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# POWER REQUIREMENTS FOR THE NASA MARS DESIGN REFERENCE ARCHITECTURE (DRA) 5.0

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**Abstract** - *This paper summarizes the power systems analysis results from NASA's recent Mars DRA 5.0 study which examined three architecture options and resulting mission requirements for a human Mars landing mission in the post-2030 timeframe. DRA 5.0 features a long ~500 day surface stay "split mission" using separate cargo and crewed Mars transfer vehicles. Two cargo flights, utilizing minimum energy trajectories, pre-deploy a cargo lander to the surface and a habitat lander into a 24-hour elliptical Mars parking orbit where it remains until the arrival of the crew during the next mission opportunity ~26 months later. The pre-deployment of cargo poses unique challenges for set-up and emplacement of surface assets that results in the need for self or robotically deployed designs. Three surface architecture options were evaluated for breadth of science content, extent of exploration range/capability and variations in system concepts and technology.*

*This paper describes the power requirements for the surface operations of the three mission options, power system analyses including discussion of the nuclear fission, solar photovoltaic and radioisotope concepts for main base power and long range mobility.*

## I. INTRODUCTION

NASA has completed a study of architecture options for a human Mars mission. As would be expected, power needs vary with the breadth of possible capabilities and mission architectures. Three architecture options were evaluated for their power requirements. Each of these architectures was then compared. Two power system technologies were considered as prime power sources, solar photovoltaic arrays with energy storage and nuclear fission. In addition to a prime power source, the architecture for Options 1 and 2 called for long-range crew mobility to expand the range of exploration beyond the immediate vicinity of the base and power systems for these mobile systems was also analyzed.

## II. MARS ENVIRONMENTAL FACTORS

The Mars environment is significantly different than the Moon's such that special consideration must be given to the design and operation of surface power systems. The Sun's light intensity is reduced at Mars' orbit 1.4 AU perihelion to 1.67 AU aphelion and additionally surface solar power systems are influenced by seasonal day/night cycles based on outpost latitude. Suspended atmospheric dust and variable intensity and duration dust storms also have a major impact on the design.

The effect of atmospheric dust on solar intensity at the surface is expressed in terms of the atmosphere's optical depth. The total optical depth, tau ($\tau$), is a measure of the quantity of light removed from a beam, by scattering ($\tau_s$) and absorption ($\tau_a$), from its path from the upper edge of the atmosphere to the planet surface. A tau of 0 corresponds to no scattering or absorption; all the incoming light reaches the surface. A significant amount of the sunlight is scattered by the dust; of this, some reaches the surface, while some is scattered back into space. Thus, although the direct solar intensity on the surface decreases with the amount of dust in the atmosphere, the actual intensity of the illumination on the surface is a mixture of direct and scattered sunlight with a complicated dependence on the amount of dust in the atmosphere and the sun angle. Data from the MER rovers indicated that a nominal day on Mars has an optical depth of about 1.0- 0.90[1].
Another important design consideration is the light blocked by dust that settles on the array surface. Data from the Pathfinder rover

Sojourner showed a 0.2% power loss per sol (1 sol = 1 Martian day). The MER rovers also experienced a similar degradation rate[1]. The rover Spirit had an estimated dust loss of ~30% by sol 300 and 40% by sol 400[2]. Results of short circuit solar cell tests on Opportunity confirm power losses due to dust accumulation[2]. However, a major "clearing event" occurred on sol 418, restoring array power to 90% followed by a slow decline down to 70% after another 100 sols. The clearing event occurred when the rover was at a 22º tilt and atop a ridge, which seems to suggest that in addition to increased wind speed the angle to the array surface plays some part in this cleaning effect. This surface feature may have contributed to a localized increase in wind speed or possibly turbulence not normally encountered in flatter terrains. It was felt that the rover tilt angle had a large part to play in the dust removal. Test results of past wind tunnel testing in a simulated Mars environment also showed greater dust removal at high "angles of attack" [3].

A third major environmental concern is the frequency, duration and severity of a Mars dust storm. Reviewing past observations by telescope, Viking and MER show dust storms to occur during northern hemisphere winter when Mars is closest to the sun in its orbit when temperature difference between the northern and southern hemispheres tends to be the greatest. These larger temperature differences create conditions for higher winds to occur and suspend the fine surface dust in the atmosphere. The 2007 storm that occurred with the MER rovers has provided excellent data to observe photovoltaic array performance under varying levels of $\tau$. Fig. 1 is a chart from Mark Lemmon, MER Science Team, of the daily values of $\tau$ during the 2007 dust storm (and compared to Viking observations). Correlating the dust data with reported array daily energy for Opportunity of 128 W-hr on July 17, 2007 and the early mission "clear day" energy of ~ 900 W-hr the array provided, ~ 14% of the maximum possible average power is produced during the worst part of the storm. As a note, both MER rovers had eight 1.0 W (thermal) radioisotope heater units (RHUs), six for the battery and two for electronics. The heat from the RHUs helped the rovers survive during the dust storm by keeping circuits warm and preventing the battery from freezing.

