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SMALL POWER SYSTEM TRADE OPTIONS FOR ADVANCED MARS MISSION STUDIES

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ABSTRACT

Small Radioisotope Power Systems (RPS) and solar panels are two of the potential power generation options for Mars exploration in orbit and on the surface. In this study, mission trades, scaling relationships and point designs are used to evaluate both power systems for proposed next decade landed missions. Solar power generation is assumed continuous in orbit but limited on the surface. RPSs could provide long duty cycle continuous power while not depending on insolation. For the targeted power range of ~25-50 We, this study envisions multiples of a conceptual single GPHS module based RPS design. For rovers, mobility and telecom are found to be key drivers for power system sizing. Landers could scale down to very small trickle-charge RPS devices, requiring only milliwatts of power, generated with stacked Radioisotope Heater Units (RHU). In orbit around Mars solar power remains a leading option to achieve science and mission objectives. The same applies to short duration surface missions near the equator. Conversely, for long duration missions, measured in months or even years and at high latitudes with low insolation, RPS based systems may present an attractive and possibly the only viable power generation option.

INTRODUCTION

The nation's vision for space exploration [1] identified Mars as one of the highest priority destinations in the solar system. Along the Mars exploration roadmap, the Mars Exploration Rovers, Spirit and Opportunity [2], provided the latest success stories with a number of new projects to follow, such as the Mars Reconnaissance Orbiter in 2005, the Phoenix Lander in 2007, the Mars Telecom Orbiter in 2009 and the Mars Science Laboratory rover also in 2009. This paper, however, looks beyond this decade and addresses potential Mars missions between 2010 and 2020, with a specific focus on power system trade options and power requirements. These concept studies were performed within JPL's Pre-Projects and Advanced Studies Office (610). Before introducing the missions, two of the key power technologies will be outlined, namely solar power generation and Radioisotope Power Systems (RPS). Today's space science missions, employing solar panels or RPS based power systems, typically fall into a power range between 0.1 kWe and 1 kWe. Missions utilizing lower power levels are less common. Hence, the primary focus of this study is to identify optimal power levels and requirements for these advanced mission concepts in order to achieve Mars exploration science and mission objectives. A comparison between these power technologies will help to assess the application trades at various locations on Mars and in orbit around it. The energy produced by these power systems comes at an expense, which will be discussed through cost and mass as a function of energy production, and presented for past and present missions. In the same context conceptual future missions will be also addressed.

POWER TECHNOLOGIES

This section describes the characteristics of two power technologies, namely solar panels and RPSs, then discusses their applicability for Mars missions.

Solar Power Generation

Solar power generation utilizes solar radiation, or insolation. Solar energy is considered an external power source, which can be converted into electric power using photovoltaic (PV) arrays or solar thermal collectors (not discussed here). PV arrays employ solar cells for power conversion. In this paper three types of PV solar cells are considered. Silicon (Si) and Gallium Arsenide (GaAs) cells convert photons of near infrared energy to usable energy. They convert energy at efficiencies of $\eta_{conv} = 14.8\%$ and $\eta_{conv} = 18.5\%$, respectively. Multi-junction or multi-layered solar cells, such as multi-junction Gallium Indium Phosphide/GaAs (GaInP/GaAs: $\eta_{conv} = 22\%$), use different spectrums of sunlight, hence increasing conversion efficiency [3]. Specific performance ranges from 14 to 47 W/kg, with high-end performance of 66 W/kg at the beginning of life (BOL). End of life (EOL) power production capability depends on cell degradation, which is $3.75\%/yr$, $2.75\%/yr$ and $0.5\%/yr$ for Si, GaAs and multi-junction GaInP/GaAs, respectively [3]. The actual life degradation (L_d) is affected by mission duration and duty cycle. Consequently, power generation depends on L_d, the power conversion efficiency and the solar constant S. (S is 1367 W/m^2 at the orbital distance of Earth from the Sun, which should be adjusted for the mission destination.) Details on additional factors influencing solar panel performance on Mars are given in [4]. Solar panel size and mass scales linearly with power. For example, a ten-fold increase in power results in the same magnitude increase in panel size and mass, although this type of scaling is bound by EDL (entry, descent & landing) limits [5].

Solar insolation varies inversely with the square of distance from the Sun (i.e., R^{-2}). Therefore, to generate the same amount of power the panel size and mass should increase with this distance. The mass of a Radioisotope Power System (RPS) system remains unchanged since it generates power independently from the Sun. Figure 1 gives a system mass comparison between solar panels and RPSs. Both systems are assumed to provide 110 We of power at BOL. For solar panels, the mass of GaAs and multi-junction panels are shown at BOL and EOL after an assumed 10 years of operation. The RPS mass corresponds to the estimated mass of a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which could generate 110 We (BOL) and about 93.8 We (after the same assumed 10 years EOL). According to these calculations, up to about 3.6 to 4.3 AU solar panels are more mass efficient than RPSs. This applies to power generation in orbit around Mars, however, on the surface solar power generation is influenced by many factors. In some instances these factors, described later in this paper, make the possible use of RPSs very appealing and can even be mission enabling. (Note that at Jupiter, for example, the solar flux is only about 3.7% of that at Earth. At this level of insolation it is likely that advanced solar cell technologies are required for power generation – such as Low Intensity, Low Temperature, or LILT – increasing power system mass, complexity and cost.)

