Comparative Analysis of Surface Power System Architectures for Human Mars Exploration

by

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Abstract

This thesis provides a comprehensive analysis of surface power generation and energy storage architectures for human Mars surface missions, including tracking and non-tracking photovoltaic power generation, nuclear fission power, dynamic radioisotope power generation, and battery and regenerative fuel cell energy storage. The quantitative analysis is carried out on the basis of equal energy provision to the power system user over one Martian day (including day and night periods); this means that the total amount of energy available to the user will be the same in all cases, but the power profile over the course of the day may be different from concept to concept. The analysis results indicate that solar power systems based on non-tracking, thin-film roll-out arrays with either batteries or regenerative fuel cells for energy storage achieve comparable levels of performance as systems based on nuclear fission power across the entire range of average power levels investigated (up to 200 kW). For solar power systems, deployment and dust mitigation methods were also considered. Possible areas of commonality between Mars surface power systems and more near term lunar surface power systems were investigated. Given the significant policy and sustainability advantages of solar power compared to nuclear fission power, as well as the significant development and performance increase for thin-film photovoltaic arrays and energy storage technologies that is anticipated over the coming decades, solar power as the primary source for human Mars surface power generation should be seriously considered as alternative to traditional nuclear fission based approaches.

Thesis Supervisor: Jeffrey A. Hoffman
Title: Professor of Astronautics

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1. Introduction and Motivation

The provision of power for human Mars surface exploration is generally assumed to be achieved using nuclear fission power sources, particularly if in-situ production of part or all of the Earth return propellant is considered. This thesis provides a comprehensive analysis of surface power generation and energy storage architectures for human Mars surface missions, including tracking and non-tracking photovoltaic power generation, nuclear fission power, dynamic radioisotope power generation, and battery and regenerative fuel cell energy storage. The quantitative analysis is carried out on the basis of equal energy provision to the power system user over one Martian day (including day and night periods); this means that the total amount of energy available to the user will be the same in all cases, but the power profile over the course of the day may be different from concept to concept. The analysis results indicate that solar power systems based on non-tracking, thin-film roll-out arrays with either batteries or regenerative fuel cells for energy storage achieve comparable levels of performance as systems based on nuclear fission power across the entire range of average power levels investigated (up to 200 kW). Given the significant policy and sustainability advantages of solar power compared to nuclear fission power, as well as the significant development and performance increase for thin-film photovoltaic arrays and energy storage technologies that is anticipated over the coming decades, solar power as the primary source for human Mars surface power generation should be seriously considered as alternative to traditional nuclear fission-based approaches. The human exploration of Mars is generally considered as the ultimate goal of human spaceflight endeavors in the foreseeable future. Power generation for use on the surface of Mars for habitation and communications, as well as for surface mobility and potentially in-situ propellant production is a key enabling component of human Mars surface exploration.

2. Background

2.1 Previous Human Mars Mission Architecture Studies

Human missions to the surface of our planetary neighbor Mars have inspired engineers, scientists, and the wider public for generations, starting with Wernher von Braun and the architecture proposed in his book "The Mars Project" in 1953 [1]. Many architectures and concepts for carrying out surface missions have been proposed since [2], culminating in the Mars design reference missions developed by NASA in the 1990s [3][4][5][6] and associated follow-on studies as part of the US Vision for Space Exploration [7][8]. Two main motivations for carrying out Mars surface missions have been described in these architecture studies: (1) the scientific exploration of Mars, in particular with regard to extraterrestrial life, and (2) the investigation of the habitability of Mars in the context of establishing a long-term human presence there someday in the future.

2.2 Previous Solar Power Studies

The provision of power to the end user on the surface of Mars is one of the fundamental functions that needs to be provided by the surface infrastructure given that virtually every other subsystem is completely dependent on power supply (perhaps with the exception of structures). A number of high-level design studies have been carried out in support of the above architecture studies: McKissock and Kohout [9] investigate the use of a power system for opposition class missions based on non-tracking thin-film roll-out arrays and regenerative fuel cells. Kerslake and Kohout [10] provide a study of a power system for conjunction class missions based on thin-film tent-arrays and regenerative fuel cells. Colozza, Applebaum, and Crutchik [11] look at a double-sided catenary thin-film tent-array design to provide primary power without consideration of secondary power or energy storage. Withrow and Morales [12] provide a comparative analysis of solar-electrochemical power system concepts based on tracking and non-tracking photovoltaic arrays as well as a variety of energy storage technologies. The main difference and drawback of these studies compared to the study done in this thesis, is that they all choose a single primary power production method, photovoltaic, without consideration of other architecture options. A comprehensive comparison of primary power production options and secondary power productions options and energy storage methods is needed to make any educated decisions on the merits of a given power system architecture over any other.

The McKissock and Kohout [9] study looks at a 40 day surface mission centered around Mars' northern hemisphere's summer solstice in order to lower the probability of the occurrence of a local or planetary dust storm. The study also only considers an equatorial mission and does not consider the effect of varying the mission's latitude. The power requirement is 40 kW daytime power for life support and science and 20 kW for life support during the night. The study only considers an architecture which includes roll-out amorphous silicon arrays and hydrogen-oxygen regenerative fuel cells for energy storage. The array is sized to provide 20 kW when the sun reaches 12.5° elevation and ramp up to 140 kW in order to supply 40 kW to the users and also recharge the fuel cells for night time use. The final power system is comprised of 80 solar array modules deployed like blankets and three fuel cell energy storage modules each with fuel cell, electrolyzer stack, and reactant storage tanks. Assumptions for the amorphous-silicone solar arrays include a 50 μm thickness and an 11.9 percent efficiency for the overall array. Figure 1 shows the array's blanket configuration and rollable deployment.

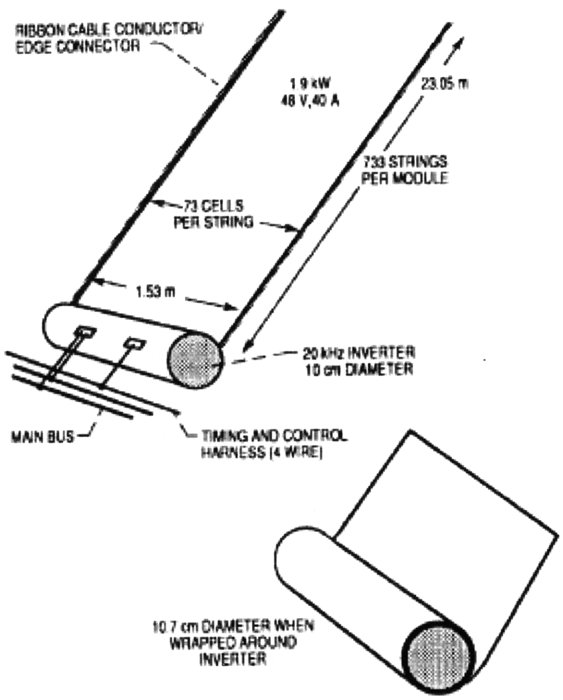

Figure 3.—Solar array module.

Figure 1. Rollout solar array [9]

The total array for the given power requirement covers 2,822 m² and has a total blanket mass of 177.6 kilograms. The fuel cells are then sized for a total operating time of 14 hours in order to provide power throughout the night and while the sun is below 12.5° with respect to the horizon. The fuel cell subsystem was modeled using NASA Lewis developments. Notably, tank pressures of 2.2 MPa are assumed, this parameter being key to sizing the reactant storage tanks which in turn dominate the mass and volume for the fuel cell subsystem. The final system provides 40 kW to the user for 9.4 hours during the day and 20 kW for the remainder of the Martian day and night. The total mass of the system is 3170.6 kg and the stowed volume is 49.66 m^3. This result gives a mass specific average power performance of 8.8 W/kg and a volume specific average power performance of 560.5 W/m^3. The study does not go on to consider other important factors that affect the architecture such as deployment methods for large solar arrays or dust mitigation techniques.

The Kerslake and Kohout [10] study has different requirements then the previous study. Here, the crew is on a conjunction class mission and will stay on the surface of Mars for 500 days. In addition, the mission scenario assumes in-situ propellant production (ISPP) of ascent stage propellant. The ISPP plant operates for 435 days prior to crew arrival. The crew arrives 200 days after the propellant has all been produced. As a result, the surface power system must operate for 1130 days. To support these loads, 40 kW average power is required over the complete day-night period. This study only considers an architecture which includes flexible solar arrays and regenerative fuel cells for energy storage. This study does consider the effects of Martian dust on solar array performance. Based on Pathfinder mission data, the study assumes that the array will experience a power production loss of 0.28% per sol. The solar array design itself is unique in that it includes a 5000 m^2 array split into 4 parts that are arranged orthogonally around the crew's base (as shown in Figure 2.) and each array is deployed as a single-sided tent raised 45° to the ground.

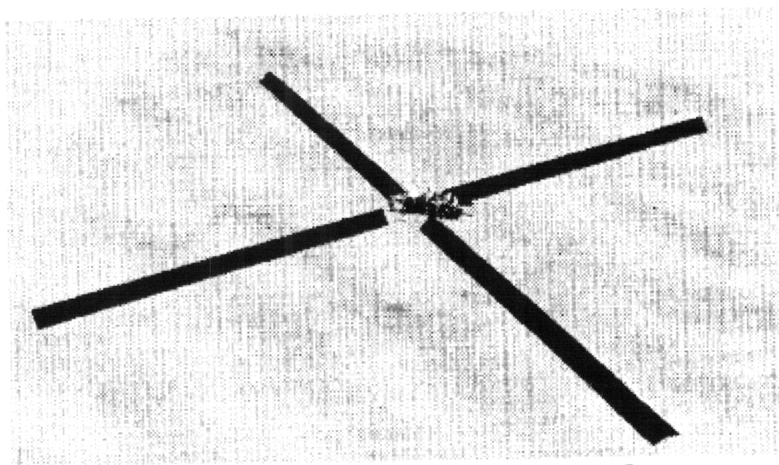

Figure 2. One-sided tent array configuration [10]

The tents are made of composite members and are deployed by an articulated mast, inflatable booms, or rovers, and are anchored to the ground. The angle is used to provide gravity assisted dust removal. Figure 3 shows a side view of these angled tents.

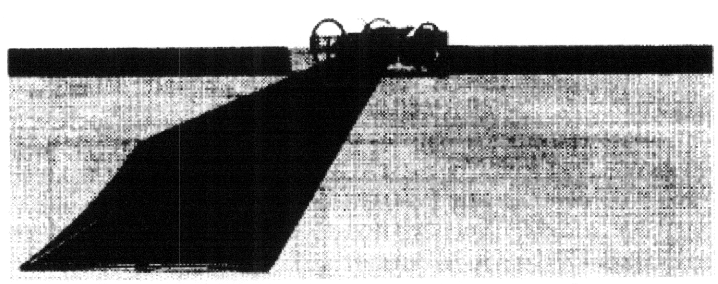

Figure 3. One-sided tent array side view [10]

The tent angle results in only 85% of power that would be produced by a flat array. The arrays are amorphous silicon with an assumed array efficiency of 15% and are 1.5 mm in thickness. The regenerative fuel cells are hydrogen-oxygen and are proton exchange membrane fuel cells. The reactants are stored at 20 MPa. The final analysis seems to have considered a number of factors. The base location is varied between 36° south latitude and 36° north, and 0-2 Mars dust storms with optical depths reaching 6 are considered. If no storms actually occur the mission average user power increases 35%. A final design is presented that provides 46 kW average power over the mission duration and requires a total system mass of 10.6 MT and resultant mass specific average power of 7.5 W/kg. Volumes are not recorded.

The Colozza, Applebaum, and Crutchik [11] study is a brief look at a double-sided catenary tent design for thin filmed solar arrays. In this study, mission requirements are neglected. The study instead only considers a unique way of deploying blanket solar arrays. The arrays are designed to self-deploy into tent form using pressurized gas expansion after being laid out manually. The structural design of the tents includes cables, beams, and columns made from composites to support the tents. Figure 4 shows an artist's drawing of the caternary tent design.

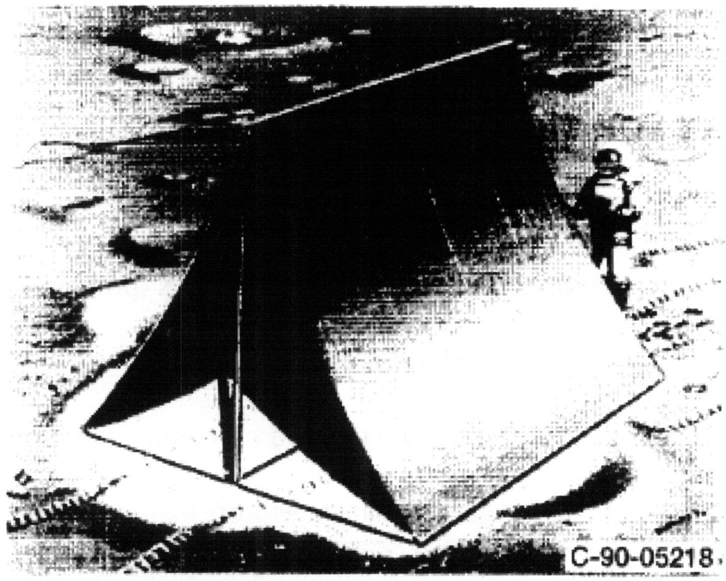

Figure 1.—Artist's conception of the self-deploying PV tent array.

Figure 4. Catenary tent solar array [11]

The study trades the use of different types of solar cells (silicon, gallium arsenide over germanium, and amorphous silicon) and different materials for structural members (carbon composite and aramid fiber composite). The analysis concludes that of all the array/structure combinations, carbon composite structure with an amorphous silicon array results in the best performance. It should be noted that here an efficiency of 10% for the amorphous silicon array is used. The performance of this combination is 32.8 W/kg just for the array component of the power production system. This demonstrates a major drawback to tent structures for flexible arrays. If the energy storage subsystem were included in this study, the overall mass specific power performance would be much worse than simple rollout blanket arrays. Another major drawback to the tent design is self shading that decreases the area's power production. The only benefit to this tent scheme is that the power profile over the Martian day is flatter than the cosine power profile produced by a flat array.

The Withrow and Morales [12] study was specifically undertaken to inform the Mars Design Reference Mission. It is slightly more comprehensive in that it evaluates architectures which include different energy storage methods (primary fuel cells, regenerative fuel cells, and batteries). It does not include any alternatives to photovoltaic primary power production. This study again considers a conjunction class mission with a 500 day crew Mars surface stay. Again ascent stage propellant is produced before crew arrival. The mission power requirements range between 4 kW and 120 kW and are split up among the subsystems that have different power requirements. The habitat, ISRU plant, and methane propellant production plant each have a different power requirement. Energy storage options include hydrogen-oxygen primary fuel cells, hydrogen-oxygen regenerative fuel cells, and sodium sulfur batteries. The photovoltaic solar arrays are all gallium arsenide on germanium and both tracking and non-tracking arrays are considered. Gallium arsenide arrays are chosen over silicon for their higher efficiencies (20% versus 14.5%). The overall power requirement is split into separate pieces corresponding to different mission elements in order to take into account dust storm considerations. The power system for the habitat is sized for a dust storm optical depth of 6 while less critical systems such as the system to power the ISRU plant is sized for hazy skies or optical depth of 0.4. The study assumes that during dust storms, power consumption will be limited to crew life support requirements. Again, two types of solar arrays were considered, tracking and non-tracking. The tracking arrays follow the sun so that the incident solar flux is always perpendicular to the arrays. It is assumed that the arrays start operation when the sun reaches 10° and therefore operate for 10.7 hours during the day. The energy storage system operates for the remaining 13.9 hours. The non-tracking arrays only operate for 7.7 hours of the day and do not begin operation until the sun reaches 30°. For energy storage, the fuel cells are hydrogen-oxygen with storage tank pressures of 20.7 MPa. The results of the study favor a system with tracking arrays and regenerative fuel cells. Looking at the methane production plant power system as an example, the mass specific power performance is 6.1 W/kg and the volume specific power performance is 353 W/m^3. The area of the tracking array system is 2,139 m^2. The power requirement for the methane plant is 40 kW, but it is unclear if this is an average power over the day or just daytime power. As a result, the average power performance could be significantly lower if the methane plant is not producing during the night. Low performance levels for this particular architecture are due in large part to the use of non-flexible solar arrays which give greater efficiency levels, but significantly greater masses.