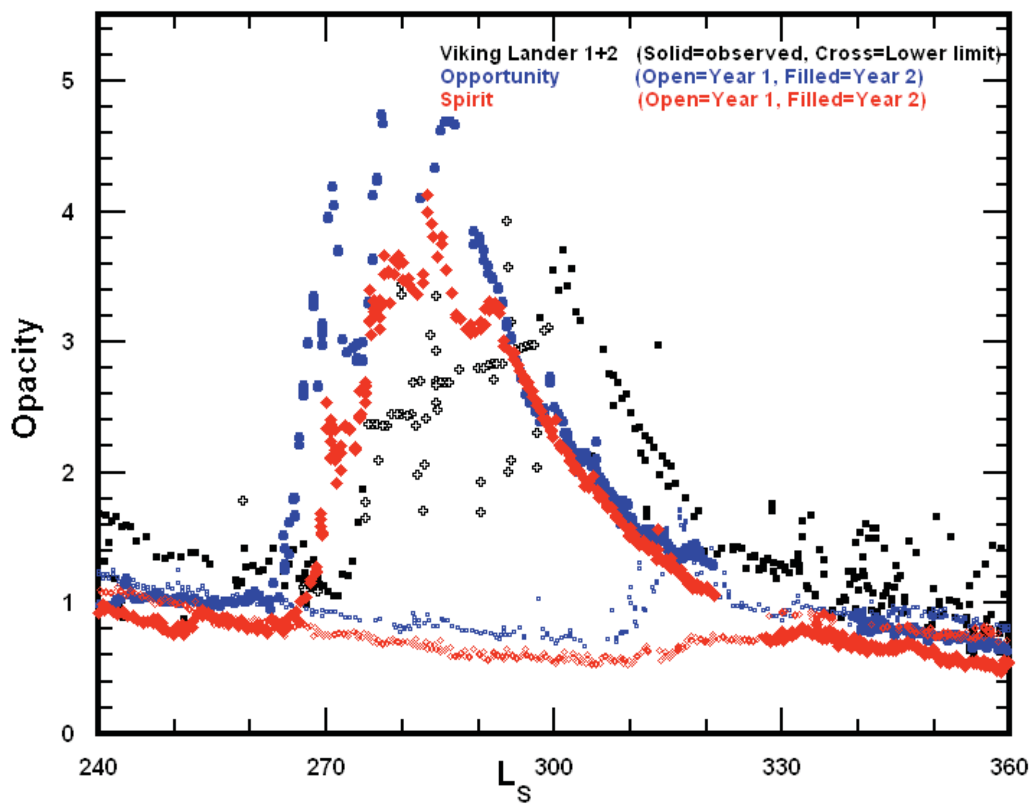


Fig. 1. Atmospheric Opacity Measurements for VL-1, VL-2 and the MER Rovers.

## III HUMAN MARS MISSION DESIGN OPTIONS

The current reference architecture calls for pre-deployment of mission assets via a cargo only spacecraft prior to the crew earth departure. Once the cargo vehicle has landed on the surface the power system will be deployed and made operational to support the production of ascent propellants, habitat readiness and other operations like robotic rover recharging, maintaining logistics modules and propellant maintenance. The power system is planned to be deployed and readied in a 30-40 sol period. Total production of the propellants and crew consumables oxygen cache must be completed prior to the crew departure. 300 sols have been baselined to make oxygen for ascent vehicle propellant, in addition to a cache of oxygen for crew consumables. This number is derived from the following; time between the cargo launch and crew launch- ~760 sols, less ~ 310 sols for cargo vehicle trip time, less ~ 40 sols for power system setup, less ~ 50 sols dust storm and ~60 sols overall contingency.

The architecture established for our analysis is the long stay option where the crew will be on the surface for the duration of 500-550 days. The power system must operate continuously and reliably for over four years. The solar power system must be designed to tolerate settled dust degradation and at least one dust storm. The MER rovers with their low power needs and higher acceptable risks easily resolved these issues by utilizing oversized arrays and small amounts of isotope decay heat to keep from freezing. They also were able to tolerate the dust losses and still function at severely reduced performance, until the right wind conditions cleared the arrays and, in addition, survived a significant dust storm.

The power system for a human mission is a mission critical function. High reliability over the required lifetime will be accomplished by sufficient flight hardware testing in conjunction with component and system redundancy as required.

The Mars environment poses a significant challenge to designing a solar powered system as previously discussed, particularly for the stringent reliability levels mandated by human missions. Table I shows the assumptions used for the analysis of the solar system design.

Since dust accumulation on the arrays is a critical factor in the sizing, it was assumed that some effective method of cleaning the arrays robotically every 40-50 sols will have been developed prior to a human mission, thus limiting loss due to settling dust to about 10% keeping array areas more manageable. A robotic or automated method for cleaning the array is necessary because power is required during the pre-deploy phase prior to crew arrival. Due to the very large array area required, significant power loss due to dust coverage as that experienced with MER, is prohibitive and would not be practical to accommodate by over sizing the array.