Due to the distance from the Sun, solar flux at Mars is only about 43% of that at Earth [6]. In addition, solar power generation on the surface of Mars is further impacted by atmospheric conditions and sand storms (addressed through optical depth), operating latitude, seasons (defined by the aerocentric longitude of the Sun, Ls), eclipses, terrain shadowing, and solar panel degradation (due to dust accumulation and thermal cycling from diurnal temperature variations) [4]. Consequently, solar irradiance values are significantly lower on the surface than for spacecraft in orbit. Under clear, and cloudy conditions for local storms and global storms, insolation could reduce to 22%, 13% and 6.5% of that at Earth, respectively (see Figure 2). Latitude dependance of solar power generation is shown in Figure 3 throughout a Martian year (i.e., 668.6 days). Although the scale is not not relevant in this discussion, the z-axis represents the energy generated over a Martian sol (Wh/sol), with a 4.28 m^2 triple junction solar panel, planned for the 2007 Phoenix mission. (Note that a sol corresponds to 24.696 hours.) These issues will be further discussed under power trades.

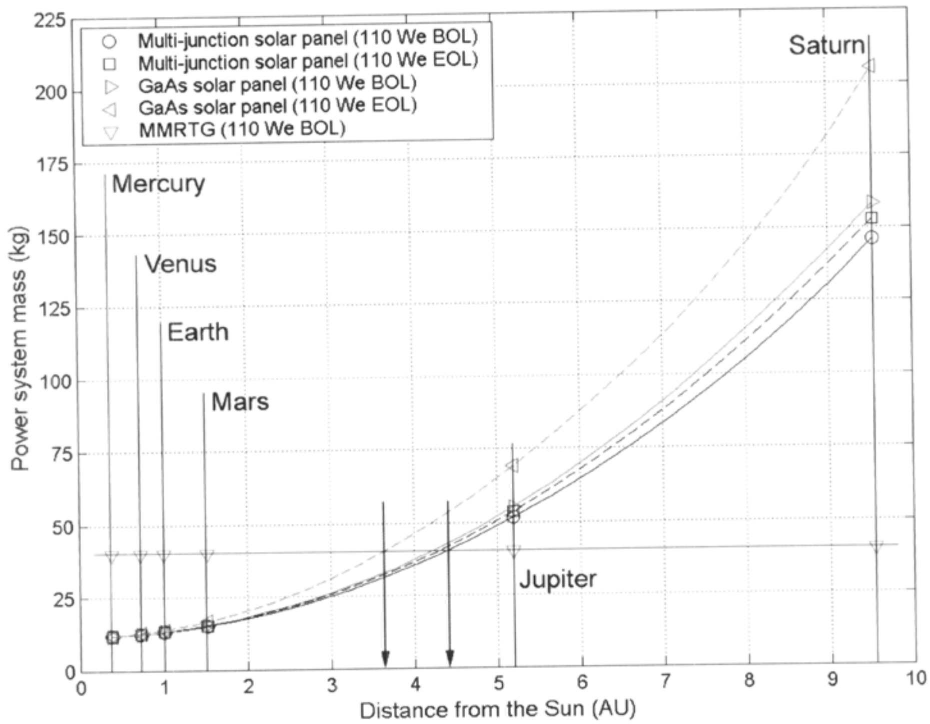

Figure 1: Comparison of power system mass between solar panels and a radioisotope power system, both assumed to generate 110 We, as a function of the distance from the Sun. Calculations show that beyond ~4 AU RPSs are more mass efficient than solar panel based power generation. In orbit around Mars solar panels are lighter than RPSs at the same power level. On the surface, however, insolation depends on several factors, that can make RPSs a viable, and in some cases the only practical, option.