2.3 Previous Nuclear Power Studies

Architectures for Mars surface power systems which include surface nuclear fission system point designs are described in the NASA design reference mission studies [3][4][5] together with point designs for auxiliary surface photovoltaic systems. The surface photovoltaic systems included are as described above in the Withrow and Morales [12] study.

Design Reference Mission 1.0 (DRM 1.0) [3] and its subsequent addendum [4] call for an initial power requirement of 60 kW before crew arrival for ISRU operations to produce the necessary life support cache and ascent vehicle propellant. As the outpost grows, power level requirements will increase to 160 kW for the increase in habitation volume and life support capabilities. DRM 1.0 considers an SP-100 type nuclear reactor with Brayton dynamic conversion. The system is required to function autonomously for approximately 2 years before crew arrival. This places high demands for reliability and robustness on the nuclear power system. In DRM 1.0, potential radiation hazards are mitigated by an enveloping shield that is part of the delivered system, thus adding significant weight to the design. A mobile platform for placement is also included. The system must be deployed from the initial landing site to a location at least 1 kilometer from the base where the crew will be located. This is due to radiation and safety concerns. The reference mission assumes that deployment will be conducted by a rover. The rover's power will be used to start up the system and deploy additional equipment such as radiators and then bring the whole system to final operating conditions. This process will be monitored remotely by workers on Earth as it is a critical mission element and risk needs to be minimized. The first deployed reactor is capable of delivering the final required power level of 160 kW so ISRU activities can proceed. A second redundant nuclear power system is delivered during the first opportunity to satisfy the fail-operational mission requirement, but this system is not started up unless the mission later requires it. The nuclear system point design results in a 160 kW power delivery for 14 metric tons and 42 m^3.

The addendum to DRM 1.0 [4] notes that the SP-100 design in the original reference mission included 3 separate 80 kW closed Brayton cycle engines operating at a temperature of 1100 K. Further studies showed that increasing the turbine inlet temperatures to 1300 K reduces the overall system mass to 10.7 metric tons from 14. This does however require temperature increases of 150 K beyond current Brayton technology, but reactor and fuel technologies stay consistent with the SP-100 program. The addendum also indicates that mass trades were being done based on the use of indigenous shielding materials to decrease delivered shielding mass. However, no conclusions are made.

The 2001 NASA Mars Surface Reference Mission [5] considers a nuclear power-based architecture very similar to DRM 1.0, but goes on to considered more detailed implications of a nuclear-based system. Again, the nuclear power system must be unloaded and moved to a distance of at least 1 kilometer from the mission base. It is expected that shielding in addition to the delivered system's integrated shielding is necessary. The additional shielding may take the form of naturally occurring terrain such as hills and ridges, or the reactor may be placed at the bottom of a crater. If naturally occurring structures are not available or do not provide the required shielding levels, constructed means may be used. Robotic vehicles could be used to dig a hole in which the reactor is placed or build up berms of Martian soil around the reactor. Additional implications arise due to this deployment scenario. Prior to deployment, robotic vehicles will be required to locate an appropriate site at the required distance from base and with the needed sitting conditions for the reactor system. A suitable site that meets all the above described requirements may not exist, so the robotic vehicles may be required to perform some amount of site preparation which may include leveling surfaces, clearing debris, digging, or piling Martian soil. This requires a versatile robotic deployment system to accompany the primary nuclear power system. Another important aspect of operation of a nuclear power system that was not considered in DRM 1.0 is maintenance of the system after initial start up. The design will require components that are known to need any inspection, maintenance, or replacement (in addition to components that could disable the system upon failure) to be designed in such a way as to facilitate accessibility by and compatibility with robotic systems. Robotic systems for maintenance will be needed to perform these tasks that require close proximity to the reactor. These robotic systems may be autonomous or tele-operated. Also, due to the radiation environment, the robotic system involved in deployment and maintenance may be forced to be dedicated systems with no other functionality for the mission.

2.4 Observations Based On Previous Architecture Studies

While this overview of references and past work in the field of Mars surface power systems is by necessity not comprehensive, it certainly indicates that the majority of work to date has gone into engineering analyses of individual power system concepts for a set of specific mission power and operational requirements, in some cases followed by local sensitivity analysis with regard to certain technologies. The studies investigated all tend to conclude the appropriate architectural elements for primary power production, energy storage, and secondary power production before carrying out any comparative analysis. Work on comparative analyses of many power system architectures, which include many possible technologies for different functionality in the architectures, for the same mission requirements and assumptions is significantly more limited. The focus of this thesis is on this type of analysis where numerous feasible technologies for architectural elements are considered in the development of overall feasible architectures. Then associated investigations are performed into the sensitivity of particular architecture concepts to changes in surface site location, deployment operations, and environmental conditions.

3. Review of Surface Power Generation and Energy Storage Technologies

This section details the technologies that will be used for subsystems in the analysis of Mars surface power systems for human missions. In terms of functionality, the scope of the analyses includes power generation, energy storage, power management and distribution and any thermal control associated with power generation and energy storage. Metrics suitable for the evaluation of surface power system alternatives are discussed later.

The following is an overview of the different power generation and energy storage technologies considered in the architecture-level analysis. Performance assumptions and references are provided where possible. Specific technologies for the architectures were researched in order to ascertain their level of readiness. A number of RTG technologies that are currently being developed by the NASA Science Mission Directorate [13] were also assessed. Traditional rigid solar arrays (tracking) and newer thin film arrays (non-tracking) were considered for the solar-based options.

3.1 Solar Power Generation Technologies

Two technologies are considered here. They include ultra-light amorphous silicon rollout blanket arrays and high efficiency inflexible tracking arrays. The ultra-light arrays have efficiencies of 15 % and mass/area of 0.063kg/m^2 [14]. Due to their much higher optical absorption, amorphous silicon solar cells are less than a micrometer in thickness. The technology developed for Sovonics Solar Systems [14] consists of tandem junction solar cells deposited by a continuous roll-to-roll process onto metal substrates. The array design is as such that any electrical shorting will only affect the defective cell and not the whole module. The substrates have been populated by a process that has been able to produce webs 35 cm wide and over 300 m long. This type of process will be necessary for production of the large scale arrays that will be required for Mars surface power systems. However, these arrays at 15% efficiency have only been tested as small units, up to 71 cm by 31 cm, so the technology readiness level for a large system that would be required for human surface exploration are lower than that for already existing inflexible systems. Some advances in the technology should be expected in order for the architecture analysis to be able to anticipate future capabilities. This seems further warranted by the above mentioned solar power studies that also estimate thin film solar power efficiencies of around 15%. Among the other positive qualities of these arrays, they are portable, stowable, deployable, retractable, tolerant to radiation and projectile impact. Figure 5 shows a prototype of the actual hardware and the flexibility and stowability can be seen.

Figure 5. Prototype of rolled amorphous silicon solar array [14]

The small thicknesses allow the modules to be rolled and unrolled repeatedly to small diameters while sustaining no damage. In tests, the arrays have been rolled and unrolled through 200 cycles around an inner diameter of 3 cm. This demonstrates the high packing efficiency which is desired for transportation to the Martian surface. This alleviates concerns over transported volume which is more of an issue with non-flexible solar arrays. For radiation tolerance, it was found that amorphous silicon has more than a 50 times greater tolerance in comparison to crystalline silicon and gallium arsenide on germanium.

High efficiency arrays were initially considered and were based on ISS arrays. They have 20 % efficiencies and mass/area of 2.5 kg/m^2. The structural overhead is based on ISS. While this efficiency is significantly higher than that of the amorphous silicon arrays, it quickly becomes apparent that the much greater weight of the high efficiency arrays could not compete with the flexible arrays. The high efficiency arrays were quickly eliminated from feasible architectures and the final analysis on both mass and volume grounds.

3.2 Battery Technologies

Batteries are generally employed for both secondary power generation and for energy storage. Li-ion batteries were considered in this study for their high energy density and common use in aerospace systems. To be conservative, current performance numbers were used. The batteries have a mass-specific energy density of 150 Wh/kg and a volume-specific energy density of 270 kWh/m^3. The battery system for the Tesla Motor Company's Tesla Roadster was evaluated to see the current state of the art Li-ion battery applications [15]. The Tesla system is one of the largest Li-ion battery systems in terms of energy storage. The system depicted in Figure 6 provides 53 kWh of electric energy and can provide power at a rate up to 200 kW which is a power level more then sufficient for crewed Mars mission overnight power needs.

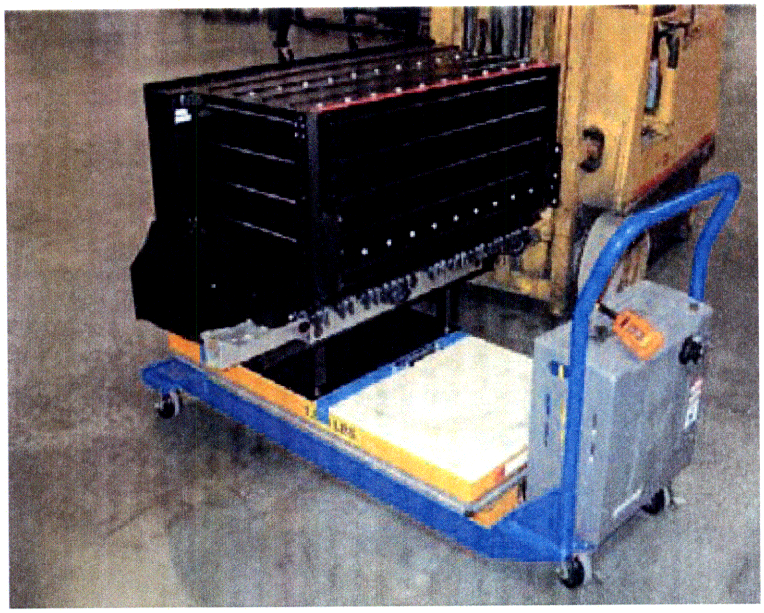

Figure 6. Tesla Roadster batter pack [15]

The mass of the entire battery pack is 450 kg giving a total energy density of 118 Wh/kg. Expected improvements in battery technology, thanks to the push for systems such as these in electric cars and other clean energy technologies, leads to the use of 150 Wh/kg for Li-ion energy density in this Mars power architecture study, as it is also a performance number seen in smaller scale systems in use today. Important concerns that arise from looking at the Tesla battery pack system are safety and reliability. The Tesla pack is composed of 6800 small cells, as large cells have not been safely tested. Some safety features include high strength casings of each battery cell and the overall packs, and coolant systems to keep cell temperatures within operable conditions. The large number of small cells also requires advanced electrical design to increase reliability of the system as a whole against individual cell failures. These concerns will have to be mitigated for future large scale systems such as those required for use in a human Mars exploration surface power system.

Sodium-sulfur batteries are a second technology considered for battery-based energy storage and secondary power production. Sodium-sulfur battery cells have been produced with performances of 220 Wh/kg and 367 kWh/m^3 [16]. These batteries have also been used to provide power levels in excess of megawatts, so power levels are of no concern for this study. The benefits of sodium-sulfur batteries include long calendar lifetimes, high cycle lifetime, and they are primarily suitable for large scale applications. Some of the drawbacks, however, include safety concerns. The inclusion of sodium, which reacts violently when it comes in contact with water, requires the system to be protected from moisture. Sealing techniques in modern sodium-sulfur batteries have decreased the chance of fire. Sodium-sulfur batteries have also been shown to perform in space. STS-87, in 1997, demonstrated the operation of the sodium-sulfur battery shown in Figure 7, with an energy density of 160 Wh/kg for 10 days.

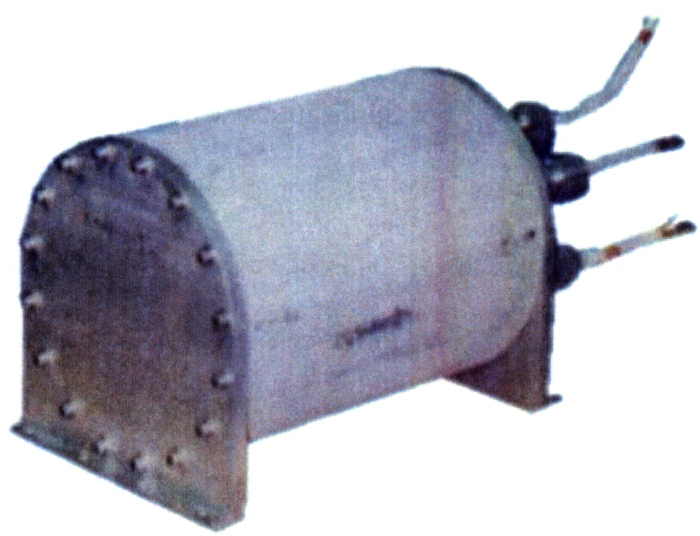

Figure 7. Sodium-sulfur test battery flown on STS-87 [17]

3.3 Fuel Cell Technologies

Regenerative fuel cells can, like secondary batteries, perform both the tasks of secondary power generation and energy storage. Hydrogen/oxygen regenerative fuel cells were considered. NASA has to date used both Alkaline Fuel Cells and Proton Exchange Membrane Fuel Cells. A study of advances in Proton Exchange Membrane Fuel Cells was used as a reference due to their superior performance to the older alkaline technology. The fuel cells themselves have undergone numerous improvements as have lightweight high-pressure gas storage tank design which leads to a large portion of the overall system's mass. Regenerative fuel cells like primary fuel cells use hydrogen and oxygen to produce water and release electrical power. Unlike primary fuel cells, regenerative fuel cells use an external power source to electrolyze the water and replenish the hydrogen and oxygen for reuse [18]. Unlike batteries, fuel cells house their reactant materials outside of the cell stack, so the energy capacity of a fuel cell power system is determined by the size of the gas storage tanks, and the size of the fuel cell stack only determines the power output level. For applications with long discharge times, such as Martian night time, the mass of the gas storage tanks is much greater than the contribution from the cell stack itself. This scenario is where fuel cells outperform batteries. If discharge times are short then the cell stack mass is dominant, and batteries have better energy density performance. The regenerative fuel cells considered for this study of Mars surface power systems come from [18]. The fuel cells have a mass-specific energy density of 700 Wh/kg and volume-specific energy density of 200 kWh/m^3 [18]. These performance numbers are based on discharge times equal to the Martian night plus the time when the sun is less than 12.5° above the horizon. Figure 8 shows the mass energy density for the cells as a function of discharge time and Figure 9 shows the volume energy density for the cells as a function of discharge time.

