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SEI Power Source Alternatives for Rovers and Other Multi-kWe Distributed Surface Applications

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ABSTRACT

To support the Space Exploration Initiative (SEI), a study was performed to investigate power system alternatives for the rover vehicles and servicers that would be used for construction and operation of a lunar base. Using the mission requirements and power profiles that were subsequently generated for each of these rovers and servicers, candidate power sources incorporating various power generation and energy storage technologies were identified. The technologies were those believed most appropriate to the SEI missions, and included solar, electrochemical, and isotope systems. The candidates were characterized with respect to system mass, deployed area and volume. For each of the missions a preliminary selection was made. Results of this study depict the available power sources in light of the mission requirements as they are currently defined.

INTRODUCTION

During the intensive mission analysis and system engineering activity that took place during the "90 day study" (Ref. 1) much of the attention focused on emplacement and operation of a lunar base. For the various mission architectures that were considered, estimates of the mission operations and major elements were developed in enough detail that design concepts for the major mission elements could be generated and their operating requirements identified to the component subsystems level (Ref. 2). Among these elements were rover vehicles and servicers. Six of these were identified, intended to service nine individual missions. These units and their missions were:

- Lunar Excursion Vehicle Payload Unloader (LEVPU)
- Mining Excavator
- Regolith Hauler
- Pressurized Rover
  - Long range man transport
  - Short range man transport
- Unpressurized Rover
  - Scientific/telerobotic mission
  - Man transport
  - Habitat emergency power
- Lunar Excursion Vehicle (LEV) Servicer

The estimates that were made for each unit included the approximate dimensions and mass, and the power required within its operational schedule. These parameters and requirements are listed in Table I. The power profiles (examples for the regolith hauler and pressurized long range rover are shown in Figs. 1 and 2) are estimates but they are traceable to the anticipated mission activities. The mass and volume allocation for each unit, delivered as cargo to the lunar surface, was limited. Since, for most of these elements the power source is the major component, it becomes a technology driver with major impact on the overall mass and volume.

POWER SYSTEM OPTIONS

The following power generation and energy storage technologies were considered:

- Solar Photovoltaic (PV)
- Hydrogen/Oxygen Primary Fuel Cell (PFC)
- Hydrogen/Oxygen Regenerative Fuel Cell (RFC)
- Pressurized Gas Reactant Storage for PFC's and RFC's
- Cryogenic Reactant Storage
- High Energy Density Sodium Sulfur Rechargeable Battery
- Radioisotope Thermoelectric Generators (RTG's)
- Dynamic Isotope Power Systems (DIPS)

These technologies are the only candidates known to be capable of meeting the mission requirements with flight hardware availability within the timeframe anticipated for the SEI (early 21st century). These technologies are at NASA Technology Readiness Level 4 (Critical functions or characteristics already demonstrated) or higher, and are either available now or anticipated through ongoing development programs.

Power source options using these technologies were generated against the nominal requirements of each mission. Options were selected if they appeared to be within the mass allowance for that unit. These selections were then characterized to meet the individual mission power profile. The characterizations included power and energy requirements, heat and mass flow rates under the various output conditions, all major components; their throughputs, efficiencies, capacities, sizes, weights and physical dimensions.

Two distinct approaches were taken depending on the degree of independence from other mission elements that was desired. The first approach, complete on-board power generation, took systems that are completely independent of the other mission elements. Examples would include PV/RFC and DIPS. The second approach, periodic refuel/recharge systems, took systems which must be periodically refueled or recharged from other elements of the lunar base; for example, vehicles which are driven to a central station for refueling. These systems would include rechargeable batteries and PFC's.

The power systems were characterized on the basis of their major sub-system components. These were represented by individual figures-of-merit from component technology developments reported in the literature. For example, figures-of-merit for primary fuel cell system major components include tankage (kilograms tankage per kilogram of reactant), the fuel cell power unit (kilograms per kilowatt), its radiator (kilograms per square meter) and so on. The figures-of-merit which were used, shown in Table II, are discussed further in Refs. 3 to 9.

For purposes of this study, the power system was defined to be those major components necessary to produce and deliver electrical power to a common busbar at an unspecified output format. For example, primary fuel cell systems included the fuel cell power unit, output power conditioning, reactants and tankage, and waste heat rejection. A structural mass allocation was also included based on component mass subtotals. No allocations were made for site installation, vehicle integration or maintenance hardware, support equipment, etc. Since shielding for the radioisotope systems can't be estimated until astronaut activity schedules and user vehicle configurations are better known, it was assumed to be negligible (more discussion about this later).

Results of the characterization were estimates of mass, volume (sum of the major components), and deployed area for each power system option considering each mission profile for that unit. These results are presented in Table III. The mass and volume estimates are obviously important for mission planning purposes. Deployed areas (solar array and/or radiator area) were also estimated because of their importance to vehicle systems, where compactness and insensitivity to orientation is desirable. When the power system requires surfaces which must be exposed outward, vehicle design must accommodate the deployed area and keep it properly oriented.

Desirable attributes of a power system would be a combination of minimum mass, minimum stowed volume and minimum deployed surface area. In order for a power system to be considered competitive for this study, it would have to be at least within the vehicle mass allowance, and no more than 1-1/2 times the mass, volume or area of the lowest option generated.