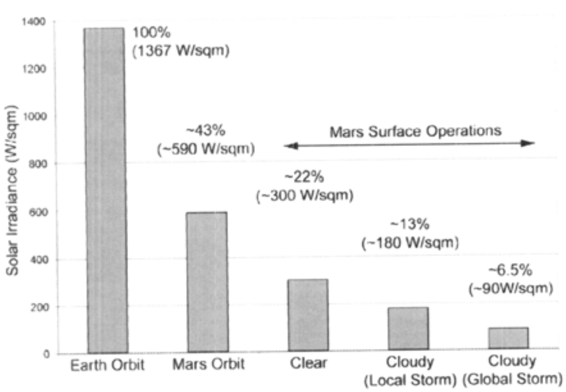

Figure 2: Solar Irradiation at Mars in W/m^2

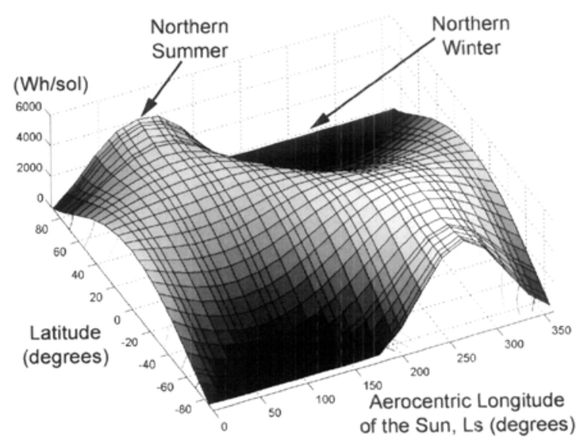

Figure 3: Energy from a 4.28 m^2 panel on Mars

RPS Based Power Generation

Radioisotope Power Systems (RPS) are powered by radioisotopic decay of the fuel. This technology could be used for both in-space and on-surface applications. RPSs convert heat to electricity. They consist of two main parts, namely a heat source and a power conversion system. The heat source includes the radioactive fuel, which is encapsulated in protective clad and shell layers. These units are called General Purpose Heat Source (GPHS) modules. There are 4 plutonium dioxide fuel pellets in each module. The masses for total plutonium fuel and for the GPHS module are 0.5 kg and 1.445 kg, respectively. The thermal power output for each module is $\sim$250 Wt at BOL. Modular design enables scalable power levels and thermal outputs, which is then converted into electricity through static (e.g., thermoelectric, TE) or dynamic (e.g., Stirling) conversion methods. RPS concepts have many unique capabilities as compared to conventional technologies, such as solar panels. They are self-contained; can operate continuously for an extended period of time; compact and strong; highly reliable; unaffected by radiation environments; and independent from solar energy. Current RPS development work envisions an operational lifetime of up to $\sim$15 years, although in the past this had been routinely extended, based on the predictable decay characteristics of the plutonium fuel (Pu^{238}), with a half-life of 87.75 years [6]. Although some of the past and present RPSs are listed in Table 1, this section will focus on a small-RPS concept only, using a single GPHS module [7].

Small-RPS Characteristics

Right sizing the power system for this set of next decade mission studies required a conceptual small radioisotope power system (RPS), which could generate power at a level below the 110 We of an MMRTG. A conceptual drawing of a single GPHS module based RPS is presented in Figure 4 [7] and is based on the works of Wiley & Carpenter [8]. It would use a single GPHS module with TE conversion (in a close-packed array, CPA, configuration). 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 $\sim$0.8% loss associated with TEs per year, while the exponential power reduction from radioisotopic decay of the plutonium fuel can be approximated at a rate of 0.79% per year [9]. The resulting total power system degradation is $\sim$1.6% per year. Based on these assumptions, a single GPHS module based RPS could generate $\sim$12.5 We of power (or $\sim$310 Wh/sol energy) at BOL and $\sim$11.72 We (or $\sim$290 Wh/sol) at EOL. (The calculated EOL values correspond to a 1 year cruise phase and 3 years of surface operation.) Due to the continuous power generation, waste heat must be rejected through all mission phases, including the cruise phase. The radiation environment of an RPS primarily consists of α particles. These particles are very heavy, energetic and slower moving than other types or radiation, which cause them to lose their energy very quickly in matter, since each interaction results in loss of energy. α particles can be stopped by a thin piece of paper or human skin. There is also a small amount of secondary radiation of γ rays and *neutrons*. The radiation impact from small-RPSs are found to be negligible [7] [10]. Acceleration load tolerance would be also an important design factor for RPSs. The two systems currently under development by NASA, MMRTG and SRG, are designed to tolerate the launch environment, which corresponds to about 40g. This would also allow for soft landing on a planetary surface. (Some of the mission concepts with small-RPSs could also consider hard or rough landing configurations, resulting in g-loads in the thousands, which would require special considerations.) The total mass of each small-RPS is assumed at $\sim$6 kg, with approximate bounding dimensions of 320 mm by 230 mm by 140 mm. The TE conversion efficiency for this system is conservatively assumed at 5%, although ongoing research performed in academia and industry indicate that this efficiency could be increased to around 10%, thus potentially doubling the power output.

RHU Based Power Source

Radioisotope Heater Units (RHUs) provide 1 Wt of thermal power with only 2.7 *grams* of fuel.