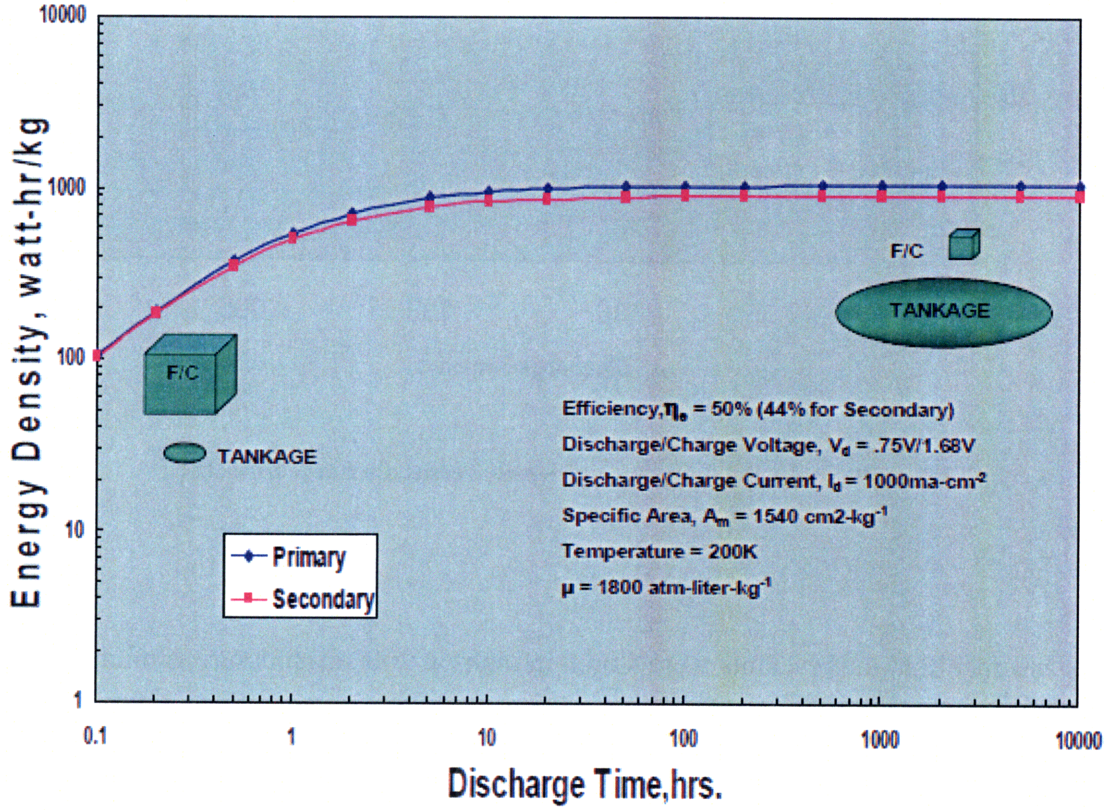

Figure 8. Fuel cell mass energy density versus discharge time [18]

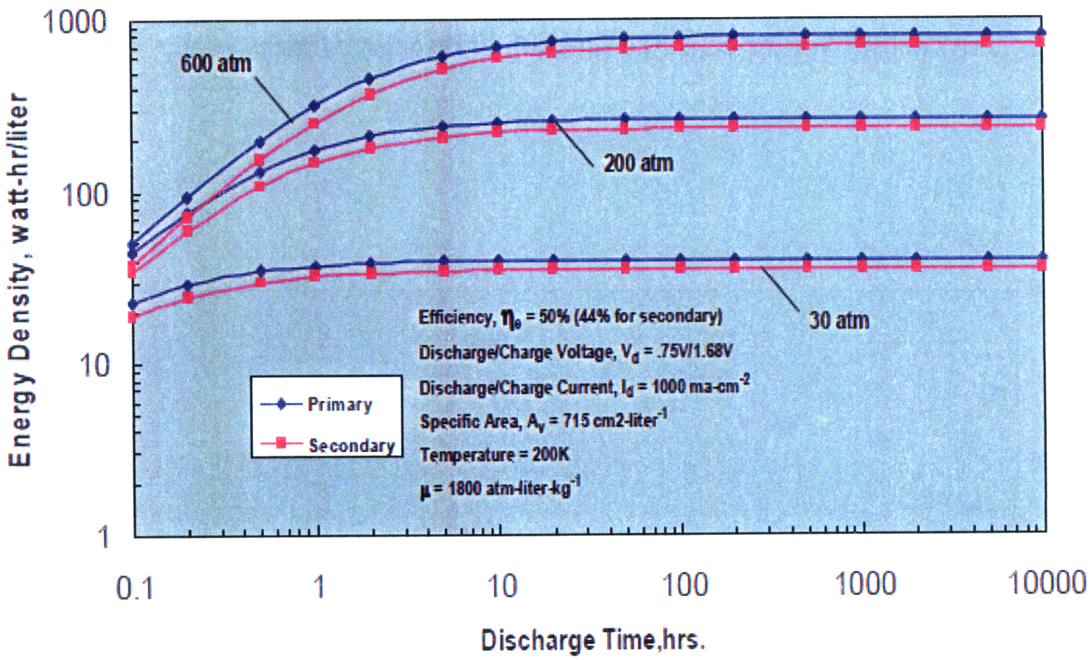

Figure 9. Fuel cell volume energy density versus discharge time [18]

It was assumed that the reactants were stored in tanks at 200 atm pressure, similar to most previous studies that include fuel cells. As seen in Figure 9, this tank pressure also contributes to determining the volume energy density of the fuel cells. The gas storage tanks were sized based on the following figure of merit:

$$\textit{Figure-of-Merit, cm} = (\textit{Pressure,kg/cm}^2 * \textit{Volume, cm}^3)/\textit{Tank Weight, kg} \quad [19]$$

The given figure of merit for current state of the art lightweight tanks is approximately 4.0x10^6 cm. Also a safety factor of 1.5 was used for tank sizing. Additionally, a 5% level of unused reactant was assumed for the tanks. Water storage tanks were sized also using a 1.5 safety factor and a factor of 1.14 was used to account for a reserve of 14% water [19]. Figure 10 shows this regenerative fuel cell design's performance compared to numerous battery technologies.

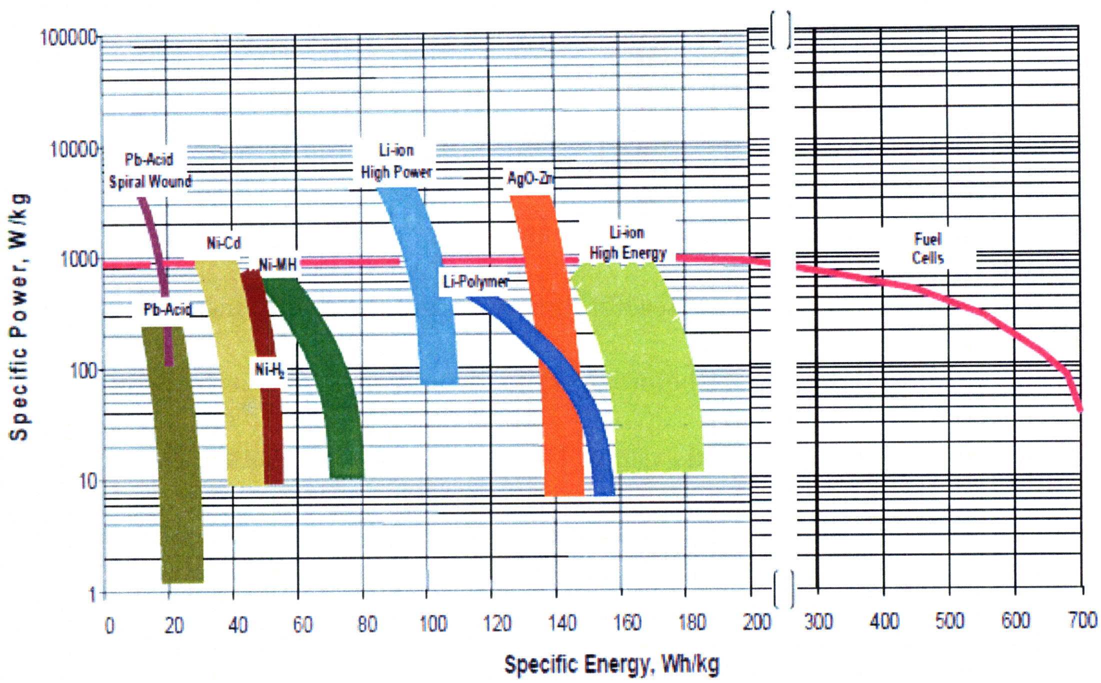

Figure 10. Specific power and specific energy performance of various energy storage technologies [18]

Here it is seen that for high energy needs such as getting through the Martian night, fuel cells easily outperform batteries as battery specific power performance (W/kg) quickly falls with increasing specific energy performance (Wh/kg). Fuel cell specific power performance does not fall off until very high specific energies are reached.

3.4 Nuclear Surface Primary Power Technologies

Two designs were considered for nuclear primary power production in this study. Both are nuclear reactors with dynamic conversion. One design uses a Brayton engine for the conversion and the other a Stirling engine. The Brayton-based design is adapted from the Prometheus design for a lunar based reactor [20]. This design has significantly more detail, both in design and operations, than the Stirling-based design. It was found that a mobile reactor would be very mass intensive and a risky operational endeavor. Therefore, the preferred strategy is to land the reactor directly at its final operational location. It was also found that a human presence before operation would greatly enhance the practicality of implementing the nuclear-based system. This is due to the fact that the use of local regolith for shielding purposes greatly decreases system delivered mass and regolith placement would most simply be accomplished by crew. Alternate scenarios could be implemented in which regolith is placed robotically. The Prometheus-based Fission Surface Power System (FSPS) is made up of three major components. These are the power plant, local electronics, and the station control electronics. These are depicted in Figure 11.

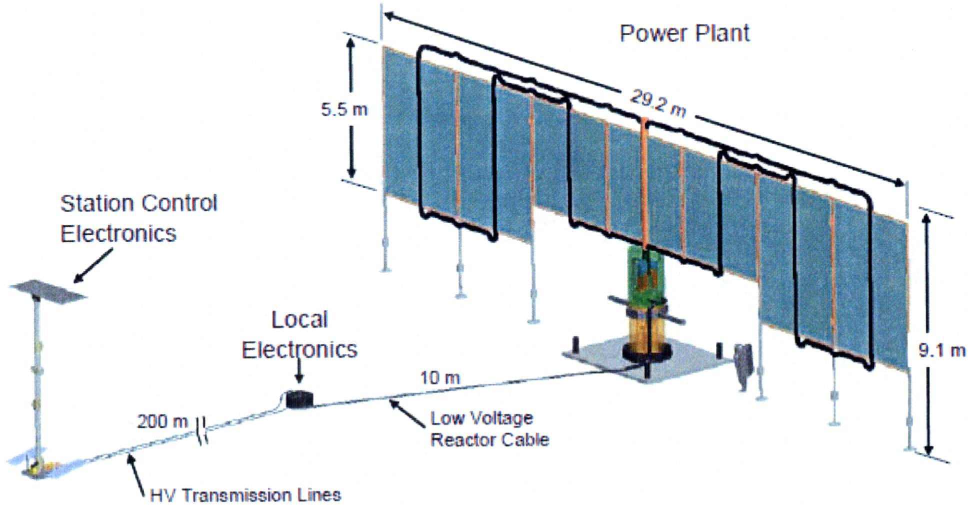

FIGURE 1. FSPS Components – Pre-operational (Regolith Shield Not Shown For Clarity).

Figure 11. Nuclear Brayton-based power system configuration [20]

The power plant includes the reactor, shield, power conversion, and heat rejection elements. The local electronics include the reactor control electronics, signal multiplexer unit, and transmission line voltage transformers. The majority of FSPS electrical subsystems are located in the station control electronics. These provide the interface between the FSPS and the base power distribution architecture. The power plant is a gas-cooled reactor with Brayton power conversion. The reactor shown in Figure 12 has a geometry that minimizes the shield mass associated with the circumferential and axial shielding requirements.

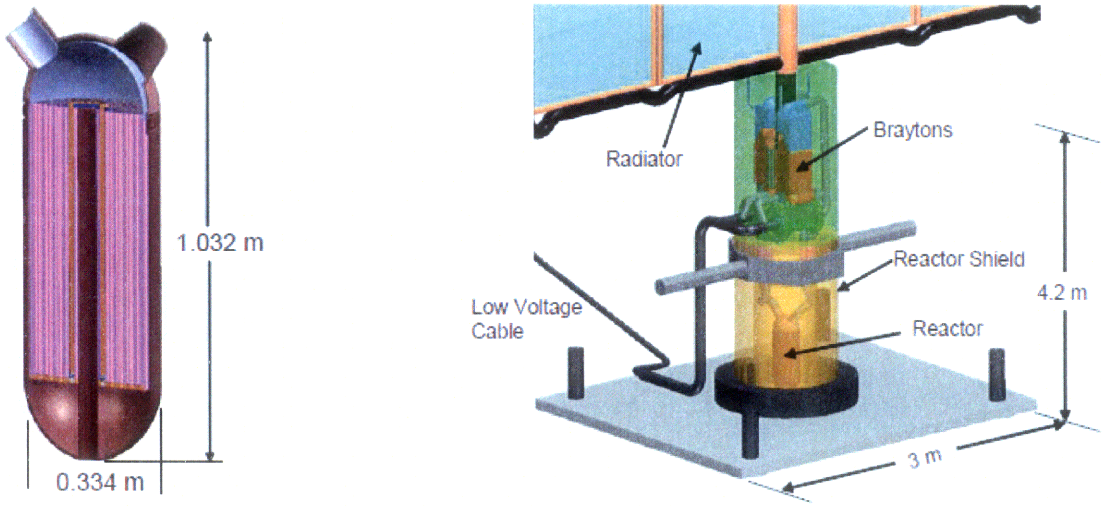

Figure 12. Prometheus-based reactor and Brayton energy conversion unit [20]

The reactor produces a 1144 K turbine inlet temperature. The system includes two Brayton converters, only one of which operates at a time while the other serves as a redundant backup. The Braytons then reject heat through a gas cooler to the system radiators. The radiator was resized from the lunar version for use in the Martian thermal environment, thus slightly reducing mass of the overall system. The design calls for the use of local regolith to provide the required shielding. For the Mars use case, the regolith must be placed robotically before crew arrival so that power is provided upon crew arrival. This strategy calls for tele-robotic regolith placement in which regolith bags are filled with loose surface material and placed around the reactor before start-up. The sequence of operations is shown in Figure 13 and is predicted to occur on a time scale of weeks.