POWER SYSTEM OPTIONS VERSUS MISSIONS

The mission power profiles fell into two basic categories:

1. Cyclic operations and idle periods in daylight with limited lunar night operations or no night operations.
   (LEVPU, Regolith Hauler, Mining Excavator, Pressurized Rovers)

2. Continuous operation with no cycles or idle periods.
   (Unpressurized rovers, LEV servicer)

These categories proved to be a definitive discriminator between the power system options because they define the amount of energy storage required, and the available opportunities for replenishing or recharging. Consider the power system options for the regolith hauler, represented in Fig. 1. The power profile for this vehicle shows that peak power greatly exceeds the (steady-state) baseline power level but the energy expenditure of the peaks is minimal due to the short time peak power is applied. Since it is inactive periodically during the day and not used at all during the night (no power required) it can be refueled/recharged at relatively short intervals. Because of the limited amount of energy storage required for this vehicle and the long and frequent recharge periods available, solar arrays with electrochemical storage are adequate. Less mass and volume is associated with the energy storage components (battery, reactants and tankage) than the power handling components (arrays, electrolysers, converter units and power conditioning). As a result, significant advantage is seen for periodically refueled/recharged systems over on board power generation.

Although not competitive with primary fuel cells on a mass basis, the sodium sulfur battery deserves consideration because of its low specific volume. When a fully independent power system is necessary little difference is seen between the battery and RFC systems. An unshielded DIPS is competitive with, but not superior to, the solar/electrochemical options.

Similar results are seen for the LEVPU, Excavator, and short range pressurized Rover.

When the active period is increased from a few hours to several days, as in the case of the long range pressurized rover, (Fig. 2) the energy storage component becomes large enough to make batteries too heavy to consider, which leaves the fuel cell systems and DIPS as the only attractive options. Where periodic refueling/recharging is allowed the cryogenic reactant storage PFC remains competitive to DIPS, otherwise, the mass advantage of DIPS to the non-nuclear options is substantial.

When the active period is increased from several days to the entire lunar night, as in the case of the LEV servicer (Fig. 3), the energy storage component becomes so large that it completely dominates the system. The only non-nuclear option which might be considered for continuous power is the a PV array/regenerative fuel cell (PV/RFC) combined with cryo plant and tankage. More a stationary power plant than for vehicles, this option is at least twice the mass and volume of its DIPS equivalent.

From this study, the dynamic isotope power system appears as the option which is competitive for the greatest number of missions, and the only competitive option for mobile continuous power. Because its competitive attributes are more heavily influenced by application-specific factors than the other systems, further examination is warranted. For example, shielding may be required for manned operation, but the shielding is specific to the user vehicle configuration and operator schedule. Its impacts on the power system cannot be fully assessed until the mission requirements and user installations are better defined.

IMPACTS OF SHIELDING ON DIPS

Generally speaking a user of the DIPS must either accept certain operational constraints on manned activity or a penalty for shielding mass. Shielding mass can be minimized by restricting proximity to the DIPS, restricting the amount of time spent in close proximity, or a combination of both. Figure 4 shows the radiation dose received during a 90 day mission from a 2 kWe DIPS, versus the amount of shielding required for various separation distances. Figure 5 shows dose received at a 2 m separation distance, versus shielding required when exposure is limited to various percentages of the 90 day mission time. If the human user is unrestricted and in close proximity for long periods of time the shielding required to fully enclose it from all directions would outweigh both the power system and the rest of the installation. Transportation costs for this type of shield would be prohibitive.

Comparisons to the non-nuclear options were made assuming the user can accept operational constraints to avoid shielding. If operational constraints cannot be accepted, Fig. 6 shows the shield mass that would be required to reduce the 90 day mission dose experienced in the vicinity of the DIPS to 22 REM, versus separation distance from the power system according to the geometry of Fig. 7. A 2 m diameter dose plane was assumed. The analysis considers attenuation only; secondary gamma production, backscattering effects (and self shielding) have been ignored. At short separation distances (2 m or less) shielding mass exceeds the balance of the power system. There is a comparison of a shielded DIPS to an unshielded DIPS in Fig. 2 ("On Board Power Generation") according to the criteria discussed above, which can be compared to the non-nuclear cryo primary fuel cell shown next to it ("Periodic Refuel/ Recharge"). Twenty-two REM is the maximum dose which would be allowed from man-made sources after exposure to natural radiation sources are considered (total allowed: 50 REM). Clearly there is an incentive to configure a DIPS installation so that it is separated from the human user and restricted in its access.

Where complete enclosure with shielding is required, use of locally obtained material for shielding is a more reasonable approach. Some powerplants could be shielded by partial burial of the DIPS heat source assembly (HSA) and converter leaving the radiator exposed; for mobile powerplants, surrounding the HSA with soil perhaps enclosed in bags or a container mounted on the vehicle platform. Figure 8 shows the thickness of lunar soil versus "keep clear" distance, that is required to limit exposure to 5 REM/yr. Five REM/yr is a reasonable value for stationary applications such as a habitat where prolonged exposure times would be expected.

ENVIRONMENTAL INTERACTIONS EFFECTS ON POWER SYSTEM OPTIONS

Because any power system must reject waste heat to its immediate surroundings, it will be in turn influenced by the surroundings into which it is placed. Not all the environmental interactions are known at this time but our present understanding of the mission environment, and the fundamental characteristics of the power system, allows us to identify some of the major interactions and estimate their impacts.

The first effect to consider is equivalent sink temperature. For any power system that radiates waste heat (this includes fuel cells and batteries as well as DIPS) the sink temperature determines how much radiator area will be required. Equivalent sink temperature results from the energy balance of solar radiation absorbed and background temperatures of the surroundings it is exposed to, and the energy emitted at that temperature before power system thermal loads are applied. The objective is to design the radiator and orient it such that the equivalent sink temperature is kept as low as possible under all conditions. Figure 9 gives representative equivalent sink temperatures for horizontal and vertically oriented flat plate radiators on the surface of the moon as a function of sun angle. The value that is actually used for system design will depend on the mission. At the extremes, SEI surface elements on the moon can experience equivalent sink temperatures ranging as low as 220 K, for a stationary vertical radiator installation oriented edge-on to the sun and employing selective emissivity coatings with a reflective sheet at its base, to as high as 384 K for a vehicle radiator unable to employ selective coatings or reflective sheets, and whose orientation and surface view factor cannot be controlled. This can affect the way a system is optimized for the mission. Figure 10 shows comparison of Brayton DIPS optimized for 384K and 220K. The higher sink temperature unit must elevate its radiator temperature by operating at a reduced temperature ratio. This reduces cycle efficiency, which in turn requires more heat source and radiator area. The overall mass penalty is 32 percent.