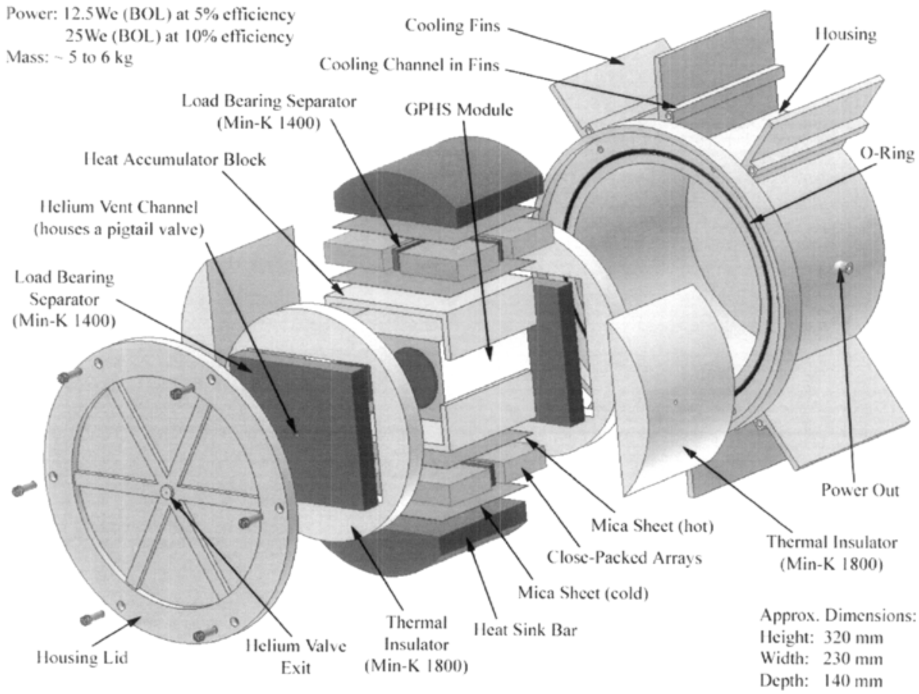

Figure 4: Conceptual small-RPS using a single GPHS module

A typical $3.2cm \times 2.6cm$ RHU weights 40 *grams* [11]. (The Galileo spacecraft used 120 RHUs.) An RHU could be also used as a power source by attaching a thermoelectric conversion module to it and packing the assembly into a protective shell. Power output could be increased by stacking several RHUs together. Such a system could generate electric power in the 20 to 160 milliwatts range [7].

POWER TRADES

For certain mission concepts, solar power generation has distinct advantages compared to RPSs out to about 3.5 to 4.5 *AU* from the Sun. However, because of its unique characteristics, there are instances where RPSs could provide benefits at locations closer to the Sun for example on Mars. This section examines the applicability of solar panels and RPSs on Mars.

The seasons on Mars are affected by the distance from the Sun and by the axial tilt of Mars (25.19°). It is evident from Figure 3 that at around $Ls = 90°$ the northern hemisphere enjoys summer, while the south pole does not receive any sunshine. The seasons are reversed between the hemispheres at around $Ls = 270°$. The asymmetry between the norther and southern summers or winters are due to the eccentric Martian orbit ($e = 0.093$). At perihelion ($\sim$1.38 *AU*) the north pole points away from the Sun (a simplification), thus the south pole receives high insolation, potentially sublimating the polar ice. This can cause both the atmospheric pressure and density to increase by up to 25%. The northern summer is longer – due to the lower orbital velocity at aphelion – but the insolation is lower too since Mars is farther away from the Sun ($\sim$1.65 *AU*). Therefore, mission designers must perform power system sizing by taking into account the arrival time, location and mission duration.

In orbit, solar panels could provide continuous power benefiting from the high solar flux, thus providing the best performance at the lowest cost (see Figure 7). Solar panels convert solar energy at efficiencies about 3 to 4 times higher than RPSs with TE conversion. (Dynamic – e.g., Stirling – conversion technologies, currently

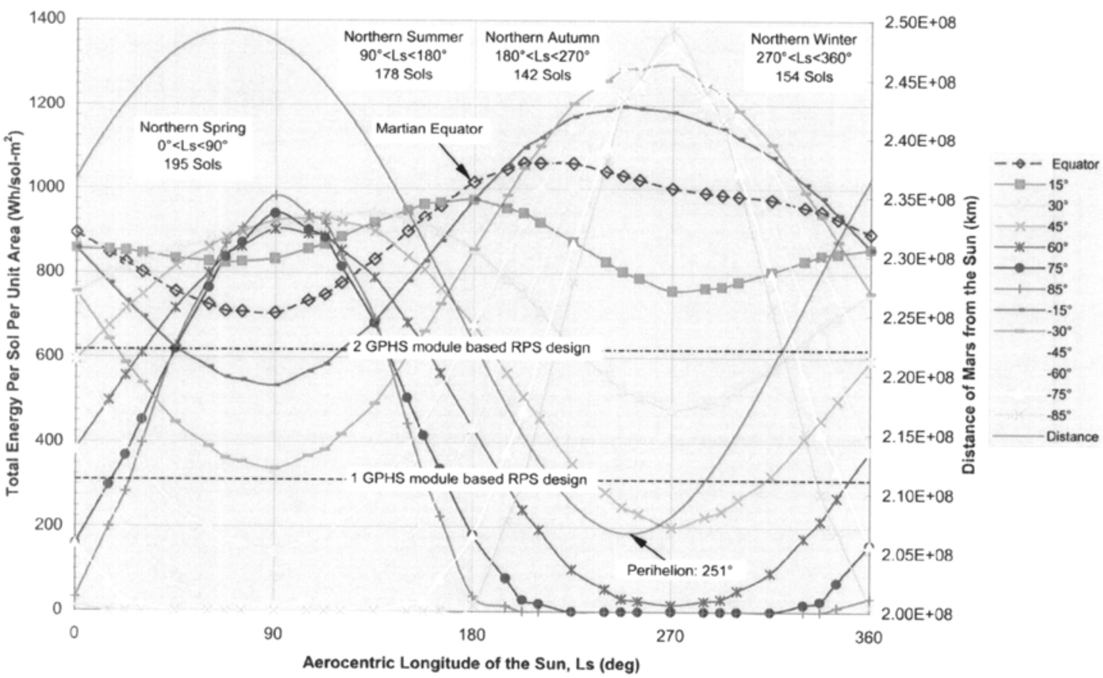

Figure 5: Power trades between small-RPSs and a $1m^2$ triple junction solar array

under development, would measure up to solar panels in terms of power conversion efficiency.) As shown in Figures 2 and 3 insolation on Mars varies significantly depending on location and season (among other variables). This can be further illustrated in Figure 5.