Latitude also becomes an important factor since the winter daylight period shortens at higher latitudes. At 30º latitude, winter solstice daylight is about 10 hours duration with a 14.5-hour nighttime. At 60º latitude the ratio is ~ 5 hours day and 20 hours night. This is problematic for solar power systems because the array area needed increases significantly in order to produce enough energy with less daylight and a longer nighttime period.

A brief description of each of the three mission scenarios evaluated is given below.

TABLE I
Power System Design Guidelines

| | |
|---|---|
| Site Latitude | 30¼ North |
| Optical Depth Clear Day | 0.9-1.0 |
| Optical Depth Dust Storm | 4.0-5.0 |
| Length of Dust Storm | 50 sols |
| Nominal Dust Deposition Loss Rate | 0.20%/sol |
| Maximum Allowable Power Loss | 10% |
| Mission Duration | 550 sols |

### *III.A. Option 1 - Mobile Home*

In the "Mobile Home" scenario the crew would live in two large long-range rovers. These rovers would be required to provide all power necessary to support the crew during their stay, as well as providing the considerable energy required for roving expeditions lasting up to 30 days, during which time the rovers would traverse as much as 200 km. No central habitat would be included in this scenario, although a central power supply needed to support in-situ resource utilization (ISRU) and other assets prior to crew arrival would be available to power the rovers at the landing site. It is assumed that the rovers would not be on a sortie during the dust storm season and the rovers would be receiving power from the main system during this time.

### *III.B. Option 2 – Commuter*

The "Commuter" scenario includes a central habitat in addition to two smaller pressurized rovers. The central habitat would provide services to the full crew in between rover excursions, maintaining a minimum crew of two when both rovers are in the field. The rover sortie requirements were set at 100 km round trip distances accomplished in a two-week period. As in the Mobile Home Option, each pressurized rover carries its own power system and Apollo type rovers at the base would be recharged off the main power system. In this particular case, the crew has a safe haven to return to and does not have to rely solely on each rover power system for shelter and life support.

### *III.C. Option 3 – Telecommuter*

No pressurized rovers are included in the "Telecommuter" scenario. The habitat is included and power requirements are estimated to be the same as for the Commuter scenario discussed above. This scenario also includes two long-range robotic rovers. These rovers, were expected to be similar to the Mars Science Lab-type design, and assumed to use their own dedicated radioisotope power systems (RPS) in the low multi-kilowatt range.

Crew mobility will be limited to shorter distances from the habitat because only the Apollo LRV type rovers are used. The power source for these rovers is assumed to be batteries or possibly fuel cells depending upon the stored energy requirements. Range will be limited by suit power, rover speed and permissible "walk back" distance as with the Apollo mission. Speed for this rover is estimated at around 10 km per hour and in the 1-2 kilowatt range. Rover distance might be extended if suit functions were powered off the rover rather than utilizing the suit battery when the crew is driving the rover. Rover recharge was estimated at 1.5 kWe during daytime only but night recharge could be considered. Daytime recharging might dictate additional rovers or spare batteries, one being used while the spares are on charge.

## IV. POWER REQUIREMENTS SUMMARY

The major power requirement is the production of oxygen for the ascent stage. The total power level of 92 kWe for this ISRU phase is based on a production time of 8 hours per sol for 300 sols and a requirement to supply ~3 kWe during the night to maintain the propellants liquid and keep the production plant equipment in a warm quiescent mode.

TABLE II

Estimated Power Requirements For Various Surface Elements

| | **Day kWe** | **Night kWe** | **Dust Storm kWe** | **Notes** |
|---|---|---|---|---|
| **Element** | | | | |
| Habitat | 12 | 12 | 12 | |
| ISRU $O_2$ Propellants (Solar) | 66 | 2-3 | 2-3 | 8 hours/sol |
| ISRU $O_2$ Propellants (Nuclear) | 22 | 22 | 22 | |
| ISRU $O_2$ Consumables (Solar) | 5.7 | 0.5-1 | 0.5-1 | 8 hours/sol |
| ISRU $O_2$ Consumables (Nuclear) | 2 | 2 | 2 | |
| Logistics Module | 1.5 | 1.5 | 1.5 | Option 1 only |
| Ascent Stage | 1.5 | 1.5 | 1.5 | |
| Rover Recharge | 1.5 | 0 | 0 | |
| ISRU Crew $O_2$ Cache | 1.5 | 1.5 | 1.5 | Maintain only |
| Drill | 3 | 0 | 0 | Pwr from Rover |

All three architecture options include robotic rovers to perform various tasks. In particular, these would be utilized during the pre-deploy phase to move and set up equipment like ISRU plant, logistics module and power system setup and perform the power cable connections. It is anticipated that appropriate recharge stations would be either attached to the habitat or a power management distribution module for rover recharge. Details of these rover designs were not assessed during this study, but assumed that they would be powered by rechargeable batteries or fuel cells due to their short-range application. The ascent stage will also require power for "keep alive" functions and propellant maintenance. An ISRU plant will produce oxygen for life support and for EVA suit re-supply for all three options while oxygen production for ascent production remains an option.

