could be either enabled or enhanced by RPS technology. The identified 24 missions represent and oversubscribed set, from which SSE and Mars Roadmap missions could be down-selected. While NASA has not made any decisions on the power source of any future mission, it is expected that the RPS DRM set could provide an insight to NASA on the possible number of missions that require RPS technologies, and point to possible RPS development strategies.

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REFERENCES

Abelson, R.D., Balint, T.S., Marshall, K.E., Noravian, H., Randolph, J.E., Satter, C.M., Schmidt, G.R. and Shirley, J.H., “Enabling Exploration with Small Radioisotope Power Systems,” JPL Pub 04-10, NASA, Washington DC, September 2004.

Abelson, R., Balint, T.S., Coste, K., Elliott, J.O., Randolph, J.E., Schmidt, G.R., Schriener, T., Shirley, J.H., Spilker, T.R., “Expanding Frontiers with Standard Radioisotope Power Systems,” Technical Report JPL D-28902, PP-266 0332 National Aeronautical and Space Administration, Washington, D.C., December, 2004a.

Abelson, R.D., Balint, T.S., Evans, M., Schriener, T., Shirley, J.H., Spilker, T.R., “Extending Exploration with Advanced Radioisotope Power Systems,” Technical Report JPL D-28903, PP-266 0333, National Aeronautical and Space Administration, Washington, D.C., October, 2005.

Balint, T.S., “Radioisotope Power Systems for In-Situ Exploration of Titan and Venus,” 4th International Planetary Probe Workshop, Pasadena, California, June 27-30, 2006.

Balint, T.S., Sturm II, E.J., Woolley, R.C., Jordan, J.F., “Can We Power Future Mars Missions?,” Paper number: IAC–06–A5.2.06, 57th International Astronautical Congress, IAC-06, Valencia, Spain, October 2-6, 2006.

Cutts, J., Prusha, S., “Solar Cell and Array Technology for Future Space Missions,” JPL D-24454, Rev. A, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, December 2003.

LEAG, Lunar Exploration Analysis Group. Website: http://www.lpi.usra.edu/, Accessed: September 24, 2006.

MEPAG, Mars Exploration Program Analysis Group, Website: http:// http://mepag.jpl.nasa.gov/, Accessed: September 24, 2006.

Mondt, J., Burke, K., Bragg, B., Rao, G., Vukson, S., “Energy Storage Technology for Future Space Science Missions,” National Aeronautics and Space Administration, Technical Report, JPL D-30268, Rev.A., November, 2004.

NASA SMD PSD – SSE Roadmap Team, “Solar System Exploration – Solar System Exploration Roadmap for NASA's Science Mission Directorate,” NASA Science Missions Directorate, Planetary Science Division, Report Number: JPL-D-35618, September 15, 2006.

NRC, “New Frontiers in the Solar System, an integrated exploration strategy,” Technical report, Space Studies Board, National Research Council, Washington, D.C., 2003.

OPAG, Outer Planets Assessment Group, Website: http://www.lpi.usra.edu/opag/, Viewed: September 24, 2006.

President Bush, G.W., “A Renewed Spirit of Discovery, The President's Vision for U.S. Space Exploration,” (2004), Website: http://www.whitehouse.gov/space/renewed_spirit.html, Accessed: August 2, 2004.

Surampudi, R., Carpenter, R., El-Genk, M., Herrera, L., Mason, L., Mondt, J., Nesmith, B., Rapp, D., Wiley, R., “Advanced Radioisotope Power Systems Report,” JPL D-20757 6/01, NASA, Washington DC, March 2001.

VEXAG, Venus Exploration Analysis Group. Website: http://www.lpi.usra.edu/vexag/, Accessed: September 24, 2006.