Continuous year around solar availability on the surface 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 for extended periods with solar panels is not practical due to seasonal variations, resulting in low solar insulation (or none) during polar winters. This low insolation places severe limitations on any mission concepts that might consider solar power.

In these regions, RPS could presents distinct advantages over solar panels. As noted previously, RPS-based power generation is independent of solar insolation and, for most practical purposes, atmospheric effects. RPS could also enable operation for extended periods (measured in years), which would translate into a longer mobility range for rovers that potentially allows for greater scientific returns and data accumulation. Therefore, RPSs would be ideal for power options for missions operating at high latitude regions, especially at the poles during winters. Similarly, RPSs could support 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 warm electronics box. This could reduce thermal cycling of the components, potentially decreasing component failures and extending operability. Batteries have tight temperature tolerances. Maintaining them at a constant 0°C would help to preserve battery performance and extend battery life. This attribute of RPSs is beneficial not only in Polar Regions, but at any given location on Mars (not to mention throughout the solar system). In comparison, solar powered systems would rely on batteries to heat components overnight using high-powered resistance heating.

Use of batteries to heat a spacecraft or rover impacts the lifetime of the batteries, uses up valuable resources and may result in an oversized power system, driven by system survivability requirements.

Power systems for all of the studied concepts were sized for total energy use over repeatable operational cycles (e.g., over a sol) and for peak power usage. During peak power usage a solar powered system would operate instruments with high power requirement and charge its batteries simultaneously. At nights the batteries would provide resistance heating to the instruments for thermal survivability. RPSs sized for a comparable total energy per sol would provide lower corresponding peak powers. This is due to the power generation characteristics of the two systems (i.e., periodic solar vs. continuous RPS). At high power mode operations (e.g., telecom, mobility, drilling) solar powered spacecraft would operate around Martian noon to benefit from peak power generation. RPSs could operate at any time during the sol, but would require to draw power from both the RPS and the batteries. Then the batteries would be recharged during low power operating modes. RHU based power systems could also use this hybrid power configuration. While the power source would not be powerful enough to perform high power mode operations directly, it could be used as a trickle charge device providing periodic operation with limited functionality. For this, beacons or other burst mode applications could be candidates.

The benefits of RPSs can be be further demonstrated through a comparison example between MER and a MER-size small-RPS enabled rover. MER employed solar panels for power generation. The unfolded 1.3 m^2 GaInP/SaAs/Ge triple-junction solar panels were capable of generating ~140 We (BOL) peak electric power for up to 4 hours per sol, depending upon the season. The total energy per sol was ~1000 Wh/sol at BOL and ~600 Wh/sol at EOL. Assuming that the small-RPS design would allow the units to be modular and stackable, two small-RPSs could generate a comparable ~620 Wh/sol at BOL. After an assumed 1 year cruise phase and 3 years of surface operation the power and energy at EOL would correspond to ~23.44 We and ~580 Wh/sol, respectively. The mass of the RPS would be (~12 kg), less than MER's 16.5 kg solar panels.

Figure 5 provides a comparison between power generated with a 1 m^2 solar panel and two small RPSs. As it was assumed a single GPHS module based RPS could generate 12.5 We which translates to about 310 Wh/sol. (Two small-RPSs would have the same approximate mass as a 1 m^2 solar panel.) The figure show that if a solar powered lander would require about 620 Wh/sol, for year around operation is would be limited to a region between about +20° and -10°, while an RPS could operate continuously.

HISTORICAL OVERVIEW

This section examines the relationship between energy generated by the power system and the power system mass and cost. The data presented here were extracted from historical databases, NASA Announcement of Opportunities (AO) and from open literature [11] [12]. A summary is provided in Table 1 and in Figures 6 & 7. The information includes "real" data at TRL9 (e.g., MER), "proposed" data at about TRL3 to TRL6 (e.g., MMRTG), and "estimated" data at very low TRL levels for systems in an early concept phase (e.g., small-RPS).

A comparison of energy as a function of the power system mass for various missions is shown in Figure 6. The total energy for all cases were normalized for a sol for better comparison. The figure can be divided in to 3 parts. Power generated in orbit is shown for a 140 We and for a 220 We solar power system. It is evident that high insolation combined with continuous solar availability results in a performance unmatched by surface operation. Solar power generation on the surface is based on BOL and EOL data points from MER, then scaled to 220 We, for comparison with two MMRTGs. (While MSL is currently considering a single MMRTG, an early designs planned for two units.) Although solar panel area and mass scales with power, the actual mass change would not be liner due to the increasing structural mass required to support the panels on a lander.) Early RPS systems, used on Voyager and Viking, performed at low power levels. The upper bound is represented by GPHS-RTGs, generating ~285 We powered by 18 GPHS modules. The Galileo and Cassini