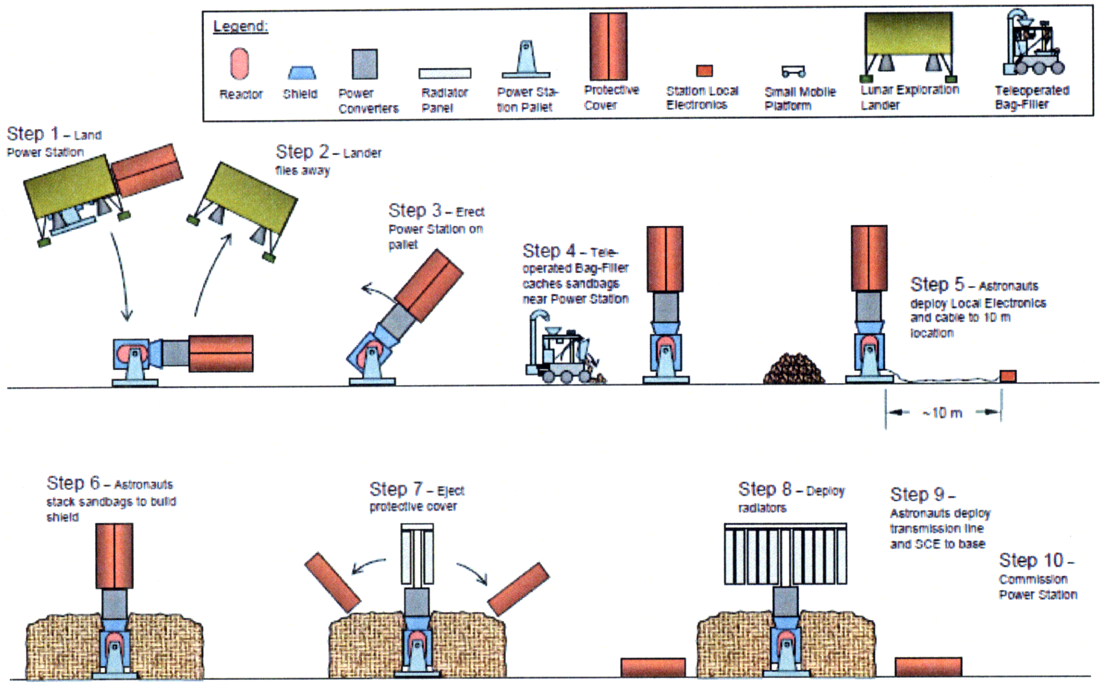

Figure 13. Deployment sequence for Prometheus-based nuclear system [20]

This FSPS Brayton design must be located 210 m from base and have a 3.5 m effective regolith shield to mitigate radiation effects.

The Stirling engine-based design comes from JSC element/systems database and is considerably less detailed [21]. It is composed of an SP-100 type reactor and 4 Stirling engines. It is designed for quick and easy deployment without on-site human intervention. Upon arrival at Mars, the radiators are deployed and the system is lowed into a pre-dug hole. The hole provides the required radiation shielding and allows short duration human proximity to the system for operational purposes. The system is pictured in Figure 14.

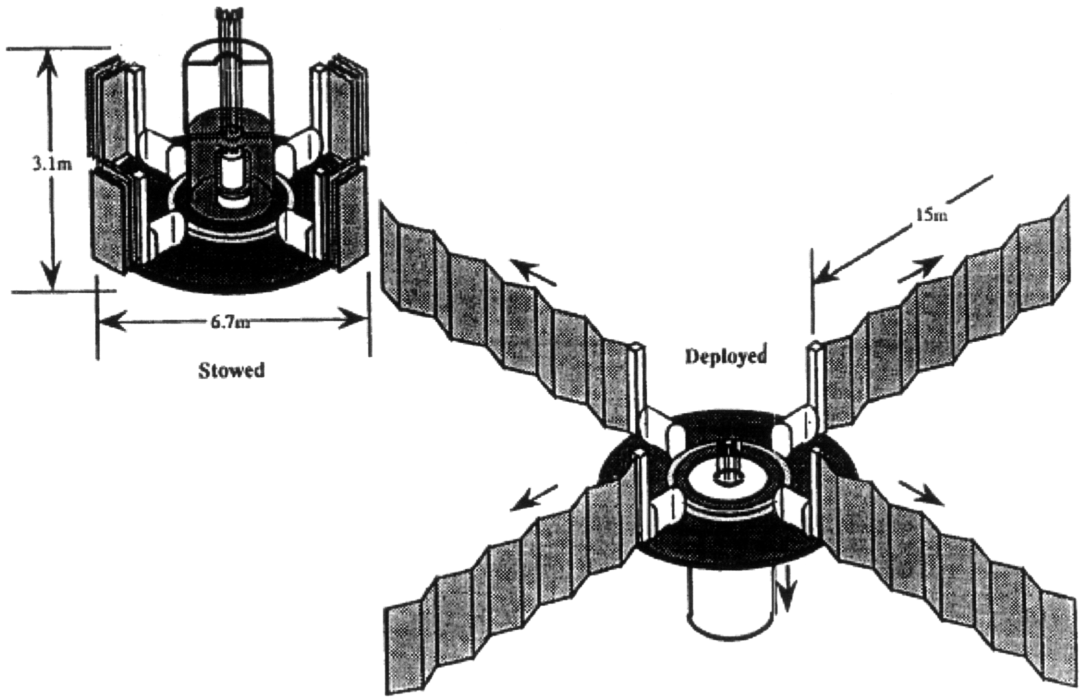

Figure 14. Nuclear reactor and four Stirling energy converters [21]

The system's performance is based on 950 K Stirling engine technology and avoids the use of refractory materials. For safety, two of the four engines are held in reserve to provide energy conversion system redundancy. The Stirling design must be located 1 km from the base. The Stirling system has an overall mass specific performance of 19 W/kg and volume specific performance of 750 W/m^3.

3.5 Radioisotope Power Generation Technologies

Dynamic conversion RTG systems can act as secondary power generation elements as well as provide a redundant constant power source for added safety in the power system. A design was considered for modular General Purpose Heat Sources (GPHS) coupled to Stirling conversion engines. New advances in high efficiency Stirling converters allow for 5-fold increases in electrical power output with the same GPHS thermal power output compared to previous designs [22]. The new design concept involves linking small GPHS modules to the Stirling converter using radiative coupling while using a sodium thermal siphon to transport the heat. The GPHS heat source is on the bottom of the assembly and the GPHS modules boil sodium in pipes, causing the sodium to rise and condense on a radiative surface at the top of the assembly. The Stirling converter portion of the system is located above the GPHS heat sources with a lower temperature radiative surface that then collects heat from the sources below. This process transfers heat to the Stirling converter and also concentrates the heat on the small surface area of the Stirling heads. Heat is then rejected at the Stirling converter cold end via a liquid water pumped loop. Due to the low level of emitted radiation by the GPHS modules, the entire system can be placed near habitation locations unlike full nuclear fission reactors that must be located more than one kilometer from crew. Specifically, the GPHS modules primarily have α-radiation emissions that can be easily shielded against and thus these units could be located close to base and don't require any kind of auxiliary equipment for excavation or regolith moving. For the Stirling converter element of the system, recent advances in technology have led to performances of 40% thermal to electric conversion efficiencies and specific masses of less than 10 Kg/kW. This system has a number of other advantages. The GPHS modules themselves are already fully defined in design and have been space launch qualified. Heat source development costs will be low. Also, the GPHS heat source is easily simulated using electric heaters. This allows much life testing to be preformed in a terrestrial setting. For system operations, it should be noted that the sodium boiler element only functions in a gravity field. Therefore, during transit to Mars, an alternative heat rejection system is needed as the GPHS continuously produces heat. To remove the heat energy when the system is not producing power with the Stirling converters, the insulation package surrounding the GPHS modules is opened so that heat is radiated directly to space. Figure 15 shows the system's configuration for transit with the insulation open and the configuration for power production with operating Stirling converter.

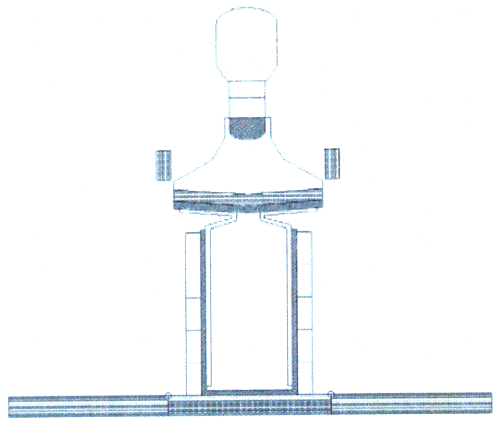

Figure 5.—In transit configuration—convertor not operating.

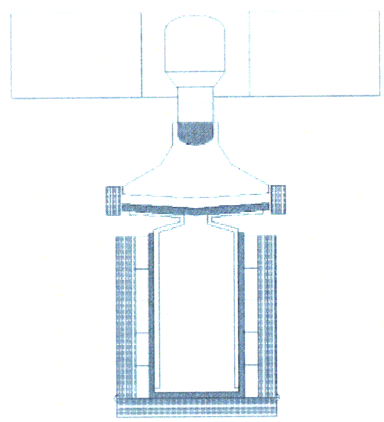

Figure 6.—System configuration during normal power generation—convertor operating.

Figure 15. GPHS system configurations [22]

During power production, the Stirling converters emit heat using a deployable vertical radiator. This design has a mass specific power of 13.75 W/kg and volume specific power of 27500 W/m^3 [22]. These units use PuO_2 for fuel; a 5 kW unit would require 62.5 kg of fuel.

4. Surface Power Architecture Options for Human Mars Missions

As was noted before, previous studies and preliminary designs for human Mars mission surface power systems have been limited in that they have not considered the full space of options for overall power system architectures. Many have focused on a single primary power production technology, whether that be nuclear-based or photovoltaic. This thesis aims to do a more thorough comparative analysis of power system architecture options for surface power systems needed for human missions to Mars. An enumeration of architectural options was carried out based on three architectural variables: the choice of daytime power generation technology, the choice of eclipse power generation technology, and the energy storage technology (if required). Constrained enumeration yields the alternatives shown in Table 1. The enumeration is described as constrained because not all combinations are considered as some do not make technical sense. For example, any system with nuclear primary power production has no need of energy storage or secondary power generation as the nuclear fission reactor will operate continuously, independent of day or night. The remaining architectures shown in Table 1 are the only technically feasible or relevant power generation architectures. For architectures where primary power generation is based on photovoltaic arrays, there is an option for using radioisotope heat sources with thermoelectric or thermodynamic ("dynamic") power conversion (these are the GPHS systems described in the technology chapter) to supply part of the nighttime power; these options also may have different characteristics for contingency operations (e.g. during a global Martian dust storm), because RTG-based architectures are to some degree independent of sunlight and the intensity of insolation. This will be described in more detail during a discussion of Martian dust mitigation, but even a 5kW GPHS-based dynamic RTG could provide a significant portion of the necessary 10kW minimum emergency stay-alive power when optical depths go as high as six during major dust storms.

Architecture	Primary Power Generation	Secondary Power Generation	Energy Storage
1	Nuclear fission - Stirling cycle	N/A	N/A
2	Nuclear fission - Brayton cycle	N/A	N/A
3	Solar - tracking	N/A	Li-Ion batteries
4	Solar - tracking	N/A	NaS batteries
5	Solar - tracking	N/A	Regenerative fuel cells
6	Solar - tracking	Dynamic RTG	Li-Ion batteries
7	Solar - tracking	Dynamic RTG	NaS batteries
8	Solar - tracking	Dynamic RTG	Regenerative fuel cells
9	Solar - non-tracking	N/A	Li-Ion batteries
10	Solar - non-tracking	N/A	NaS batteries
11	Solar - non-tracking	N/A	Regenerative fuel cells
12	Solar - non-tracking	Dynamic RTG	Li-Ion batteries
13	Solar - non-tracking	Dynamic RTG	NaS batteries
14	Solar - non-tracking	Dynamic RTG	Regenerative fuel cells

Table 1. List of analyzed power system architectures

Also, when considering the GPHS-based dynamic RTGs for secondary power generation, a reasonable assumption for size of the system was needed. The decision to use an RTG sized to provide 5 kW of secondary power was based primarily on the RTG fuel requirement. The dynamic RTG technology used in this analysis uses Plutonium Dioxide (PuO2) for fuel and requires about 12.5 kg of PuO2 per kilowatt power produced [22].

Discussions with NASA engineers have shown that Plutonium is expected to be expensive and difficult to acquire, so a conservative allowance for a 5 kW RTG system using 62.5 kg of Plutonium fuel was assumed for this analysis. Another motivation for assuming a small 5 kW RTG system is that the technology has only been tested and implemented on a scale of about 5.5 kW. Therefore, this analysis is conservative and does not try to anticipate the rate of future developments in this area.

A set of metrics is needed to compare the set of architectures given above. Major metrics considered for the surface power analysis were total power systems mass and volume, captured in normalized form (average power / total system mass [W/kg] or average power / total system volume [W/m^3]) These metrics are arguably the most relevant in a comparison of architectures as they are most closely related to the costs of transportation of assets to the Martian surface. Mass of course is directly translated into monetary cost as well as costs related to overall mission performance. Delivered mass is allocated among all of the mission's necessary subsystems so any mass reduction in one system leads to additional delivered capabilities in other systems. Landing capability is also volume limited, so decreases in system volume are also desirable for the same reason. The analysis that was carried out for each architecture was an equal energy analysis, which assumes that all systems provide the same energy per Martian day, but not necessarily the same continuous power output. In other words, for a nuclear fission-based system and a solar-based system, the user receives the same energy per Martian day, but whereas the nuclear system provides a near-constant power output, the solar power system provides the majority of the energy during the day to reduce the amount of energy storage required at night (which is a major contributor to system mass). The evaluation of power system mass and volume is critically dependent on the operational mode of the system. The two general modes of operation that are conceivable are:

- **1.** The system provides constant continuous power to the end user over the course of the Martian day, and indeed over the course of the entire surface stay. In this case average power and momentary power generation are identical.

- **2.** The power usage pattern is optimized such that given minimum power constraints the power system mass for each system is minimized, i.e. the power is used and generated when is causes the minimum power system mass requirement. In this case the power system still provides the same amount of usable energy over the course of a Martian day as a continuous power system would.

For nuclear-fission-based power systems, there is practically no distinction between the two operating modes because nuclear reactors provide approximately constant power over their life-cycle. For power systems incorporating photovoltaic power generation and secondary battery or RFC energy storage there is a significant difference between the two operational modes: equal continuous power generation during the Martian night would lead to very heavy energy storage systems which would dramatically increase the normalized metrics described above. The ability to move the majority of power consumption to the Martian daylight period when power generation is cheap and no energy storage is required has the potential to radically improve the metric values for power systems based on photovoltaics, while still providing the same usable energy during the course of a Martian day as a continuous power system would. Therefore second mode of operations is assumed as the basis for the evaluation of power system architecture alternatives for the analysis presented in this thesis.

It should also be noted that as the solar-based systems are sized for the worst possible day, i.e. the day with the shortest insolation period / longest eclipse period during the Martian year, the energy provided by the solar-based system over the course of the surface mission is actually underestimated. When doing a comparison of photovoltaic based architectures with nuclear based architectures, there is an additional mass and volume performance increase that is not accounted for directly in this analysis and it is present to some degree every day of the Martian year other than the day that experiences the minimum solar incidence.

While mass and volume performance based metrics are arguably the most important metrics to look at when comparing the possible power production architectures, other operations related metrics are also of interest. In addition, the effort of deploying the surface power system prior to routine operations is considered as a secondary metric. Here, different factors may be considered. If deployment is to be carried out remotely, as is the case with the nuclear power based architectures, additional mass may be needed in the form of robotic assistants for either digging an emplacement for the system or for placement of regolith-based shielding. Photovoltaic based systems may also use some form of robotic system for pre-deployment of arrays. On the other hand, if photovoltaic-based systems are deployed manually by crew, considerations such as deployment time, associated crew work load, and provision of power prior to full deployment are necessary. In all cases of nuclear fission power systems, deployment must be accomplished remotely with the use of robotic assistants due to radiation hazards. Cost, both in terms of up-front development cost as well as life-cycle cost including development, production, as well as transportation costs are important metrics to be considered. As the fidelity of estimates at this early stage is severely limited, and preliminary estimates of development and production cost tend to be based on system mass, we will just use system mass as a substitute for cost, thereby reducing the number of metrics we need to estimate. Transportation cost is, of course, also primarily driven by power system mass.