The presence of dust stirred up from the lunar surface will have negative effects on radiator performance. A thin layer of dust can change surface absorptivity/emissivity (Ref. 10); any appreciable layering of dust will greatly increase thermal impedance to the radiating surface. The effect of dusting on a Brayton DIPS which results from changes to its radiator surface is to raise equivalent sink temperature and thus (the isotope heat source is essentially a constant input) increase all cycle temperatures, including the turbine inlet temperature (TIT). Converter performance and life are reduced. For this off-design condition, it is possible to return TIT to its original value by raising the turbine speed, but at the expense of further reduction in performance. On the other hand if the Brayton cycle were re-optimized to accommodate the dusted condition, original performance and TIT is achieved by a 5 percent increase in heat source and a 22 percent increase is radiator area. The overall mass penalty is about 5 percent compared to the "undusted" case.

Another environmental effect that impacts the radiator is meteoroid attack. On the moon the probability of puncture is high since the lunar surface is exposed to constant bombardment by meteoroids of all sizes. The larger ones occur relatively infrequently but smaller ones become more numerous with decreasing size (Ref. 11). On the Moon, the lack of atmosphere creates a high probability that the power system will be struck at least once during the mission (Ref. 12). It may be possible to shield most of the power system by partial burial or by careful location aboard the user vehicle, but in any event the radiator must remain exposed in order to do its job. For a 15 year mission, probability of an unarmored radiator (0.010 in. wall thickness) escaping puncture is less than 95 percent for any exposed area greater than 3 cm^2. Since all of the radiators considered exceed this area, a puncture is virtually unavoidable. It will be necessary to either armor the radiator, add redundant capacity in parallel, or apply both strategies in combination to ensure a high enough probability of radiator survival to meet the failure criteria of Ref. 2.

Generally a redundancy factor of approximately 20 percent, in combination with modest levels of armoring, results in the lowest mass for meteoroid survival probability levels exceeding 99 percent (Ref. 13). Figure 11 shows the relation between armored heat pipe mass versus redundancy for three constant levels of survivability for heat pipe radiators applied to a 2.5 kWe Brayton DIPS on the lunar surface. Heat pipes are preferred for meteoroid survivability because of they are modular and result in a radiator composed of redundant elements.

CONCLUSIONS

The power technologies that could be developed to the flight hardware phase within the SEI timeframe can produce power system options that meet the requirements for lunar surface elements as they are presently defined. The power system will be a significant component of mass; typically a third to a half the mass budget. With only one exception most of the options fall within the vehicle mass allocations. In the case of the Mining Excavator all the power systems exceed the vehicle allowance except for the cryo storage equipped PFC.

Where the missions are restricted to daytime operation and idle periods are allowed, it is possible to reduce mass, volume and deployed area of power systems by resorting to periodic refueling/recharging. No advantages are seen for nuclear power sources in this regime. When the mission period extends through the lunar night, energy storage considerations render the non-nuclear options uncompetitive. The DIPS emerges as the primary choice for these missions. More definition is needed since the DIPS attributes are heavily influenced by vehicle configuration and crew schedule which is unspecified at this time.

The power system options will be influenced by environmental effects (thermal background, dust, meteoroids), which indirectly drive the system design parameters.

This study provides a characterization of the best available power technologies when they are applied to presently defined SEI lunar surface mission requirements. This is done so that the mission planner and power system user can evaluate the proposed mission scenarios in the light of the mass, stowed volume and deployed area of power systems that would be needed to support them. This evaluation could result in changes to the scenario, which in turn could change the requirements. This process is iterative and ongoing. Presently there is less definition in the missions than in the power system options. As the missions become better defined, discrimination between the options will become clearer.

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TABLE I.—MISSION ELEMENTS AND SPECIFIED REQUIREMENTS

Mission element	Mission								
	LEVPU	Mining excavator	Regolith hauler	Pressurized rover		Unpressurized rover			LEV servicer
				Short range	Long range	Scientific telerobotic	Man transport	Recharge and emergency power	
Crew size:									
Maximum	1	1	1	4	4	4	4	4	0
Minimum	0	0	0	2	2	0	0	0	0
Capability:									
Payload lifting and hauling capacity, kg	10 000	750	750	(a)	(a)	1200	1200	1200	(a)
Average velocity, m/s	1	2	2	2.8	2.8	2.8	2.8	2.8	(a)
Maximum slope, deg	6	6	6	20	20	20	20	20	(a)
LEV payload mass allocation, kg	15 000	1000	1000	4500	6000	600	600	600	(a)
Power requirement, kWe:									
Peak	10	40	15	(a)	(a)	3	0.7	5	10
Nominal	3	22	3	7	12	2	0.3	5	10
Standby	3	10	1.5	3	(a)	(a)	(a)	5	10
Operation parameters per cycle, hr at–									
Peak power	1	1	1	(a)	(a)	16	336	(a)	8560
Nominal power	11	8.6	8	10	96	24	336	960	8560
Standby	0	1.4	1.4	0	(a)	0	(a)	0	8560
Inactive	12	13.6	13.6	14	48	0	(a)	0	0

[a]No specification.