Mission (or Concept)	Power Source	Mass kg	Power We	Energy Wh/sol	Cost $M FY03
Radioisotope Power Systems					
Cassini-Huygens	3 × GPHS-RTG	225	855	21084	125
Galileo	2 × GPHS-RTG	150	570	14056	85.7
Pluto/Kuiper Belt	1 × GPHS-RTG	75	285	7028	42.85
Voyager 1 & 2	MHW-RTG	38.5	150	3699	19.15
Viking	SNAP-19	13.4	40.3	994	28
MSL (early variant)	2 × MMRTG	80	220	5425	40
MSL (pre-decisional)	MMRTG	40	110	2713	20
-	SRG-110	34	110	2713	15
-	2 × SRG-110	68	220	5425	30
(2nd Generation, $\eta = 12\%$)	MMRTG	40	240	5918	N/A
(2nd Generation)	SRG	13.5	95	2343	N/A
(Small-RPS, $\eta = 5.5\%$)	1 × GPHS module	6	12.5	310	N/A
(Small-RPS, $\eta = 11\%$)	1 × GPHS module	6	25	620	N/A
(Teledyne, $\eta = 6\%$)	1 × GPHS module	4	15	370	N/A
(Teledyne, $\eta = 12\%$)	1 × GPHS module	4	30	740	N/A
Thermal power only					
Cassini-Huygens	157 × RHU	6.3	157Wt	3872Wt	0.57
Solar powered missions					
MER (BOL)	triple-junction	16.9	140	1000	3.27
MER (EOL)	triple junction	16.9	~100	~600	3.27
Mars Pathfinder	GaAs/Ge	0.34	16.5	93	-
MGS	GaAs & Si	-	980	24166	10.4
Mars Odyssey	GaAs	86	750	18500	27.7
MTO (BOL)	triple junction	78	1300	32058	6.3
MTO (EOL)	triple junction	78	1100	27126	6.3
MSR lander (BOL)	triple junction	77	973	6950	10.2
MSR ERV (BOL)	triple junction	23	810	19974	3.4

Table 1: Summary of power system mass, peak power, energy, and cost. For comparison purposes, the total energy for all entries are calculated from multiplying the power by 24.66 hours (1 sol), in effect normalizing for "Mars equivalent" energy values. The cost is adjusted for FY03. The first subgroup under RPSs represents existing power systems. The second set refers to power systems under development, while the third shows potential future RPSs, still in a conceptual development phase. RHUs are shown for completeness. Although concepts exist for RHUs as power sources, the example Cassini-Huygens mission employs them for local heating only. The first subgroup under solar power generation refers to past and present missions, while the second subgroup shows proposed future missions. (Note that these cost and performance values are approximate or based on projected estimates, therefore, they are provided for discussion purposes only. The presented information is assembled from open literature, which could result in potential inconsistencies, contributed to the way subcomponents are accounted for.)

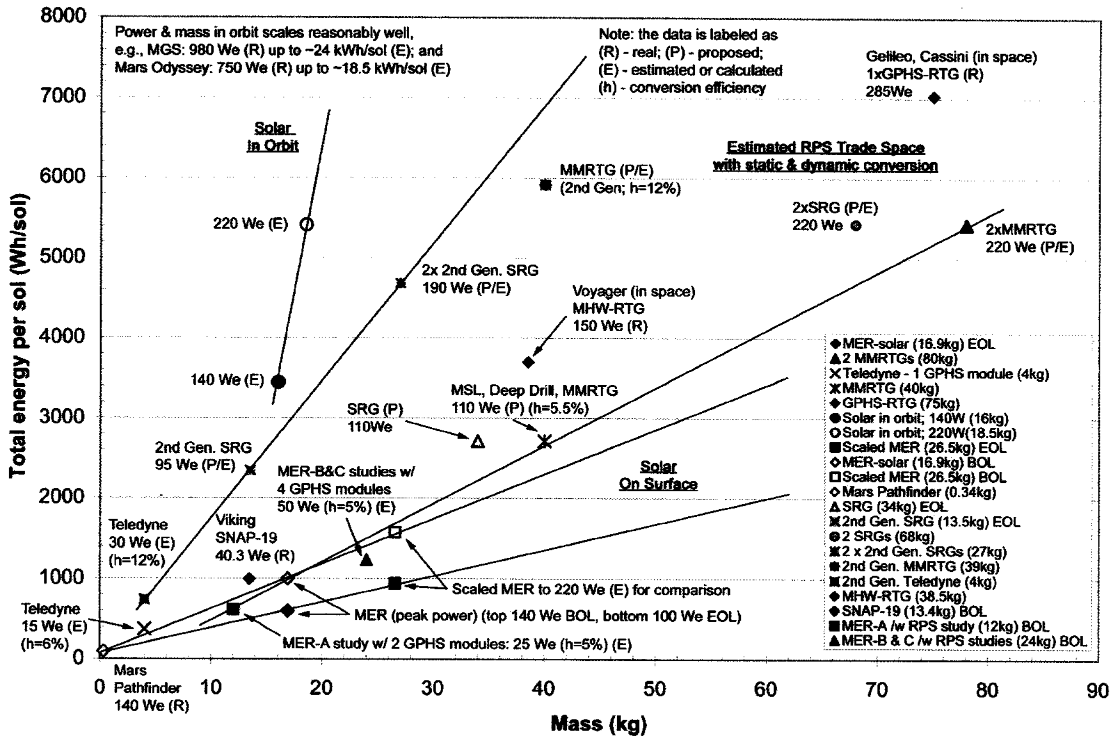

Figure 6: Power system mass for surface and orbital Mars missions with RPSs and solar power