5. Quantitative Analysis Models

The major quantitative modeling effort for this analysis focused on the photovoltaic-based architectures. The two nuclear-based architectures that were considered are NASA developed designs with predicted performance levels included. The only alteration necessary was for the Brayton-based nuclear architecture. The referenced design was based on requirements for lunar operations. Therefore, the thermal rejection system was oversized for Martian cases primarily due to Mars' further distance from the sun. A simple thermal control model was used to down size the radiator size and mass for the Brayton-based system. The photovoltaic based architectures required extensive modeling as the architectures took as inputs various technology choices for secondary power generation and energy storage. Simple point designs did not exist for the architectures before this analysis. Also, it should be noted that current higher efficiency non-flexible arrays such as those used on the International Space Station were considered in the technology review. Upon preliminary modeling, it was quickly noticed that the larger masses associated with these systems made architectures based on these technologies infeasible for Mars use. The large mass requirements make these architectures uncompetitive with all other possible architectures and this array type was not considered in the final analysis. This chapter focuses on the major modeling effort for this thesis for the sizing of photovoltaic power architectures. The main outputs of the model are the mass and volume-based metrics described in Chapter 4.

5.1 Assumptions

Like all models, the development of the model for sizing the photovoltaic-based Mars power architectures relied heavily on a set of reasonable assumptions. Here, these assumptions are catalogued. A major assumption for any photovoltaic power production system relates to the atmospheric conditions during operation of the solar arrays. There is a theoretical solar flux at the surface of Mars that is the output of another model that will be described later, but this value does not account for the presence of the Mars atmosphere and dust that may be present in the atmosphere. A quantity called optical depth accounts for these factors. Optical depth is a measure of transparency and ranges from zero which is completely transparent on up for increasing levels of opacity. The optical depth describes the amount of solar energy flux that is scattered or absorbed along its path to the solar arrays. The equation for optical depth is given as:

$$I/I_0 = e^{-m\tau}.$$

Equation 1.

I_0 is the intensity of the solar radiation expected at the source. I is the actual intensity of solar radiation that reaches the array after scattering and absorption. Also, $m = 1 / \cos\theta$ where θ is the zenith angle between the sun and the Martian surface. Hence, the model accounts for the position of the sun in the sky over the Martian day. Finally, τ is the value of the optical depth. For modeling, an optical depth of 0.4 was assumed. 0.4 corresponds to hazy skies as experienced by numerous Mars rover missions. This value was used as it corresponds to a conservative set of Martian atmospheric conditions experienced during a majority of the Martian year. During major dust storms, optical depth goes up as high as six, and these off-nominal conditions are considered later in the thesis. Optical depth accounts for scattering and absorption of solar radiation as it travels through the atmosphere. Some scattered light also reaches the solar arrays and therefore contributes to power production. When the optical depth is lower, as in the 0.4 case, the scattered component of incident light is relatively low (less than 30%) [23]. Exact modeled numbers for the amount of scattered light are not readily available so the model conservatively neglects this component of incident light. Also, for dust storm cases where optical depths are high, the majority of light that reaches the arrays is actually scattered. When dust mitigation is later considered, experience from the Mars Exploration Rovers is used to approximate the performance of the photovoltaic system during storm situations.

Architectures that employ tracking solar arrays were part of the overall analysis. In these architectures, it was assumed that the arrays have multi-axis tracking capabilities and that the incident solar energy is perpendicular to the arrays over the Martian day. This is not a conservative estimate, but as will be seen in the results, these architectures are not competitive even with this liberal assumption.

A crew of six is assumed for the conjunction class Mars mission. This then dictates the important assumption of 12 kW for the night time power requirement. This assumption is a major driver as it accounts for the sizing of the energy storage system that operates during the eclipse time. Energy storage in turn dominates the mass and volume performance, especially for architectures using non-tracking thin-filmed amorphous silicon arrays.

A number of other assumptions were made that act as inputs to the model. As with all solar array sizing models, end of life conditions are assumed for the final sizing. For this, array degradation must be assumed. In addition to standard array degradations due to radiation and other factors as noted in *Space Mission Analysis and Design (SMAD)*, the model also assumes some degradation due to dust build-up. Previous rover missions have measured this degradation to be approximately 0.028% per sol [23]. This was used with an additional assumption that this component will be limited to thirty sols through the use of some dust mitigation technique to be discussed later. Another important model input and assumption is array lifetime. Lifetime was assumed to be 2 years. If the photovoltaic power production system is used for more than one mission, which seems beneficial with such a large dedicated system, the lifetime would greatly exceed 2 years. To account for this it was assumed that on each additional mission, a supplementary array will be delivered and deployed. Commonly used power distribution efficiencies for both primary power production elements and energy storage elements were assumed based on *SMAD* as well.

From an operations perspective, it was assumed that the solar arrays do not start power production for the day until the sun reaches 12° above the horizon. So the energy storage system must be sized to continue to provide power at all other times. The power requirement also does not jump to the daytime requirement until the sun reaches 12°. Another assumption relates to the packing of the flexible non-tracking array option. Here, the technology for the amorphous silicon arrays as described above is reported to be as thin as 8μm. For added strength and a conservative packing density assumption, this thickness was increased to 2mm, which is similar to many Kevlar material applications.

5.2 Modeling Method

In order to compare all the architectures seen in Table 1, a model was created to assess mass and volume required to provide sufficient power through the Martian day and night. The nuclear options were modeled directly from reference data available, with the addition of the alteration of the thermal rejection system for the Brayton system as described above. The solar power options required the creation of a new model. The major requirements driving this model are as follows. The arrays must be sized for end-of-mission power requirements so that the required power levels can be provided throughout the mission's duration. If several missions go to same site, supplementary arrays are brought each mission to make up for degradation. Importantly, arrays must also be sized to provide the required power during the year's minimum incident solar energy period, as conjunction class missions include surface stay times of over 500 days. Finding the year's minimum incident solar energy for a given base location was the first step in the modeling process. For this, we used a model produced by Paul Wooster, a former MIT student and research scientist. Wooster's model takes base longitude and latitude as inputs and then finds how the incident solar energy at that location varies over the Martian year. Figure 16 shows sample outputs of the model as the daily solar incidence levels over time for three different latitudes. It is seen that some northern latitudes actually have a higher minimum solar incidence over the year than the equator. In fact 31° north has the highest minimum incident energy compared to the rest of Mars and is thus the location that most enhances the performance of a photovoltaic system. Also, it is found that all southern latitudes have lower values for minimum incident solar energy during the year than corresponding northern latitudes. This is due to the fact that when the southern hemisphere experiences winter due to the axial tilt of Mars, Mars is further from the sun in its eccentric orbit then during the northern hemisphere's winter.

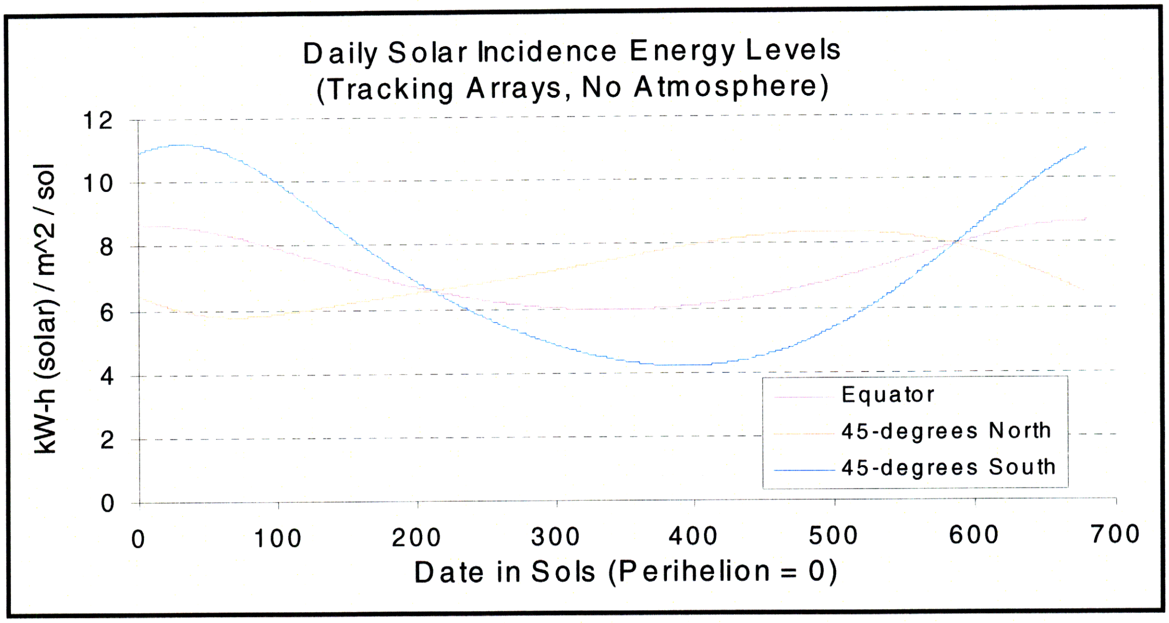

Figure 16. Daily solar incidence energies for different Martian latitudes

These location-based characteristics of the minimum solar energy for the year greatly effect the decision for the desired power production architecture. The modeling process takes this into account. An initial run of the model for the photovoltaic-based architectures assumes an equatorial location. The results of this analysis are then examined and the competitive architectures are reevaluated on the basis of varying the location on the Martian surface where the system operates. The competitive architectures are again modeled, but now for various latitudes and thus various minimum solar energies. In this way, the effect of location on mass and volume performance is evaluated. The architectures can then be compared to the nuclear-based architectures, which are unaffected by the location in which they operate.

The model created for this thesis begins with the minimum incident solar energy for a location that is output from the above described model. The steps taken in the modeling process are briefly outlined below in Table 2.

Step #	Description
Step 1.	Calculate total energy in Joules that must be produced by the solar arrays in a day based on the days power requirement
Step 2.	Calculate the power per unit area being produced by the solar array as the sun sweeps the sky on the given latitudes minimum solar energy day based on the array's end of life characteristics
Step 3.	Integrate to find the total energy that a square meter array can produce over the day
Step 4.	Comparing the energy produced by a square meter and the total energy required find the needed array area for the system
Step 5.	Calculate the mass and volume for this array area
Step 6.	Based on night time energy requirements calculate the mass and volume of the secondary energy production components

Table 2. Solar power system modeling sequence

The first step in the modeling process converts the power requirement over the entire Martian day into the actual energy that must be converted from solar radiation into usable electrical energy. The day's power requirement is broken into two parts: the 12kW eclipse time power requirement and the daytime power requirement that is allowed to vary for the analysis. These power levels are simply multiplied by the times that they are enforced to yield the electrical energy that must be produced. Here, assumptions on energy distribution efficiencies between different components as described above are accounted for. Also, charging efficiencies for energy storage systems such as batteries and regenerative fuel cells are accounted for and cause the energy requirement to be higher than would have otherwise been expected.

The next step is to evaluate the performance of a unit area of solar array over the daylight period as the sun sweeps across the horizon. For this the model takes all the assumptions described above regarding degradation of the array at the end-of-life, optical depth, and array energy conversion efficiency described in the technology review to find the power that can be produced by a unit area as the sun travels across the horizon. Two versions of the model are needed for this step. The model used to evaluate the non-tracking thin film rollout array architectures accounts for the sweep of the sun over the day which results in a cosine loss in energy incident to rollout arrays laying on the Martian surface. Thus the power output of the arrays is considerably lower in the morning than at noon. The second model is used for evaluation of the tracking array-based architectures and there is no cosine loss as it is assumed that the arrays track such that the incident solar energy is always perpendicular to the arrays. In both cases, the model outputs the power production level at roughly 50 second increments over the Martian day.

Step three in the modeling process then calls for the integration of the power production profile found in step two over the daylight hours. This tells how much energy in Joules was actually produced by a unit area of solar array during the daylight hours. After this, it is simply a matter of taking the total energy requirement found in step one and dividing by the energy that was found to be produced by a unit area of array in step three. This results in the required total array area to produce all the energy needed for a Martian day.

Next, the metrics of interest are calculated by finding the masses and volumes of the components that make up the various photovoltaic-based architectures. For the solar arrays themselves, there are again two versions of the model, one for non-tracking arrays and another for tracking arrays. The non-tracking arrays are the flexible thin filmed blanket arrays and have masses and volumes based on values from the technology review and assumption on packing. The tracking arrays use the same array material, but have additional structure and thus additional mass and volume due to the tracking functionality. The additional mass and volume are based on structural fractions for arrays used on the International Space Station. The mass and volume of the energy storage systems, whether they be batteries or regenerative fuel cells, are also calculated. These are based on their energy densities and the energy that they must store for the night time energy requirement. Any architectures that employ 5kW RTGs for secondary energy production are sized based on the values given in the technology review.

This model must be run separately for every architecture listed in Table 1. For each architecture option, the model is run for a varying daytime power requirement, and the masses and volumes of all architectural elements are summed and the mass specific power performance (W/kg) and the volume specific power performance (W/m^3) are found over the varying daytime power requirement.

6. Discussion of Analysis Results

The solar power system sizing model was run for each of the six photovoltaic-based power system architectures. For each, the daytime power requirement was varied such that the average power level over the whole day was varied from 0 to 200 kW. The first set of results then compares the performance of each architecture, including nuclear-based architectures, as a function of average power level for the day. In this way, the mass specific power (W/kg) and volume specific power (W/m^3) performance for each architecture versus the average power level and thus energy produced can be compared across architectures. After performing this comparison, the competitive architectures are chosen and then further evaluation of these is performed. A point design for a system with 100 kW for average power over the Martian day is evaluated. Each competitive architecture is modeled again for the 100 kW average power condition, but this time the free variable is the latitudinal location of the base where the power system is employed. In this way the overall effect of location on power system performance can be evaluated. Again the competitive architectures are compared on a performance basis. These two forms of analysis focus on the mass and volume-based metrics. Further metrics considered for architecture comparison include deployment methods and complexities, dust mitigation considerations for photovoltaic-based architectures, and possible areas of power system commonality between lunar surface power systems and Mars surface power systems that could lead to additional benefits of some architectures over others.

6.1 Architecture Performance Based on Power Requirement

The results of the first analysis, in which all architectures are compared on a mass and volume basis for varying average power levels, are shown in Figures 17 and 18. The mass specific power results in Figure 17 show that among the nuclear-based options, the Stirling power conversion-based system has the best performance. The architectures based on thin film rollout solar arrays and RFCs quickly outperform the nuclear Stirling architecture when the average power level exceeds 25kW. As was seen in the previous architecture case studies, desired power levels for human Mars missions easily exceed this level, thus making these architectures competitive practically as well. The architectures which include thin-film rollout solar arrays and batteries, either lithium ion or sodium sulfur, never outperform the Stirling nuclear system on the power range studied, but their performance does rise as the average power level increases. Also, as the average power approaches 200kW, rollout arrays with NaS batteries come within 2 W/kg of the nuclear Stirling mass performance and rollout arrays with Li-ion batteries come within 5 W/kg of the nuclear Stirling system. In all architectures that employ the thin-film rollout solar arrays, the trend of increased performance with increased average power level is observed. This is true because the ultra-light solar arrays begin to dominate the more massive secondary power generation components at higher average power levels. As average power level increases, only daytime power level increases. Nighttime power remains constant at 12kW and thus the energy storage system remains constant. Therefore the mass of the system becomes dominated by the very light weight solar arrays that are used to produce higher power levels during the daylight periods. All tracking array architectures are easily seen as non-competitive on a mass specific power basis. Also note that all solar-based options where 5kW RTGs were included see a slight mass performance boost over their non-RTG counterparts, but the performance increase is small and the major benefit of the RTG is still the added safety that a continuous power supply imparts. Looking at the Brayton power conversion-based nuclear architecture, it is observed that the architecture underperforms all thin-film rollout solar architectures on the power range studied. However, the increase in performance as power increases is greater than that of the rollout solar options, and the Brayton nuclear architecture would outperform the solar architectures at power levels slightly higher than 200kW. 200kW was chosen, however, as an upper bound based on previous architecture studies and the fact that it would allow modest in-situ resource utilization.