TABLE II.—SELECTED POWER SYSTEM TECHNOLOGIES AND PERFORMANCE

(a) GaAs/Ge PV array

Specific power, W/kg	94
Specific mass, kg/m^2	2.05
Efficiency, percent	18.3

(b) Electrical power management and distribution (PMAD)

Specific mass, kg/kWe	10
Specific volume, m^3/kg	0.00025
Efficiency, percent	90

(c) Batteries

IPV NiH battery:	
Cell capacity (at 100 percent DoD), A-hr	81
Operating DoD, percent	50
Operating temperature, K	293
NaS battery:	
Cell capacity (at 100 percent DoD), A-hr	54.7
Operating DoD, percent	80
Operating temperature (radiates directly to space), K	623

(d) Fuel cell systems

Hydrogen-oxygen alkaline fuel cell:	
Current density, mA/cm^2	215–1075
Cell active area, m^2	0.092
Operating pressure, MPa	0.4
Operating temperature, K	355
Conversion efficiency, percent	70
Electrolyser:	
Current density, mA/cm^2	215
Cell active area, m^2	0.092
Operating pressure, MPa	2.2
Operating temperature, K	355
Conversion efficiency, percent	83
Radiator:	
Effective emissivity	0.595
Specific mass, kg/m^2	5
Rejection temperature, K	355
Sink temperature, K:	
Day	220
Night	20

(e) Radioisotope thermoelectric generator (RTG)

Heat source	GPHS
Generator	Mod-RTG
Heat rejection, K	525
Specific power, W/kg	7.7

(f) Dynamic isotope power system (DIPS)

Heat source	GPHS
Engine	Brayton cycle
TIT, K	1300
Temperature ratio	4.15
Recuperator effectivene	0.88
Efficiency, percent	30
Radiator	Double sided
Temperature range, K	484–295
Emissivity	0.8
Specific mass, kg/m^2	2.44
Sink temperature, K:	
Day	250
Night	20

(g) Fuel cell reactant storage

Low pressure storage, psi	300
Tankage specific mass, kg per kg reactants	2.7
Specific volume, m^3 per 1000 kg reactants	116
High pressure storage, psi	3000
Tankage specific mass, kg per kg reactants	2.4
Specific volume, m^3 per 1000 kg reactants	14.6
Cryostorage, psi	15
Specific volume, m^3 per 1000 kg reactants	2.6
Tankage mass, kg per m^2 enclosure	42
Cryoliquifier plant:	
Liquid hydrogen refrigeration	
Capacity, kg/kW refrig. at 20 K	69.6
Effectiveness, kW-hr per kg H_2 liquified	12.2
Liquid oxygen refrigeration	
Capacity, kg/kW refrig. at 77 K	7.88
Effectiveness, kW-hr per kg O_2 liquified	0.89

TABLE III.—POWER SYSTEM OPTIONS—MASS VOLUME AND AREA CHARACTERIZATION

(a) Periodic refuel or recharge

Power system option	Mission								
	LEVPU	Mining excavator	Regolith hauler	Pressurized rover		Unpressurized rover			LEV servicer
				Short range	Long range	Scientific telerobotic	Man transport	Recharge and emergency power	
Primary fuel cell with 3000–psi reactant storage:									
Mass, kg	283.6	1137.8	379.2	297.8	1811.4	—	—	—	—
Stowed volume, m^3	1.302	5.351	1.767	1.1838	7.62	—	—	—	—
Deployed area, m^2	13.3	52.9	19.76	9.29	15.95	—	—	—	—
Primary fuel cell with 300–psi reactant storage:									
Mass, kg	305.1	1234.3	399.7	330.3	2210.7	—	—	—	—
Stowed volume, m^3	3.47	17.49	3.815	4.694	65.453	—	—	—	—
Deployed area, m^2	13.3	52.9	19.76	9.29	15.95	—	—	—	—
Primary fuel cell with cryostorage:									
Mass, kg	272.1	992.9	369.1	269.9	992.4	—	—	—	—
Stowed volume, m^3	1.437	4.485	1.901	1.281	4.443	—	—	—	—
Deployed area, m^2	13.3	52.9	19.76	9.29	15.95	—	—	—	—
Regenerative fuel cell with 3000–psi reactant storage:									
Mass, kg	410.6	1494.5	499.2	437.2	2228.2	—	—	—	—
Stowed volume, m^3	1.45	5.755	1.909	1.345	8.088	—	—	—	—
Deployed area, m^2	13.3	52.9	19.76	9.29	15.95	—	—	—	—
Regenerative fuel cell with 300–psi reactant storage:									
Mass, kg	432.6	1594.5	519.7	469.7	2627.5	—	—	—	—
Stowed volume, m^3	3.618	17.894	3.956	4.855	65.921	—	—	—	—
Deployed area, m^2	13.3	52.9	19.76	9.29	15.95	—	—	—	—
Sodium/sulfur battery system:									
Mass, kg	640	3448	674	955	—	—	—	—	—
Stowed volume, m^3	0.3217	1.648	0.353	0.437	—	—	—	—	—
Deployed area, m^2	0.81	3.26	1.22	0.57	—	—	—	—	—