Table II shows the power required for the various architecture elements for normal day and night operations and also during a dust storm. The habitat power estimate is scaled for Mars based on a monolithic habitat design for the lunar South Pole with a crew of four. It might be possible to reduce the night and dust storm habitat power by the reduction in the habitat power during a dust storm compared to normal operations power levels. This would make a significant difference in additional "dust storm" array area and mass of an "all fuel cell" power option. The ISRU plant, making ascent stage $O_2$ propellant is clearly the dominant power requirement at 66 kWe operating nominally for 8 hours a day (22 kWe continuous). This strategy of limiting the operational time for the propellant production reduces the required array size. Any energy used at night has to be recharged during the day with additional power for electrochemical recharge inefficiency. For an efficiency of 50% and a 2:1 charge to discharge ratio, (i.e. 8 hour charge/16 hour discharge), an array has to produce 25% more power for continuous operation than if operated only during daytime only.

Total rack up of estimated power levels of the photovoltaic system option is shown in Fig. 2. Nominal total load power for the crew phase is approximately 20 kWe, for both day and night operation. With ascent $O_2$ propellant production the total daytime average power required is ~ 96 kWe. If only crew consumable $O_2$ is produced total average day power is reduced to ~ 12 kWe. It should be noted that this is not peak power at noon delivered by the arrays but rather a time averaged value.

Thus in the consumable ISRU only case the habitat has the greatest power demand. A system sizing to meet this requirement will have ample power available for pre-deploy phase activities. However, if ISRU for ascent $O_2$ production were adopted then it would become the predominate load for power. The PV/RFC system module size was selected at 5 kWe. As it turns out, if one additional unit is delivered, than the total array area of all five modules is sufficient to provide the day time power. In fact, the ratio of ascent ISRU power and the habitat power level is such that the five PV/RFC modules could support continuous operations both day and night. The downside to doing this is that two years of RFC lifetime would be used and additional electrolyzer and fuel cell stacks would be needed to maintain the reliability of the system during the crew phase. The impact of component lifetime and overall system reliability was not evaluated in this phase of the study.

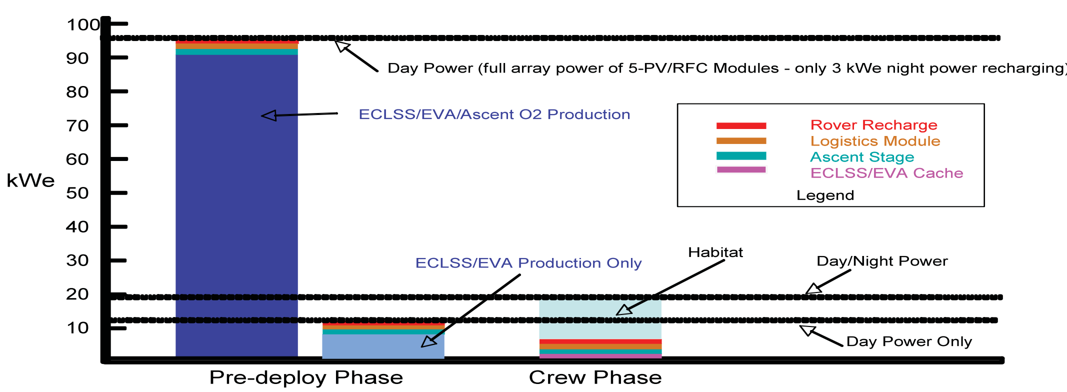


Fig. 2. Power Requirements Based On the Use Of a Solar Power System.

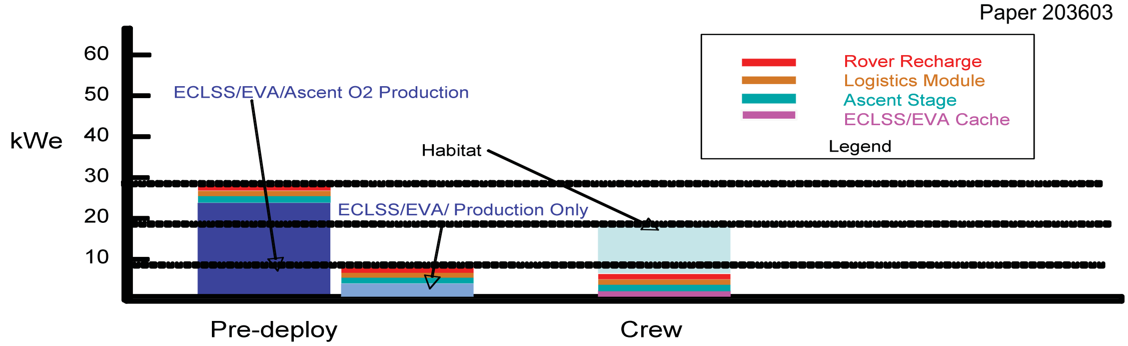


Fig. 3. Power Requirements Based On the Use Of a Nuclear Power System.