The volume specific power results in Figure 18 show that both nuclear-based options underperform all the non-tracking rollout array-based architectures. Also, it is observed that all non-tracking array architectures quickly plateau around 1800 W/m^3. This is again due to the fact that the thin-film arrays with relatively small volumes dominate the volume of the overall system as average power level increases and nighttime power remains constant. Within the non-tracking solar array architectures, it is seen that there is increasing volume performance from architectures that employ RFCs to those with Li-ion batteries and best of all those with NaS batteries. This is just the trend of increasing volumetric energy density for the energy storage systems. Also, again all corresponding architectures that include a 5kW RTG have a slight volume performance increase over architectures that do not include them. Also, we see again that all tracking array architectures are non-competitive on a volume specific power basis. The Brayton power conversion-based nuclear architecture again sees an increase in performance on a volumetric basis as the average power level increases, but the system would have to produce significantly more than the 200kW upper bound to compete with the non-tracking array architectures. This would be relevant for systems sized for considerable in-situ resource utilization, but these cases are not considered in this study.

As was stated, after the preliminary analysis covering all architectures was performed, the most competitive architectures were then analyzed further. From the above discussion, the competitive architectures included the two nuclear-based architectures and all non-tracking array-based photovoltaic architectures. Next, these were again modeled, but this time as a point design for a power system producing an average power level of 100kW. This corresponds to a system with a daytime power requirement of about 200kW useful power. Figure 19 shows the mass specific power performance versus the volume specific power performance for this point design. The best architectures would be located in the upper right portion of the plot, with the worst being in the lower left. It is quickly observed that the best architectures based on these performance metrics are the non-tracking solar architectures with regenerative fuel cells for energy storage. Also, while the non-tracking solar array architectures with batteries for energy storage slightly underperform relatively to Stirling-based nuclear power on a mass basis, they have more than double the performance on a volumetric basis. This could be a major factor in lander design. The Mars lander may be more volume limited for the Stirling nuclear architecture, while the difference in mass seems less likely to have a strong effect on the design. Clearly, the Brayton power conversion-based nuclear architecture is the least desirable architecture for the 100kW point design. Also, solar-based architectures that use batteries for energy storage have a very slight performance boost volumetrically, but the near doubling in mass-based performance for architectures with RFCs makes these architectures more desirable.

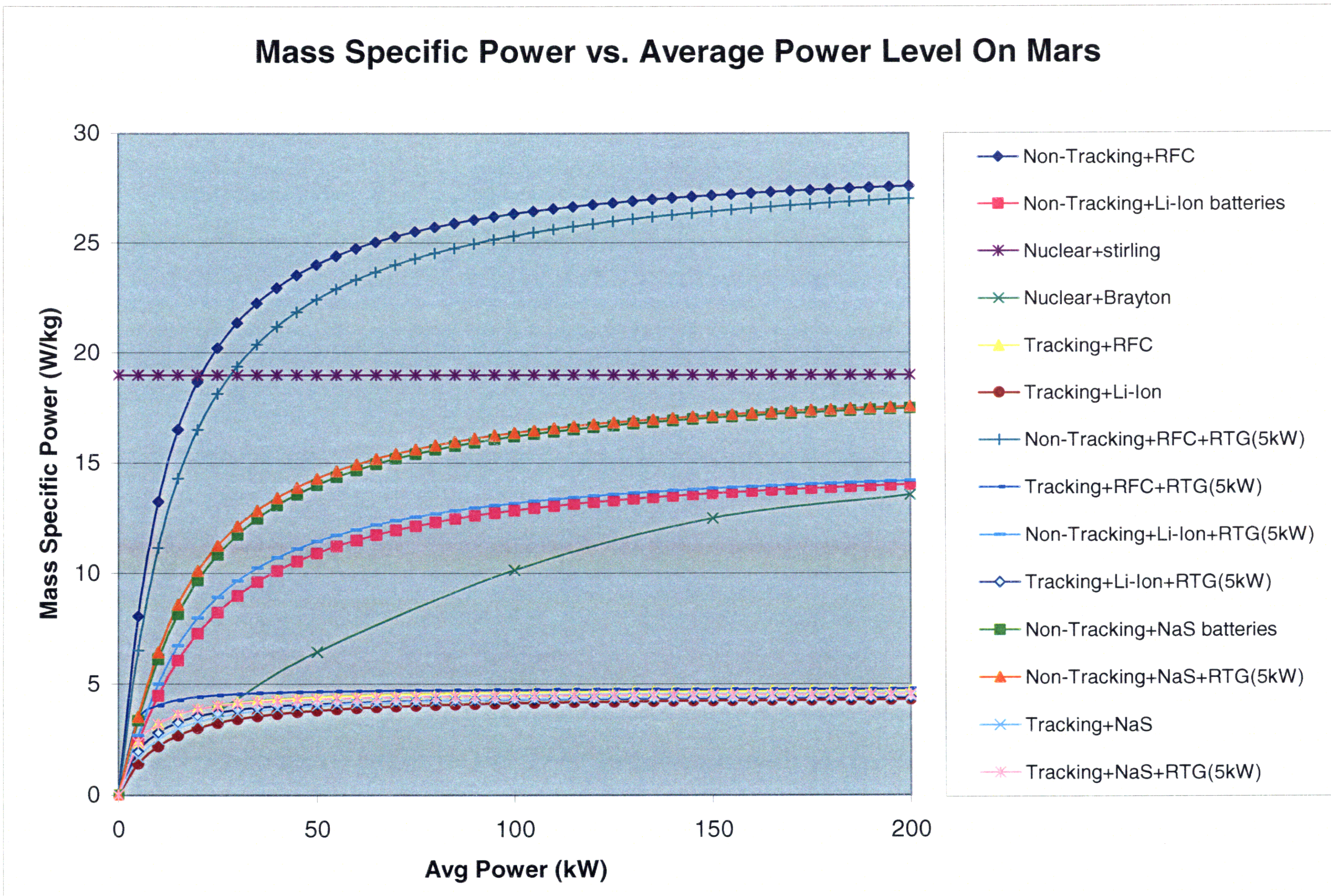

Figure 17. Architecture analysis results showing mass specific power performance versus system average power

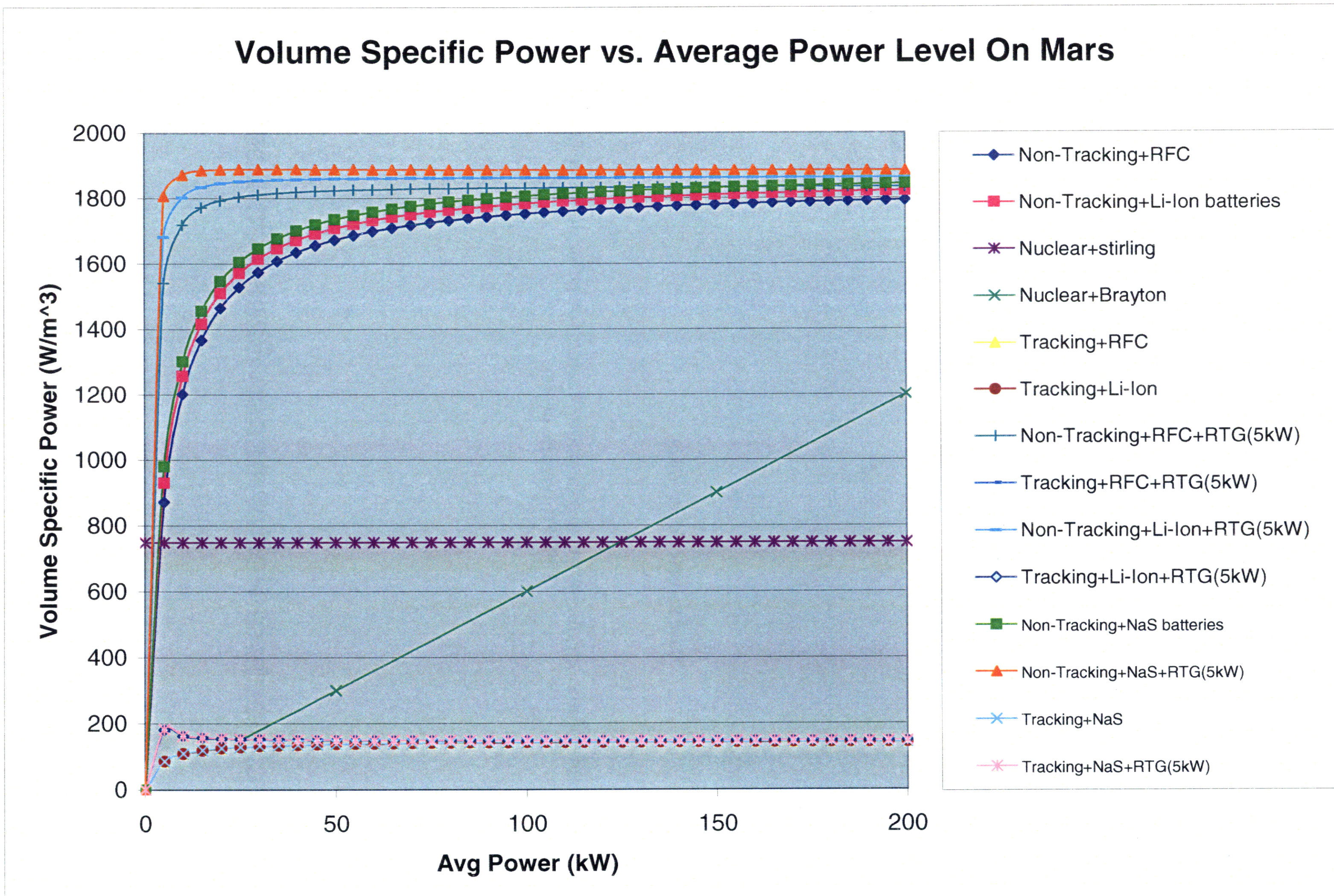

Figure 18 Architecture analysis results showing volume specific power performance versus system

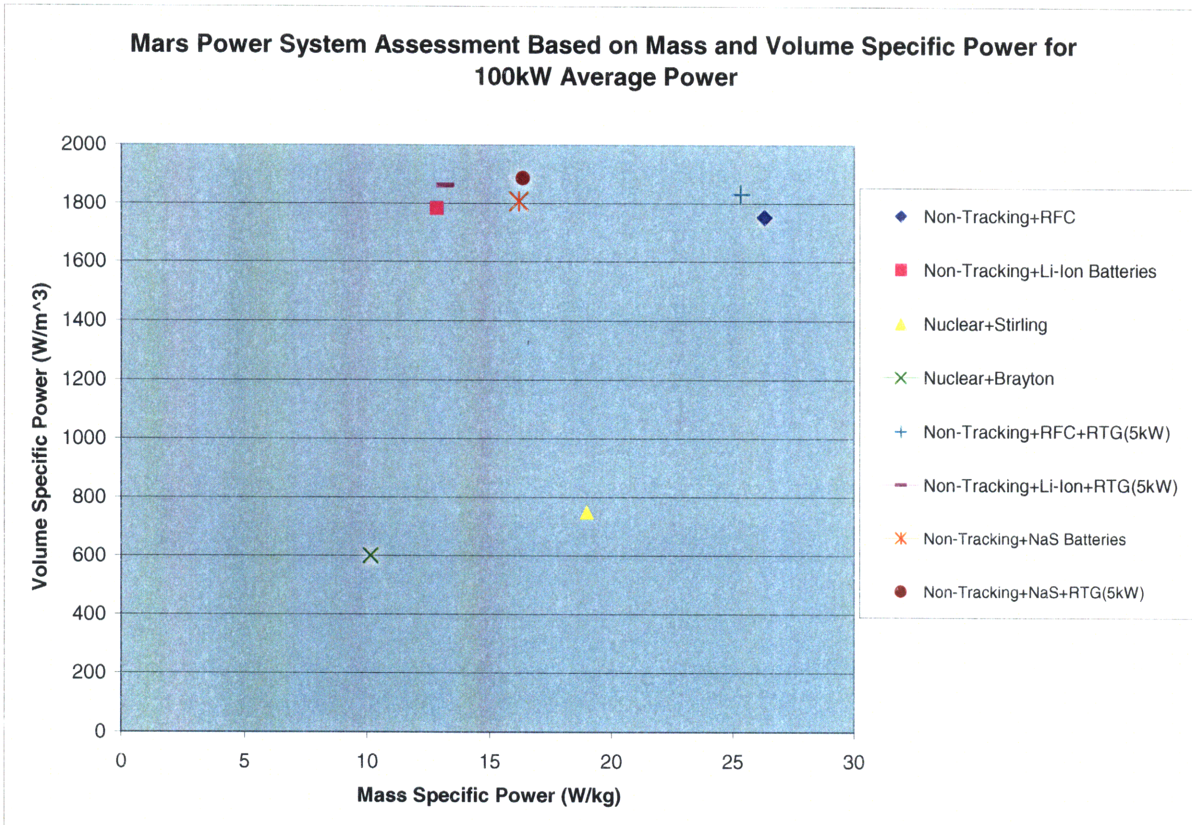

Figure 19. Mass and volume specific power performance results for point design architectures with 100kW average power

6.2 Architecture Performance Based on Location

The next analysis performed relates to the effect of Mars surface location on mass and volume performance of the surface power system. Now that thin film solar architectures with RFCs, Li-ion batteries, or NaS batteries have been singled out as the most interesting competitive architectures as compared with nuclear options, it is interesting to look at the effect of latitude location on the power systems' performance.

This way, more suitable locations for solar-based architectures can be assessed. Taking in the planet's axial tilt and orbital elements about the sun, the minimum solar energy flux based on latitude can be found as noted using Paul Wooster's model. For this part of the analysis, only three non-tracking solar-based architectures were studied. Architectures which include 5kW RTGs were omitted for simplicity as they gave little performance increase and are mainly useful for contingency systems. The overall trends seen would not differ, but simply be shifted up in performance slightly if RTGs were included. Figures 20 and 21 present the mass and volume-based performance of the power architectures for a range of Mars latitudes. First of all, the nuclear-based architectures are represented as flat lines due to the fact that there are no factors that cause any differences in performance depending on their location. They are unaffected by where they are deployed. The results show that there is an optimum location for solar architectures around 30° north. Here the minimum yearly solar flux is actually maximized. The results show that northern latitudes are always better than their southern counterparts. The trends for solar-based architectures show that it would be quite infeasible to use a solar-based power system at latitudes much lower than -60° or much higher than +60°, as performance falls off rapidly. Looking at Figure 20, as expected, non-tracking solar power systems with RFCs dominate the other power systems. They also dominate nuclear-based architectures when located between -38° and +50° latitude. In the original analysis, we saw that non-tracking solar architectures with batteries were similar in mass performance to nuclear Stirling architectures, but here we see that this competitiveness is strongly based on location. Variation from mid-latitudes decreases this competitiveness. While systems with NaS batteries are just 2 W/kg below Stirling performance at +30°, they fall below 6 W/kg difference at -30° latitude. They continue to outperform the Brayton-based nuclear architecture over a much greater range. Figure 21 shows volume specific power performance versus power system location. Here, all non-tracking solar architectures have similar performances over the given range. Also, all are seen to outperform the nuclear bases architectures over a range of -50° to +50° latitude. Thus, mass specific power is the performance metric most effected by surface location.