(b) Onboard power generation

Power system option	LEVPU	Mining excavator	Regolith hauler	Pressurized rover: Short range	Pressurized rover: Long range	Unpressurized rover: Scientific telerobotic	Unpressurized rover: Man transport	Unpressurized rover: Recharge and emergency power	LEV servicer
PV array/regenerative fuel cell with 3000–psi reactant storage:									
Mass, kg	541.1	2115.7	604.8	—	3060.3	—	—	—	—
Stowed volume, m^3	1.794	7.392	2.187	—	10.282	—	—	—	—
Deployed area, m^2	46.1	209.1	46.36	—	225.25	—	—	—	—
PV array/regenerative fuel cell with 300–psi reactant storage:									
Mass, kg	562.6	2212.2	625.3	—	3459.6	—	—	—	—
Stowed volume, m^3	3.962	19.531	4.235	—	68.115	—	—	—	—
Deployed area, m^2	13.3	209.1	46.36	—	225.25	—	—	—	—
PV array/regenerative fuel cell with cryoliquifiers and storage:									
Mass, kg	—	—	—	—	—	—	—	—	3049.4
Stowed volume, m^3	—	—	—	—	—	—	—	—	12.846
Deployed area, m^2	—	—	—	—	—	—	—	—	159.3
PV array/sodium sulfur batteries:									
Mass, kg	732.7	3910	752.2	—	—	—	—	—	—
Stowed volume, m^3	0.5647	2.8635	0.5584	—	—	—	—	—	—
Deployed area, m^2	38.2	119.3	20.82	—	—	—	—	—	—
Dynamic isotope power system[a]:									
Mass, kg	808	2800	1150	570	970	290	97	450	808
Stowed volume, m^3	2.8	10	4.05	2	3.4	1	0.34	1.6	2.8
Deployed area, m^2	35	120	50	26	42	13.5	4	19.5	35
Dynamic isotope power system[a] with sodium/sulfur battery for peak:									
Mass, kg	458.4	1930	660	—	—	210.41	—	—	—
Stowed volume, m^3	1.3	6.247	1.47	—	—	0.734	—	—	—
Deployed area, m^2	15.07	72.46	17.2	—	—	9.03	—	—	—
Radioisotope thermoelectric:									
Mass, kg	—	—	—	—	—	—	122	—	—
Stowed volume, m^3	—	—	—	—	—	—	0.89	—	—
Deployed area, m^2	—	—	—	—	—	—	2.9	—	—

[a]Shielding mass not included.

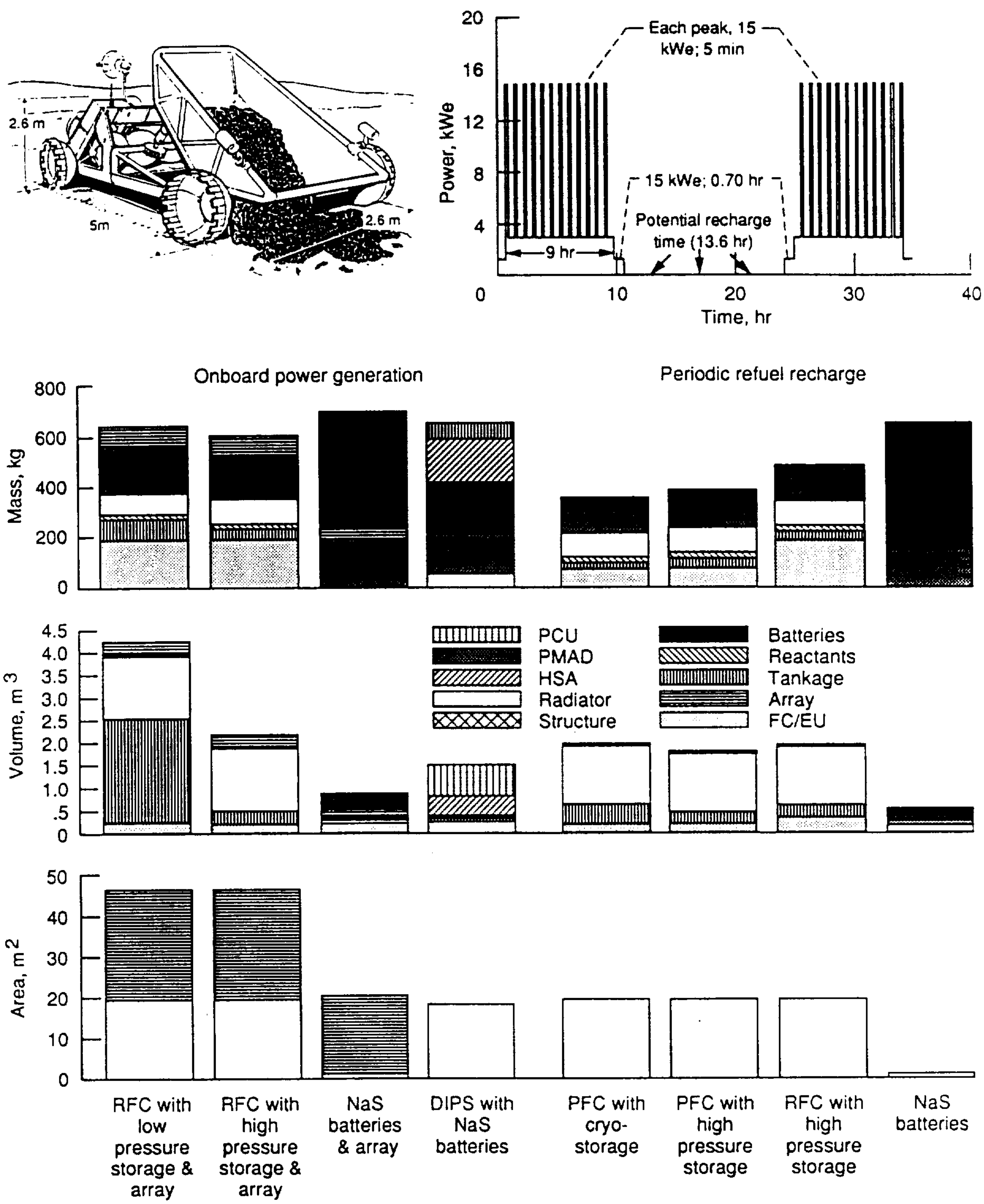

Figure 1.—Regolith hauler.