As an option to the PV/RFC system a nuclear power system can also be considered as the main power source for the base. Fig. 3 shows the total levels if nuclear power were the power technology chosen for the architecture. Again, ISRU for ascent propellant production requires the greatest amount of power. Whereas the crew phase needs (mainly the habitat) is the driver for the ISRU consumables case. Because a nuclear power source produces power continuously without the need for energy storage, the peak power required is significantly reduced when compared with the solar /RFC system. For an hour daylight/16 hour night the solar system produced a peak power output of ~100 kWe while the nuclear system is around 30 kWe. An item of note here is that the sizing for the nuclear system is valid at all latitudes while the solar casesized for this study is valid at 30 N latitude or the equator.

Power system masses were estimated for both solar and nuclear power systems for each architecture option. The architecture options included base and habitat power with consumable O2 production only and base and added power for ascent vehicle $O_2$ production. The results of these mass estimates are shown in Fig.4.

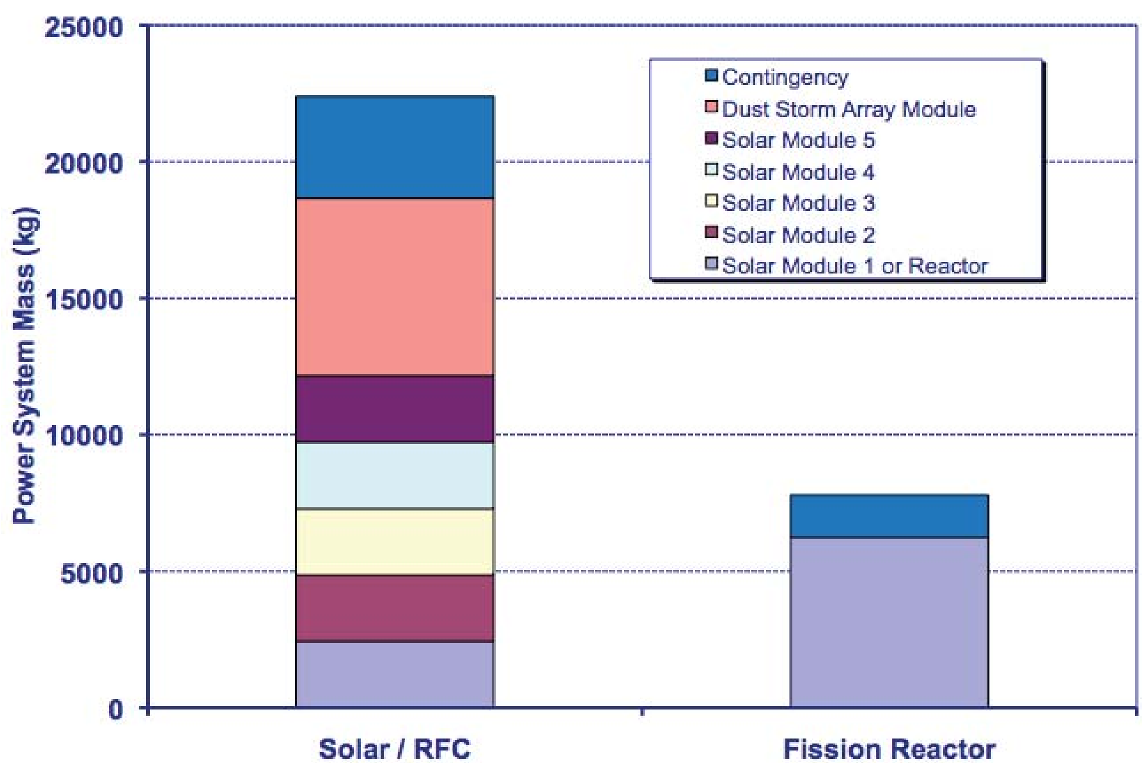


Fig. 4. Estimated Total Power System Masses for Option 2 – Commuter

## V. SOLAR OPTION

The solar power system masses include an additional 8,000 kg mass for an additional array, deployed in the event of a major dust storm. The array area required during a dust storm is ~ 4,300 $m^2$ in addition to the array area of the five PV/RFC modules for a total of 5800 $m^2$. It is envisioned that the crew at the start of a dust storm would roll out the thin-film array, possibly a high efficiency technology will be available. The arrays could be spooled on 8.5 m wide by 100 m long sections, in which case approximately 5 spools would be required. Since each spool would be about 1,500 kg they could be emplaced with aide of the rovers readied for future deployment. An all fuel cell option to supplement the power loss during the dust storm was assessed to supply the required energy but it was two to three times heavier than the roll out array option.

This particular architecture calls for only one visit by a crew and subsequent missions would be at another location. This means that all the power system assets are only used once and require a lifetime of four years. A different power system strategy, i.e., technology selection, system sizing, back-up emergency power system selection, etc. might be chosen based on a multiple visit scenario with greater power level and increased lifetime requirement.