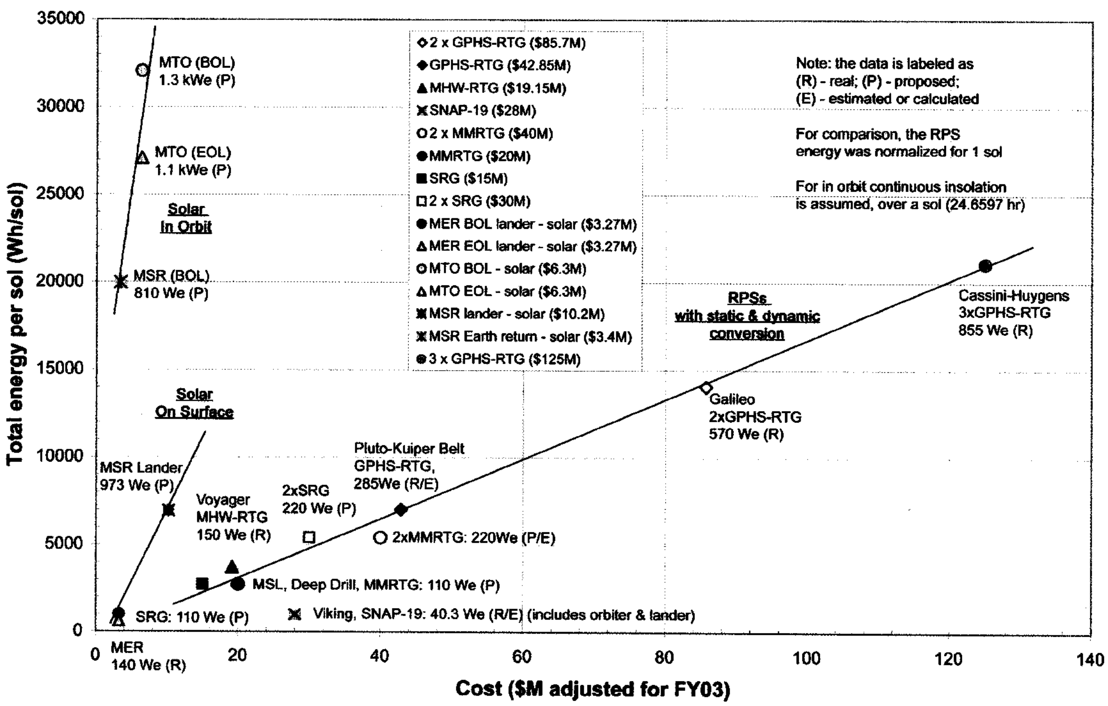

Figure 7: Cost of energy for surface and orbital Mars missions with RPSs and solar power

missions used 2 and 3 GPHS-RTGs, respectively. These systems are discontinued, the last GPHS-RTG is planned for the upcoming Pluto-Kuiper Belt mission. The next generation RPSs, currently under development, include the MMRTG and Stirling Radioisotope Generator (SRG) designs, each generating about 110 We. The first will use 8 GPHS modules and a static thermoelectric power converter ($\sim\eta_{conv} = 5.5\%$), while the second will use 2 GPHS modules and a dynamic Stirling converter ($\sim\eta_{conv} = 25\%$). Future development efforts will likely address mass reduction and conversion efficiency increase [11]. While still in a conceptual exploration phase, it is believed that the technologies are such that single GPHS module based power systems could be developed and offered as early as 2011, for the upcoming Mars Scout missions.

A similar comparison is provided for power generation as a function of power system cost, shown in Figure 7. This figure shows the relative linear nature of power versus cost for both solar panels and RPSs. (At Mars, solar panels are more efficient on orbital systems than on landed systems.) It also also depicts the relative price premium paid for the same amount of power from an RPS. Note that these values include the power system cost only. For RPSs there is an additional overhead to cover RPS provisional element costs (described in the New Frontiers AO [13]), which could add over $10M to the total cost. While cost is the highest for RPSs, it is shown in this paper that for some of the mission categories RPSs present the only option to achieve science and mission objectives.

POWER SYSTEMS FOR NEXT DECADE MARS MISSIONS

In a continuing effort, advanced studies were performed at JPL to address next decade Mars exploration missions. These mission concept studies can be divided into four categories. Surface mobility was addressed through rover studies. Subsurface access considered deep drills. Human precursor missions employed stationary lander concepts, sizes between the Phoenix lander and a heavy lander bound by near term EDL mass limits. A network of small landers were considered with a rough landing configuration. The last category explored Mars surface sample return concepts. High level details of these are provided below.

A rover mission would address astrobiology driven science goals, identified by MEPAG [14]. The rover could operate for up to 2-3 years on Mars, powered by small-RPSs. (Note that mission duration would be limited by potential component failures other than the RPS.) Studies indicated that $\sim$50 We of continuous electric power, supplemented by secondary batteries during high power modes, would be optimal for a rover slightly larger than MER. The 50 We could be achieved with 4 small-RPSs, each based on a conceptual design utilizing a single GPHS module. The rover could operate at any landing location on Mars, since the power source would not depend on solar flux. At latitudes above about $\pm60°$, power generation with solar panels would not be possible during the Martian winters. Therefore, mission requirements would not be met for year around operations. Due to the expected cell degradation, this conclusion on mission duration would likely apply to a rover operating near the equatorial region of Mars, where the solar flux is reasonably steady. Further analysis of this assumption will have to be performed, based on the latest knowledge gained through MER operations, which have far exceeded their original operational lifetime.