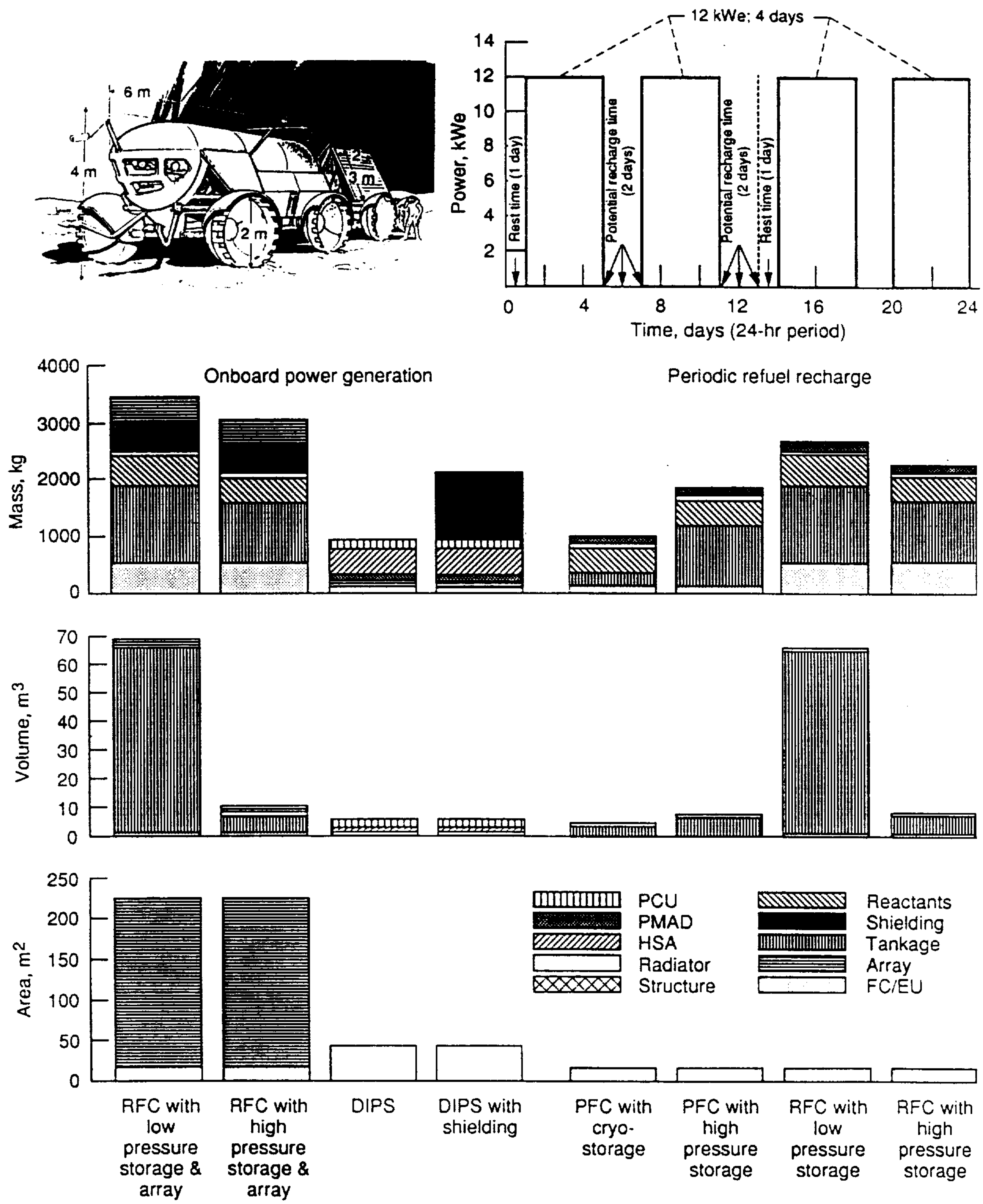

Figure 2.—Pressurized long range rover.