The final 5-module configuration of the solar power system is shown in Fig. 5. Each module consists of a 5 kWe RFC for nighttime power production and a PV array with 29% efficient solar cells with an area of 290 $m^2$ for both wings. The array panels are inclined 30º to optimize the overall power profile by increasing output during early morning and late afternoon and reducing peak power at noon. Dimensions of the module are 1.5 m x 2.0 m x 3.0 m. Each array wing is 2.5 m high x 58 m in length. Total capability of the five units is 25 kWe nighttime and 25 kWe day power to loads plus RFC recharge power. It is anticipated that each module would be off-loaded from the cargo lander and set in place by robotic rovers. A robotic rover, tele-operated from earth, assists deployment of the array wings. Support legs drop down and lock in place as the wing is pulled out. The array has a 0.5 m clearance off the ground so a fairly flat area is needed since the total array span from end to end is almost 120 m.

The array deployment system concept was not assessed in great detail and has been identified as an area needing future in-depth design study because current array deployment systems are designed to deploy in zero gravity.

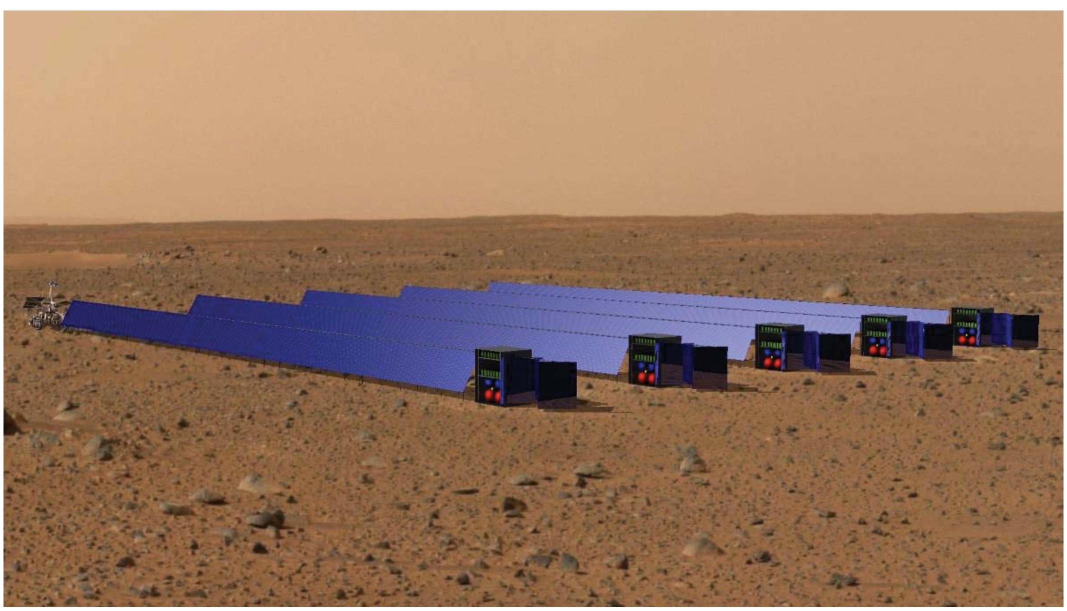

Fig. 5. Solar PV/RFC System

## VI. NUCLEAR OPTION

The nuclear power reactor concept used for this study is based on a lunar design that is capable of operating on the Martian surface.[4] The low operating temperature of the reactor fuel enables use of stainless steel, a material that is compatible with Mars' predominately $CO_2$ atmosphere. The nuclear power system mass used for comparison was for a 30 kWe version of this design. The image in Fig. 6 shows the reactor in a stowed configuration as off-loaded from the cargo bay and ready for emplacement with external power taken from a utility power cart that would have multiple functions. The power cart could be PV/RFC, battery powered or powered by a Radioisotope Power System (RPS). For this study it was assumed that a dynamic isotope power system (DIPS) would be utilized for the power cart and could also be an option for powering the pressurized rovers. Plutonium 238 isotope has fueled numerous deep space missions as well as for the Apollo and Viking missions, would be used with advanced power conversion technology to increase power output 3-4 fold when compared with thermoelectric devices that are currently used.

The advantage of this technology is that continuous power is available from this unit without need for any recharging energy storage. It is envisioned that the DIPS cart would provide power to the reactor mobility chassis while it is being transferred to a location approximately 1 km from the landing site. The reactor has an external shield to protect the crew from radiation and adopted a guideline of 5 rem/yr dose to the crew. Since the shield is a significant portion of the system mass, a shape shield is employed whereby the radiation is limited to 5 rem/yr (at 1 km) toward the habitat and 50 rem/yr (at 1 km) in all other directions. This creates a small exclusion zone and limited pass through zone for the base. One option to reduce or eliminate the exclusion zone and to save shield mass is to bury the reactor below grade where the soil provides additional radiation protection as has been suggested for lunar applications. However the team felt that this option was risky due to numerous factors and had opted for the above ground emplacement. If a second reactor were required for risk reduction, it would be possible to consider the crew assisting in burying and setting up the second nuclear power system, utilizing power available from the first reactor unit.

With the above ground option, the reactor would be driven about 1 km from the lander trailing the power cable. Once at the site, the mobile chassis would be aligned (orientate the shield), leveled and secured by jacks. The DIPS cart, outfitted with appropriate equipment, would assist in the deployment of the radiators if needed. The power cart would be driven back to the landing site and the reactor started. It was assumed that the total time to perform this is 30-40 sols.