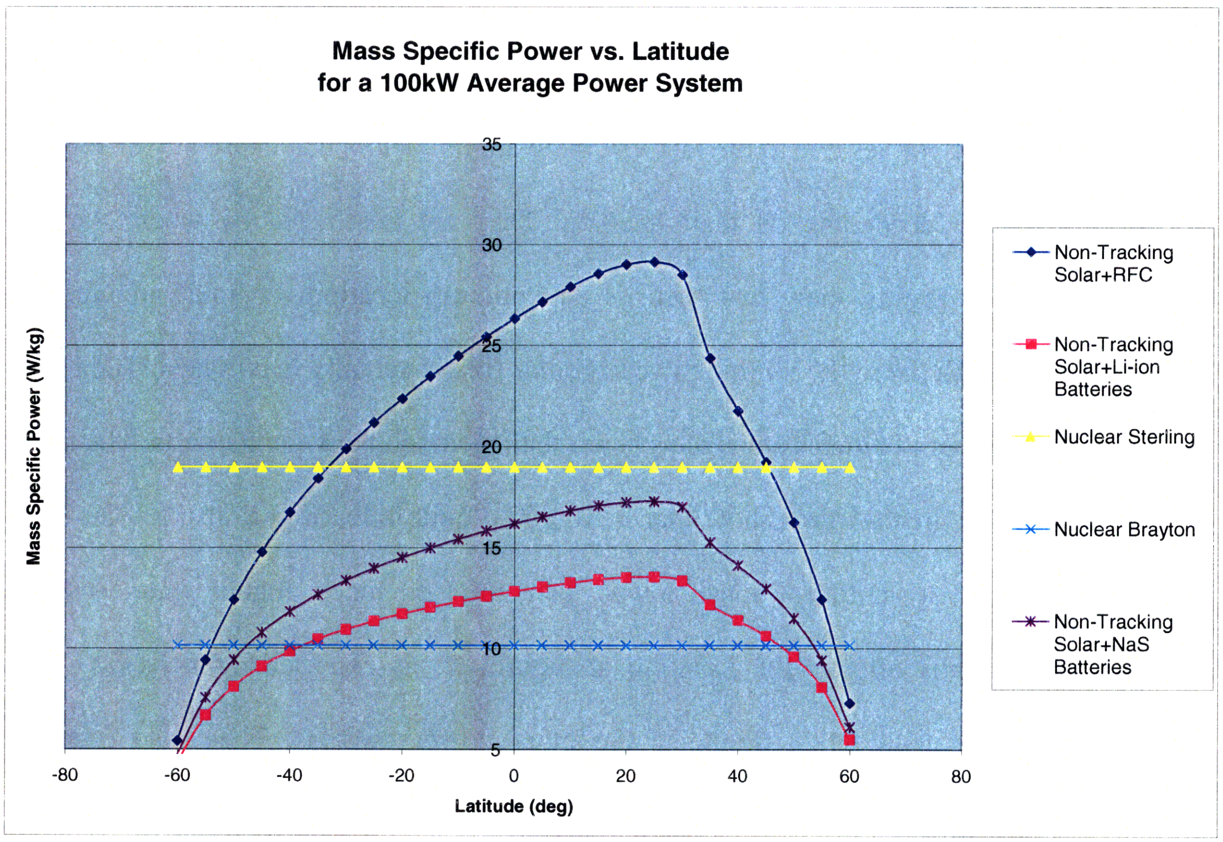

Figure 20. Mass specific power for interesting architectures versus latitudinal location on Mars

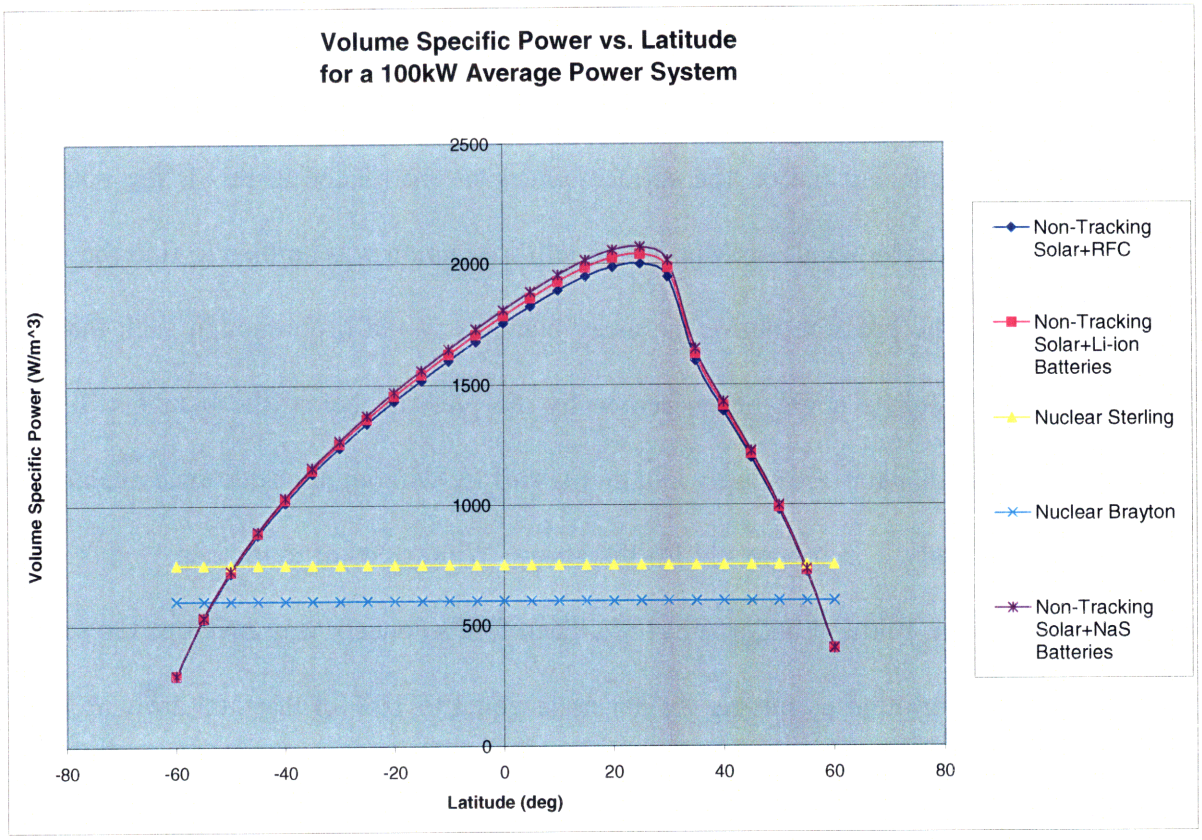

Figure 21. Volume specific power for interesting architectures versus latitudinal location on Mars

6.3 Deployment Considerations

Aside from mass and volume-based performance, deployment time of these arrays is important. Looking at the 100kW point design, it was found that for the non-tracking architectures an array of 25,000 m² is required for an equatorial-based system. The implications of such a large array field must be considered to check the feasibility of such a power system for use on manned Mars missions. Before considering actual deployment, another implication arose. The non-tracking solar array architectures are favorable in large part due to their extreme light weight and thinness. The arrays are rolled out like blankets and simply lay flat on the surface. One concern related to this is the possible lifting of the arrays by winds on Mars. Bernoulli's equation was applied to find the wind speed at which the pressure above the array blankets would drop enough such that the weight of the blankets could be overcome by the pressure below the blankets. It was found that if the blankets are simply laid on the surface without any additional anchoring, a light wind of only 7.35 m/s would lift the arrays. Wind gusts of more than 15 m/s were experienced at the Viking Lander sites [24]. Therefore a concept was developed to secure the arrays to the ground by adding Kevlar areas equal to 10% of the total array area, on which rocks will be placed. Other techniques such as staking the arrays down were also considered; however, extra array area for staking would have to be provided, and the mass of the stakes that would be needed outweighed the necessary mass of Kevlar sections for the regolith placing scheme. Also, placement of stakes would potentially take more time during deployment than regolith placement, as extra tools and precision would be required. It was found that 9.2 kg/m^2 of rock is needed in the 10 % Kevlar regions to secure the array against the top recorded Mars wind of 25 m/s. For example, if the overall needed array area is 1000 m^2 to fulfill an energy requirement, then 100 m^2 of Kevlar will be required and 920 kg of Martian rocks must be placed on the array. The major effect of this consideration is increased deployment time, which will be discussed below. Also, after this wind lifting issue was discovered and the above mitigation technique was evaluated, all analysis was redone to include the added weight and volume of Kevlar in the overall architectures. All results presented have included these factors.

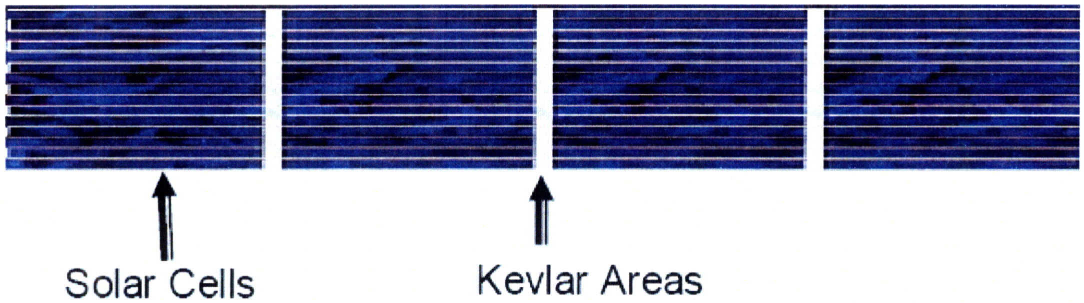

Figure 22. Top view of arrays with Kevlar sections for rock placement

Deployment time includes off-loading the arrays, unrolling the arrays, and finally placing rocks to weigh down the arrays. An estimate for the actual deployment time is useful in assessing system feasibility. Again, for this analysis we considered the 100kW average power system located at the Mars equator in order to get an estimate for deployment time. This requires a 25,000 m^2 rollout array field, which includes the addition of the Kevlar areas for wind mitigation. It was assumed that array blankets are 2m wide and weigh 36kg for easy storage and handling by two astronauts. With 0.07 kg/m^2 as the expected array density, only 18 blankets are required. If we assume astronauts can unroll an array at a walking speed of 1m/s, the unrolling requires only 7 hrs. Time will also be needed for unloading, positioning, and hookup of the arrays. If it is assumed that this requires an additional 1 hr for each, this adds 18 hrs. In addition, rocks must be placed in the Kevlar areas. Assuming Kevlar areas are 0.3m in length and 2m in width, 5.6 kg of rock in each area is needed. There are 225 of these Kevlar areas per array, making a total of 4050 areas to be covered with rocks. Assuming 2 rocks are needed per area to secure the 2 sides of the array; this requires 8100 rocks to be placed. If 30 seconds is needed to pick up and place a rock, this will take 33.75 hrs for 2 crew. All of this combined results in a total of 66hrs to deploy the solar array field by two crew members. Realizing that this is an initial early estimate that would require experimentation involving suited individuals attempting the deployment phases to get a more accurate deployment time estimate, sensitivities of the deployment time estimate to various factors were calculated. The relevant factors include array area, walking time, rock placement time, and off-load and hook-up time. These sensitivities allow us to see which factor if changed, would most effect the overall deployment time. Sensitivities also reveal how much mistakes in estimation of time needed for each deployment task used in the above analysis actually effect the predicted deployment time. The results are shown in Table 3.

Sensitivity of total deployment time to different factors:
1) Sensitivity to array area=0.99
2) Sensitivity to walking time=0.96
3) Sensitivity to rock placement time=0.97
4) Sensitivity to off-load and hookup time=0.965

Table 3. Deployment time sensitivity results

The sensitivities were calculated by first estimating total deployment time as described above and then doing revised estimates in which a single deployment factor was varied by 10%. This was done for each factor. The sensitivity values given are the ratios of the individual revised time estimates to the original time estimate. Numbers closer to 1 indicate that a factor has less effect on deployment time. Here we see that the deployment time estimate given is most sensitive to the assumption of walking speed. This also says that the actual deployment time will be most limited by the speed at which the astronauts can walk in their suits while laying out the blanket arrays and placing Mars regolith. Therefore an actual rollout solar array design should be made with ease of unrolling in mind.

Another important consideration is that stay-alive power must also be provided during the deployment process. Deployment operations give 0.76 kW per man-hour; therefore only 14 man-hours are needed to reach a capability of 10 kW, which is enough for minimal stay-alive power. To be very conservative, we can neglect this and find out how many additional fuel cells or batteries are needed to get through the deployment period. Assuming that full deployment and initial power-up takes 1 week, either a 10kW RTG or fuel cell system to provide 10kW power over the week is needed. The RTG system would be approximately 1200kg and 0.6 m^3. A RFC system would need a 2400kg system with volume 8.4 m^3. This is overly conservative however, and in fact little more than fully charged nighttime power generation would be required, as 2 crew could achieve the needed 10kW in less than 7hrs.

Another deployment option that could mitigate many of these deployment concerns would involve the use of autonomous or tele-operated rovers for deployment of the power system before crew arrival. This possibility was not considered in great detail as it is more conservative to consider the need for human deployment, especially when comparing feasible architectures. Any robotic deployment system would require the ability to offload and unroll the arrays as well as pick up and place Mars regolith on the arrays for wind mitigation. As a baseline point design, the VECNA Bear prototype was considered. Shown in Figure 23, this is a prototype autonomous robot used for casualty retrieval. Its dexterity for its intended mission would easily allow it to perform the necessary tasks for deployment of the array fields for the studied non-tracking solar power architectures on Mars. The robot weighs approximately 200kg, can travel at 5 m/s, and is volumetrically the size of an adult male. If employed, a robot of this type would incur negligible mass and volume additions to the overall architectures. The VECNA design demonstrates a level of technology that exists, not actual hardware that could survive and function in the Mars environment. The technology level demonstrated by the design is, however, sufficient for the power system deployment operations requirements described above.

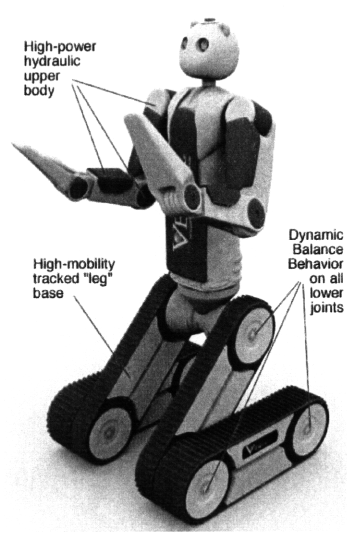

Figure 23. VECNA casualty retrieval robot design

6.4 Dust Mitigation Considerations

Dust on Mars is a concern for any surface power system that employs photovoltaics. Two cases are important to consider. First, dust storms cause a significant increase in optical depth and thus decrease the power output per unit area of the array. It is necessary to be sure that the power system can provide stay-alive power for the crew during these storms. Next, it has been found that even during non-storm periods, Mars dust will accumulate on the arrays over time causing a decrease in power production performance. This effect must be mitigated by some form of dust removal or the system must be sized for end-of-life conditions based on no dust removal.