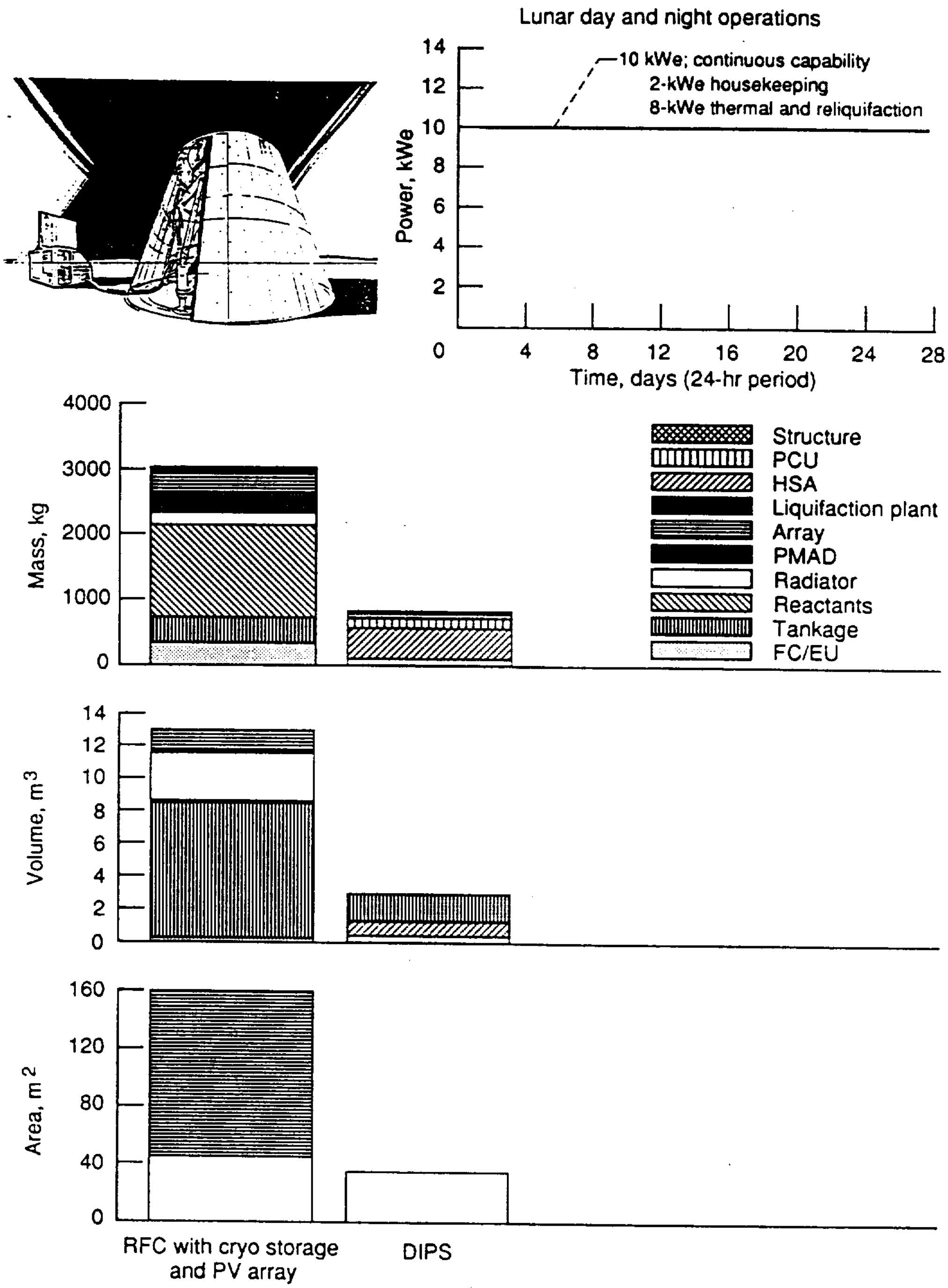

Figure 3.—LEV servicer, LEV housekeeping, thermal control, and reliquifaction of H_2/O_2.

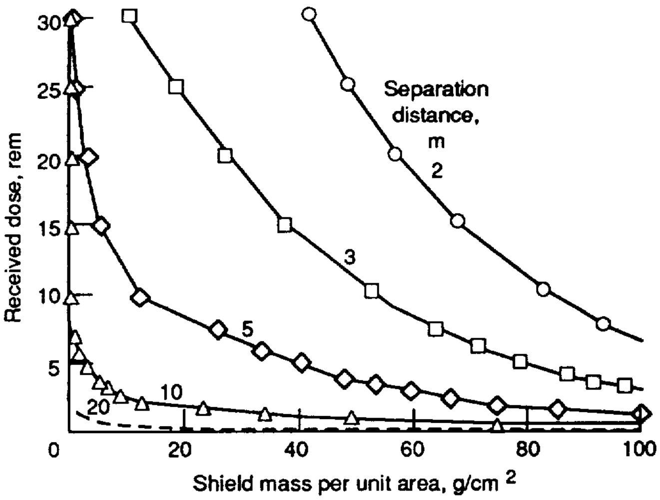

Figure 4.—Dose from 2-kWe DIPS, 90-day mission, 100 percent exposure for various separation distances.

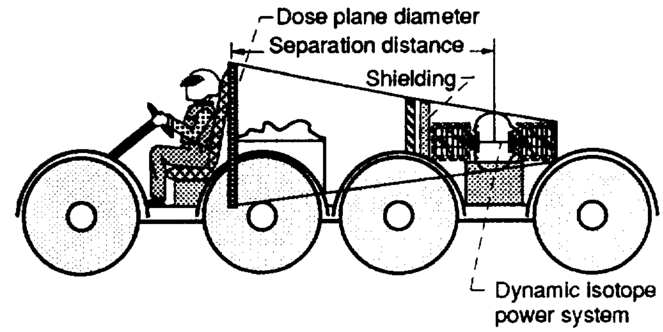

Figure 7.—Shadow shielding geometry.

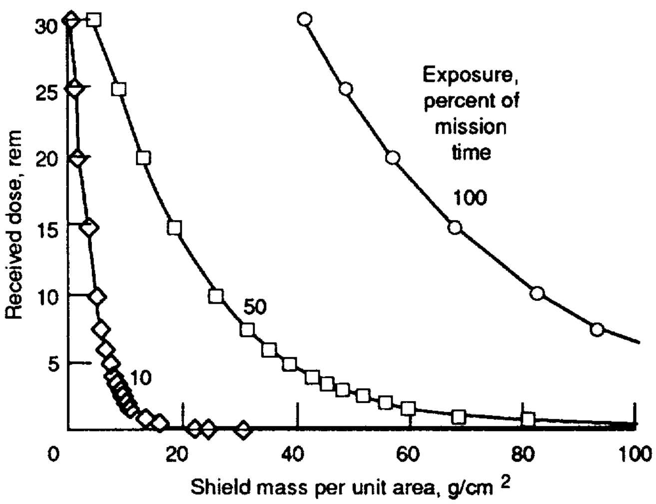

Figure 5.—Dose from 2-kWe DIPS, 90-day mission, 2-m separation distance for various exposures.