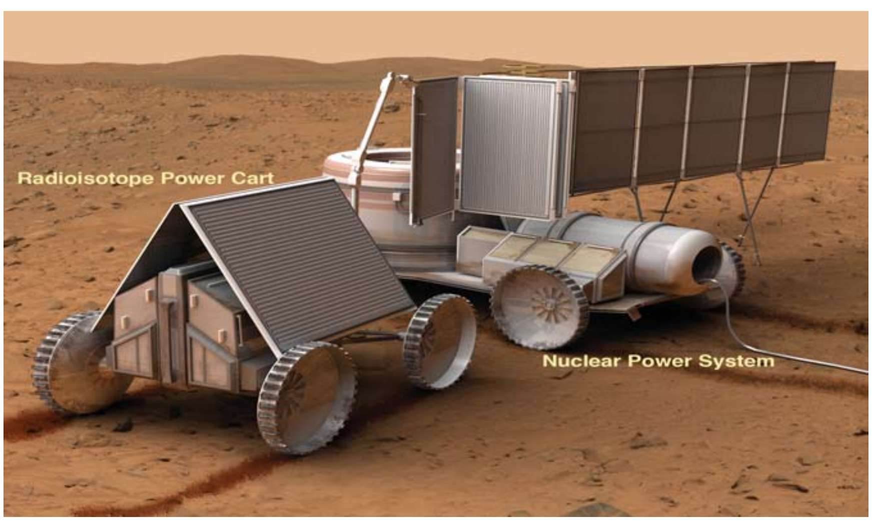


Fig. 6. Nuclear Reactor and Radioisotope Utility Power Cart

## VII. PRESSURIZED ROVERS FOR THE MOBILE HOME AND THE TELECOMMUTER OPTION

In addition to the main base power system, power system options were looked at for powering the pressurized rovers.

The Mobile Home option had two large pressurized rovers that each house three members of the crew with the capability of supporting all six for a short term during an emergency. There is no habitat, but the rovers come back to the landing site to get re-supplied with consumables, oxygen, water, food, etc. Each sortie is planned to travel 200 km in 30 days, with possibly 10-15 total sorties per mission.

The guideline from the science team was the desire to maximize distance traveled and maximize field science time. For the basis of the power system analysis, it was assumed that half the time was spent roving and half the time stationary. It was assumed that a trafficability factor of 30% (avoid rocks, steep grades, soft sand, etc.) be used to capture an "odometer" distance that rover speed would be based on, thus a total of 260 km is actually traversed during the sortie.

The Commuter option had two smaller rovers that will house a crew of two and traverse 100 km (130 km total) in 15 days. This option did have a habitat that the crew would return to and stay in between sorties.

Many scenarios exist for exploration during each sortie. Since there were no operating timelines from the science team the following assumptions were used to evaluate the different power system options. Drive time was 5 hours each day, which dictated a speed of 3 km per hour to cover the total distance in the time allocated and driving was only during sunlight.

Three power system options were evaluated for both the large and small rover these are summarized in Table III. These options included; PV/battery, PV/battery with DIPS augmentation and fuel cell only. The significant drivers for both power and energy are the rover mass and drive speed. Drive power to achieve the 3 km/hr speed for the large and small rovers is 47 kWe and 25 kWe, respectively, shown in Table III. This is a major challenge to meet the specified requirement of sortie distance in the allotted time. To keep the array area and battery mass to a minimum, recharging the system on as short a cycle as possible is needed. Therefore, for this analysis, we adopted the operation scenario of driving and stopping to do science and recharge on alternating days. Even with this strategy the array size required to recharge the batteries is 800 $m^2$, which must be deployed and stowed. If we assumed a 5 m long rover and two 400 $m^2$ arrays the crew would need to deploy each array about 80 m out from the rover. Adding a 5 kWe DIPS did not have much impact on the sizing due to the low ratio of load power to DIPS output. However, if the sortie 30-day duration were relaxed, speed could be reduced and the resultant drive power reduces greatly.

A speed of 0.5 km/hr brings the drive power close to the nominal crew power of 5 kWe. Array area and battery mass is reduced and now the addition of the DIPS system allows a major reduction in array area and battery mass. One additional case was evaluated at 0.1 km/hr to reduce array area to a size that could be fixed on top of the rover eliminating need for array deployment/stowage.

The small rovers have much less demanding power requirements than the large rovers mainly due to the lower rover mass of 7,500 kg vs. 15,000 kg, not including the power system mass. It is still a challenge to meet the speed requirement but the Commuter option seems much more plausible. Here again, a DIPS system augmenting the array for power generation helps reduce the mass because it outputs power continuously and reduces the required battery capacity.

A fuel cell (FC) only option was assessed whereby the $O_2$ reactant could be produced by the ISRU plant during the pre-deploy phase. The $O_2$, $H_2$ and total FC mass estimates are shown based on accomplishing the full sortie R/T distance within the required duration.