A deep drill mission with a subsurface access to 10 meters could operate with the same power configuration as the rover above. Deeper subsurface access, to $\sim$50 m, would require an MM-RTG class power source, generating $\sim$110 We. For deep drill missions analysis time for a predetermined number of samples on the lander, and turnaround time for science post-processing from Earth would define total mission duration. It was found that a larger power source could only speed up drilling operations, however, it would not reduce the time-line for the mission itself, due to these operational bounds. If the mission would target a latitude band between $\pm30°$, then solar panels could also be considered. However, certain combinations of arrival times, latitudes (which may be of particular interest to the science community) and mission durations would not be feasible, placing constraints on the

mission design.
A network of small landers could reach multiple locations and monitor the environment over an extended period of time, measured in years. Each lander would utilize crushable materials for landing, and use a small power system with a single GPHS module generating about 12.5 We on a continuous basis. Rough landing results in acceleration loads on the lander in the thousands of g's. For this, the g-load tolerance of the RPS power system should be enhanced, potentially requiring a customized development effort by NASA/DoE. Solar power generation, however, would constrain the landing location and mission time for these net landers. In addition, the mass and size allocation could result in potentially power limited landers, compared to a configuration enabled by a small-RPS.
Stationary landers would likely be used as human precursor testbed missions. These missions would operate on Mars for a nominal 90 days within a $\pm 30°$ latitude band, making solar panels suitable to power them. A suite of HEDS instruments planned for these missions would require a peak power level in the 400 to 600 We range and above. Therefore, future mission studies may consider using MMRTG class power sources and extending the mission duration in order to test in-situ resource utilization (ISRU) and life support system applications. However, this power range was beyond the scope of the present study.
A sample return mission would likely target an easily accessible region on Mars, close to the equator. The mission duration would be short and would not require a large science instrument suite. Landing a short mission with limited science goals at a region with high insolation would make solar power generation ideally suited for this type of a lander.
The Mars Program for the next decade will periodically include Mars Scout mission opportunities with a cost cap of $325M. These missions will have targeted science and mission goals at this low budget. Details on the missions are not yet available, but conceivably they could utilize either solar panels or small-RPSs for power generation. While at present small-RPS systems are only is a conceptual phase, it is conceivable that they could be offered for the 2011 Mars Scout mission opportunity.

CONCLUSIONS

The two themes of NASA's Mars program target scientific and robotic exploration. Science missions are planned to progress towards astrobiology driven objectives identified by MEPAG. Robotic exploration missions are designed as testbed missions to validate future technologies and to utilize resources for human precursor missions.
Historic data indicates that RPS based power generation is significantly more expensive than the solar equivalent. Therefore, selecting RPSs over solar panels for Mars exploration requires careful considerations.
As insolation decreases with the distance from the Sun, at around 4 AU a crossover exists between the mass of solar panels and RPSs at the same power level. Mars is only $\sim$1.5 AU from the Sun, with solar flux levels at $\sim$43% of that at Earth. In addition, power generation in orbit with solar panels can be considered continuous, making it more mass efficient than that with an RPS if within the 4AU crossover. When cost is taken into consideration, it is concluded that solar panels in orbit could be better suited to achieve mission objectives.
On the surface, however, insolation could vary from just over 20% of that at Earth to practically nil (e.g, at polar regions during winters). Mission duration also have a significant impact on power system selection and sizing. It was found that the trade space for next decade Mars missions accommodates both power technologies. In these studies high performance triple-junction GaInP/GaAs solar panels and single GPHS module based small-RPSs were considered. RHU based systems, generating power in the tens of milliwatts range, were found not applicable for the explored concepts. These power systems, nevertheless, could play roles as adjunct instruments to larger future missions or on small Scout class missions.
Study results indicated that for short surface missions at locations near the equatorial region (i.e., between $\pm 30°$) solar panels would provide the best option for power generation. A sample return type mission would fit into this category. A deep drill mission could use solar panels under some constraints, but RPSs would be

more enabling. For a 10 meter subsurface access 4 single GPHS module based small-RPSs (~50 We) could power the mission. For a 50 meter deep drill an MMRTG would be required. RPSs would also remove the constraints on landing location and mission duration. Rovers would clearly benefit from RPSs. A slightly scaled up MER class rover would require only 4 small-RPSs to achieve astrobiology related science objectives. In fact, these studies indicated that a MER size rover with the same or slightly modified instrument suite could operate with only 2 small-RPSs (~25 We; 620 Wh/sol) [7] over an extended mission duration (compared to MER). The upcoming missions in this decade will use both of these power technologies. For example the orbiters, MTO and MRO, will use solar panels. Future orbiters will likely follow this trend, due to solar availability. The MSL rover selected an MMRTG for its power source, which could enforce design heritage on future missions. Solar power generation will likely be accommodated on some of the surface missions as well. Mission concept studies over the past year demonstrated the feasibility of a number of potential missions, powered by conceptual RPSs providing only a fraction of the power generated by an MMRTG. Therefore, in order to expand the power trade space, it is suggested that next decade Mars surface missions could keep the option open for using small-RPSs should they become available.

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