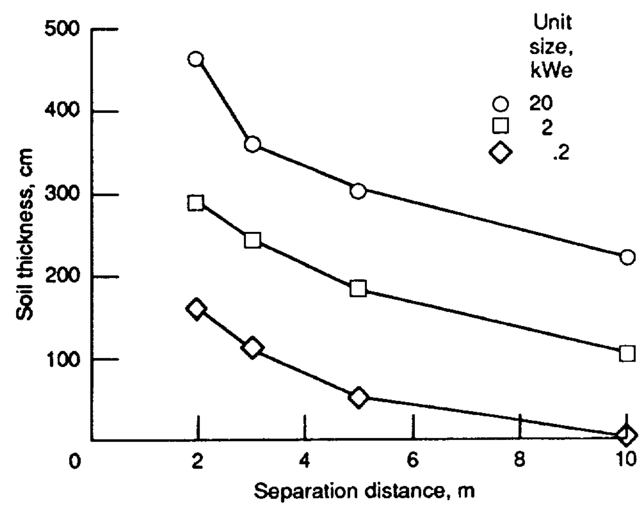

Figure 8.—Lunar soil thickness needed versus separation distance. Allowed dose, 5 rem/yr .

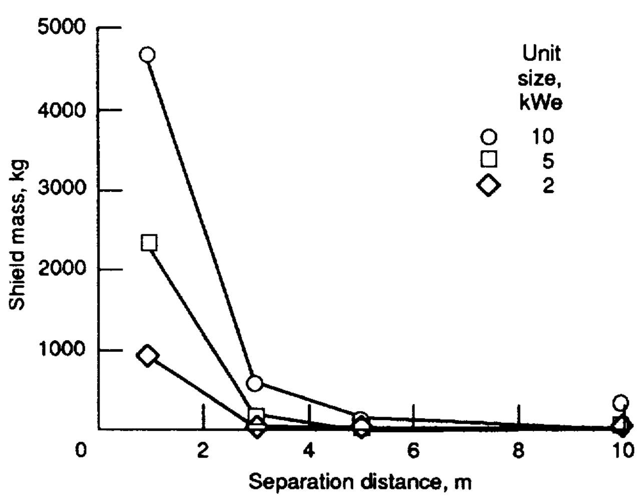

Figure 6.—Shadow shield mass versus separation distance. Allowed dose, 22 rem/90 days.

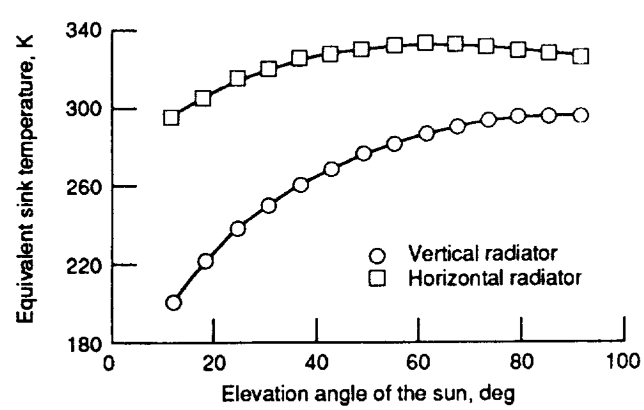

Figure 9.—Sink temperatures for lunar radiator, vertical and horizontal configurations (emissivity, 93%; solar absorptivity, 30%), radiator located at the equator and oriented along the meridional plane.

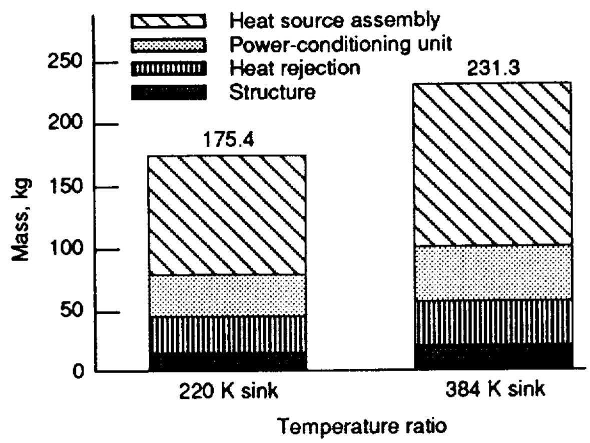

Figure 10.—2-kWe Brayton DIPS optimized for two different sink temperatures on the Moon.

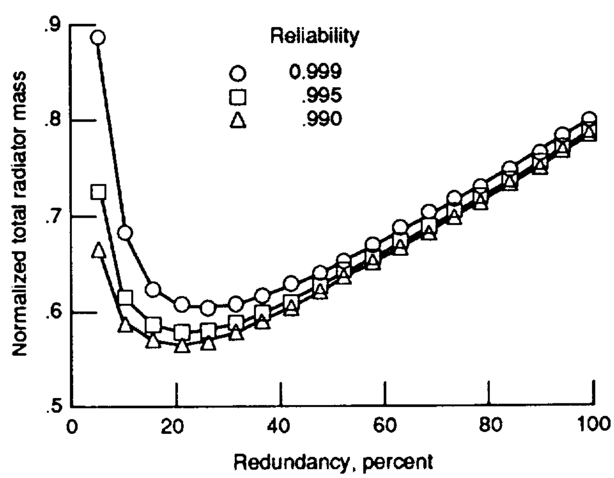

Figure 11.—Segmented radiator mass versus redundancy (normalized to fully armored non-redundant case).

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15. Supplementary Notes

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16. Abstract

To support the Space Exploration Initiative (SEI), a study was performed to investigate power system alternatives for the rover vehicles and servicers that would be used for construction and operation of a lunar base. Using the mission requirements and power profiles that were subsequently generated for each of these rovers and servicers, candidate power sources incorporating various power generation and energy storage technologies were identified. The technologies were those believed most appropriate to the SEI missions, and included solar, electrochemical, and isotope systems. The candidates were characterized with respect to system mass, deployed area and volume. For each of the missions a preliminary selection was made. Results of this study depict the available power sources in light of the mission requirements as they are currently defined.

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