TABLE III
Summary of Pressurized Rover Power Systems

| Large Rover (15,000 kg) | | | | | | |
|---|---|---|---|---|---|---|
| Speed km/hr | Array Area m2 | Isotope Power kW | Drive Power kW | Battery kg | kW-hr | DIPs mass kg |
| 3 | 800 | 0 | 47 | 4370 | 437 | 0 |
| 0.5 | 323 | 0 | 8 | 1850 | 185 | 0 |
| 0.5 | 80 | 5 | 8 | 100 | 10 | 375 |
| 0.1 | 20 | 5 | 1.5 | 100 | 10 | 375 |
| Small Rover (7,500 kg) | | | | | | |
| 3 | 400 | 0 | 25 | 2500 | 250 | 0 |
| 0.5 | 160 | 0 | 4.2 | 1100 | 116 | 0 |
| 0.5 | 40 | 2.5 | 4.2 | 300 | 30 | 190 |
| 0.1 | 10 | 2.5 | 0.8 | 130 | 13 | 190 |

Notes:
Average slope 5°
Recharge Time 1 sol
Drive Time 5 hrs/sol
Array sized for winter soltice
Crew Power 5 kw day; 3.5 kW night Large rover, 3.4 kW day; 2.4 kWe night, small rover
Li-ion Battery, 100 wh/kg, 70% DOD
Latitude 30
FC PEM, 70% eff., 2000 psi

| All Fuel Cell | | | |
|---|---|---|---|
| Large Rover | 3470 kg O2, 433 kg H2 | 9590 kg total | 3 km/hr case |
| Small Rover | 975 kg O2, 122 kg H2 | 2840 kg total | 3 km/hr case |

Many options and combinations of such a hybrid system exist and since there was not time to come to closure on the exploration sortie ops scenario, we only investigated a portion of the trade space. Additional investigation of the use of differing DIPS power systems would be assessed. We limited the power level to the minimum because of the cost and availability of the Plutonium 238 isotope. In fact, use of the DIPS mobile "Power Utility Cart" has many advantages. Since the DIPS supplies continuous power output it has application to provide/augment power for many functions including; deployment of the reactor or PV/RFC modules, power assist the pressurized rovers, augment habitat night power and provide habitat dust storm power.

Drive power calculations were estimated using a software package developed for the In-Situ Resource Utilization (ISRU) Excavation system.[5] This software models the excavation activities on the lunar surface that include excavation of regolith and transportation of the regolith to a processing plant. This software, written in Visual Basic with Microsoft Excel used for input and output, was used to simulate the travel of a rover on the surface of Mars. The code was initially written for activities on the lunar surface. The properties input to the code were adjusted to simulate those of the Martian surface. These properties are used in the equations that model the interaction of the rover wheels with the Martian soil. The geotechnical properties values that were assumed for the Martian surface are shown in Table IV.

Drive motor power estimates were made for a large (15,000 kg) rover and a small (7500 kg) rover. Each rover was assumed to have four wheels and experience an average 5° terrain slope. Rover dimensions assumed in the analysis is shown in Table V.

TABLE IV
Mars Surface Geotechnical Properties

| | |
|---|---|
| Mars Gravity (m/sec^2) | 3.72 |
| Regolith Density (kg/m^3) | 1000 |
| Cohesion (Pa) | 10,600 |
| Modulus of Friction | 20,000 |
| Modulus of Cohesion | 306,800 |

TABLE V
Large and Small Rover Characteristics

| Vehicle Total Mass (kg) | 20,000 | 10,000 |
|---|---|---|
| Length (m) | 8.96 | 7.11 |
| Width (m) | 5.98 | 4.74 |
| Height (m) | 3.20 | 2.54 |
| Wheel Diameter (m) | 2.80 | 2.25 |

## VIII. CONCLUSIONS

The Option 2 or Commuter was selected as the architecture option for increased focus near the end of the study period. The mass of the solar based system for the commuter option was over 22,000 kg for a 25 kWe system, including a dust storm survival array, and the nuclear power system mass was approximately 8,000 kg for a 30 kWe system including above ground shield and deployment cart. These power levels are lower than previous reference architectures because this study baselined a different location for each mission, where prior studies returned to the same location to better utilize surface assets instead of more diverse exploration sites.[6] Power levels would more than double during subsequent crew visits because ascent stage propellants are produced while supporting the crew and habitat.

Mobil power for both the large pressurized rover of Option 1 and small pressurized rover for Option 2 posed a significant challenge to provide a low mass power system option while trying to meet sortie driving speed requirements. Traveling at slower speeds helps reduce system size and possibly remaining at a "camp site" for several days would help recharging times, but would compromise the duration away from the habitat or expected distance traveled during each sortie.

Dust storm survival is a key driver for the solar power system. Long surface stay missions must accommodate a high probability of a dust storm. Since solar power is greatly diminished during these times additional arrays must be used or stored energy, which would be hard to properly size due to the variability of the intensity, duration and frequency of a storm. The uncertainty of the Martian environment particularly impacts a solar power system design in determining a "worst case" scenario. Nuclear power has a significant advantage in that the intrinsic characteristics makes it insensitive to any variations imposed by the atmospheric environment or outpost latitude site selection.

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