For the first case of dust storms, the architecture sizing analysis was based on the assumption of an optical depth of 0.4. This is for hazy skies, and in the event of a dust storm, the optical depth can rise as high as 6. Previous experience from the Mars Exploration Rovers in dust storms with high optical depths has shown that this is actually not a concern. Remember that this analysis did not include a model for scattered light, which is present during the storms. The MER rovers experienced at most power drops of 65%. This is significant for rover systems that do not have power systems that are oversized for their stay-alive needs. However, the architectures that have been analyzed for human surface power systems are greatly oversized for stay-alive requirements. The stay-alive power requirement for a crew of six is 10kW, and as long as the chosen system is sized to have an average power of 30 kW, the scattered light present during a dust storm with optical depth of 6 is sufficient to keep the crew alive no matter what the duration of the storm.

The second case involves mitigation of natural dust accumulation over even non-storm periods. Previous Mars rover missions have shown that dust accumulation results in an array performance degradation rate of 0.028% per sol [23]. For the performance analysis presented above, solar array degradations were based on the assumption that dust would only be allowed to build up over a period of a month. Therefore, some monthly dust mitigation technique must be employed. Mars dust adheres to array surfaces through Van der Waals adhesive forces. These forces are very strong for Mars dust particle sizes which range from 50-100 micrometers [24]. Dust is deposited on solar arrays through two major mechanisms. First, saltation is the lifting of particles from the ground by wind. At Mars atmospheric pressure of 6 to 10 mbar, wind speeds higher than 15 m/s will cause dust movement. The Viking lander did experience winds of this speed and higher during short gusts. Also, rotary winds called dust devils on the surface lift dust that can be deposited on array surfaces. The second major mechanism for dust deposition is the settling of suspended dust in the atmosphere. The rate of this settling dust is not well known, but the mechanism was experienced during the Pathfinder mission. Major dust removal methods fall into four categories: natural, mechanical, electromechanical, and electrostatic [24]. Natural dust removal by winds on Mars does not seem to be a reliable method. Experiments have shown that winds velocities of at least 35 m/s are needed for significant dust removal from array surfaces [24]. Over a 100 day period, Viking never recorded winds speeds approaching this mark. Mechanical dust removal includes methods such as wiping or blowing. Mechanical wiping could be accomplished using a broom type device and is preferred for simplicity over blowing devices. The broom could be used to clean off the arrays during a crewed EVA and would take on the order of the same time as the unrolling portion of deployment described above. This process could also be performed robotically either by the robotic system used to deploy the arrays, if this method were used, or by a dedicated mechanical arm with a brush or rotating whisk [24]. Electromechanical dust removal could be accomplished by shaking or shocking the arrays, or by using sound or ultra sound. These methods are more complex than simple mechanical methods and have not been tested. Electrostatic dust removal uses electrostatic forces to prevent dust deposition in the first place. Mars dust particles are expected to have a specific charge due to photoelectric and cosmic-ray-induced charging. Therefore, dust could be repelled from the arrays by giving the arrays a dust-like charge. The breakdown of the Mars atmosphere by Paschen discharge limits the potential that can be applied to the arrays. The limit is about 350-400 volts. Experiments have shown that 350 volts is ineffective in repelling dust from arrays. Higher potentials of around 700 volts is effective, however, this is outside the feasible range. Therefore, among the studied dust removal techniques, mechanical removal by astronauts or robotic assistants is favored over the others. It is the simplest technique and also experimentally shown to be the most feasible.

6.5 Commonality Opportunities With Lunar Systems

A brief study was done to investigate possible areas of power system commonality between Lunar and Mars surface systems. With a focus on lunar outposts located at the poles, a few conclusions about lunar power systems were made right away. Fist, the low zenith angle of the sun at the lunar poles led to the favoring of tracking arrays for any power system architecture based on photovoltaics. Also, Lunar missions are assumed to occur much sooner than human Mars missions. Thus, the technology development needed for large scale amorphous silicon arrays with reasonable efficiencies is not assumed to be ready for lunar missions, and modern high efficiency crystalline arrays such as those used on the International Space Station are instead assumed. This means that commonality in the solar arrays themselves does not exist. However, other components of the power system architecture may be potentially common and some analysis to determine the favored lunar architecture is needed. A very limited architecture performance analysis similar to the extensive analysis performed for Mars was done for the lunar case. Here, only three major architectures were analyzed to find whether a solar-based or nuclear-based architecture is favored for lunar missions. The three architectures include solar power with either Li-ion batteries or regenerative fuel cells for energy storage, or a nuclear option based on the lunar specific Brayton conversion design made for the Prometheus project. The Brayton design was used as opposed to the Stirling design since the Brayton design is a more detailed design and it is a design that was specifically developed for a lunar outpost. Performance results in the same format as was presented for the Mars architectures are given in Figure 24-26 below.

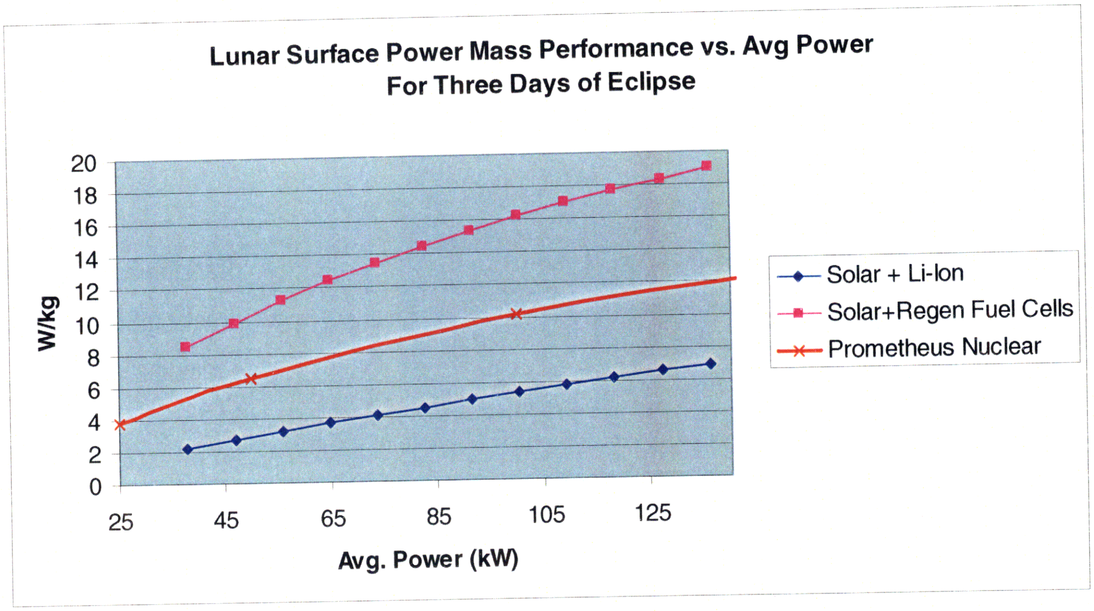

Figure 24. Mass specific power performance for three power system architectures on the moon versus average power

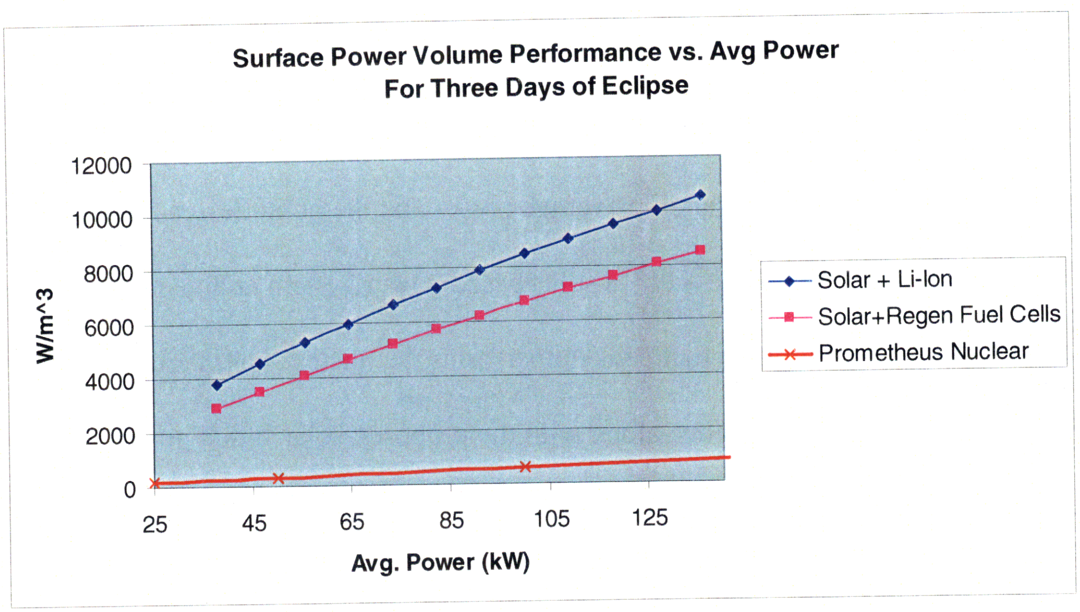

Figure 25. Volume specific power performance for three power system architectures on the moon versus average power

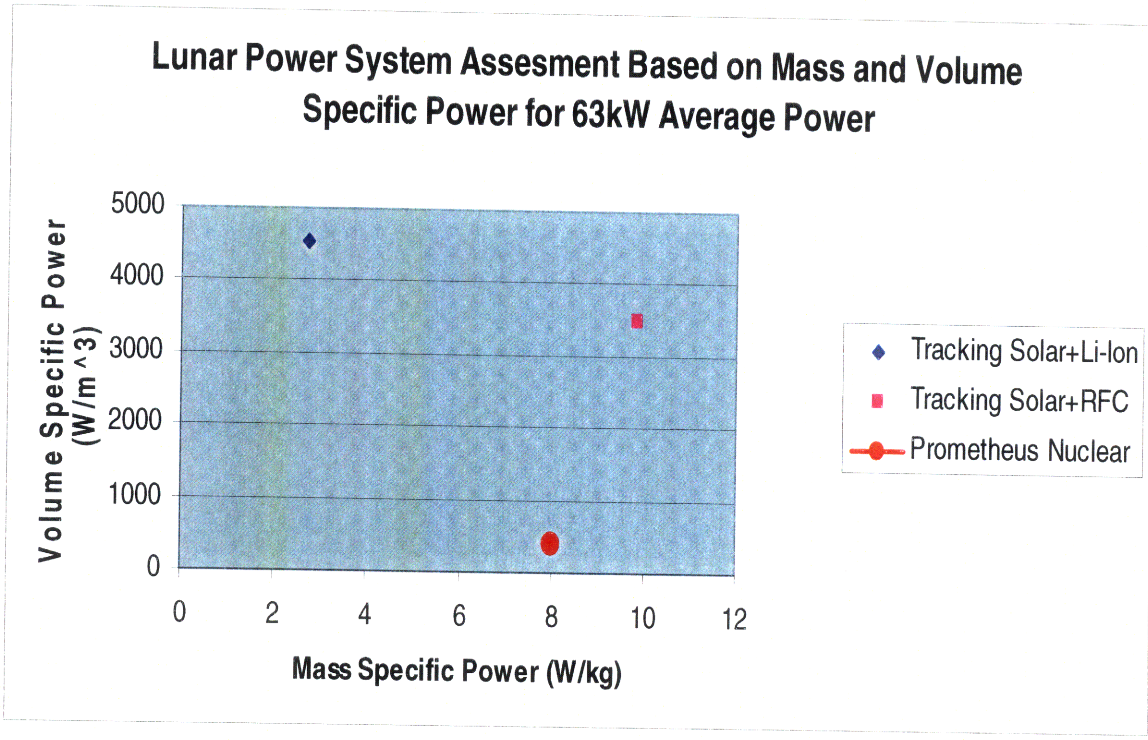

Figure 26. Mass and volume specific power performance on the moon for a 63kW average power point design

The general results spanning a variable average power and the point design results for a 63kW average power system show that a solar-based power system architecture with tracking arrays and regenerative fuel cells outperforms the nuclear-based architecture on both a mass and volume basis. This, along with the proposed solar-based power system that is being assumed by the Lunar Architecture Team at NASA, leads us to look at possible commonality between a Lunar surface solar power system and a possible Mars surface solar power system. Table 4 shows the similarities and differences in the major elements of the power system architectures for the two locations.

	Moon	**Mars**
Power Generation	**Tracking Solar Arrays**	**Non-Tracking Solar Arrays or Nuclear**
Array Type	**Current Solid Substrate**	**Flexible Thin Film**
Primary Energy Storage	**Regenerative Fuel Cells**	**Regenerative Fuel Cells**
Thermal Control	**Larger radiator but other components common**	**Smaller radiator but other components common**

Table 4. Areas of possible commonality between major power system components for Lunar and Mars systems

For the reasons mentioned above, the actual technologies used for the solar arrays are not common between the Moon and Mars. Also, as was seen in the Mars architecture analysis, tracking arrays on Mars incur an infeasible mass and volume penalty. Therefore, Mars can not employ common tracking array system elements such as structure or tracking mechanisms. Regenerative fuel cells are the most efficient energy storage devices in terms of mass, and it seems that they will maintain this dominance over batteries for the foreseeable future. This makes them the choice for both Mars and Lunar energy storage. Performance levels are 700 Wh/kg for fuel cells as opposed to 200Wh/kg for top of the line Li-ion batteries. Regenerative fuel cell systems can be common for the Moon and Mars if they are modular in design. A different number of units would be sent based on the mission duration, mission power requirements and eclipse times. The Mars design would not have to be identical to lunar design, but instead a block upgrade that relies on lunar operation and testing to fix any problems that arise would be useful for the reduction of cost and risk for Mars surface missions. Thermal control components other than the radiator itself can be common. The thermal environment on Mars allows for the use of a smaller radiator than that on the Moon. As a side note, both locations could use RTGs as small supplemental energy sources. The RTG system is not necessary for the success of solar-based architectures, but it does add to the overall safety of the system, as mentioned in the Mars architecture analysis.

Another possible area for power system commonality is in the power distribution and control elements of the power architecture. These elements were not considered in the more extensive architecture analysis, but commonality here could act to alleviate development costs and increase system reliability for Mars power systems. Table 5 below describes some of the possible areas of commonality in the power distribution and control systems for Moon and Mars surface missions.

	Moon	**Mars**
Generated Current	**DC**	**DC if solar, AC if nuclear**
Internal Habitat Voltage	**Arbitrary AC voltage and can be standardized**	**Arbitrary AC voltage and can be standardized**
Transmission Voltage Limit	**kV range**	**500 V**
Misc. Components	**Step-up and step-down transformers, switch gear, human interfaces**	**Step-up transformers if solar, step-down transformers, switch gear, human interfaces**

Table 5. Areas of possible commonality in power management and control for Lunar and Mars systems

Requirements for power distribution and control allow for much commonality of components. DC to AC conversion is required on the Moon and Mars if solar power is the basis of the power generation component of the architecture. Solar power generation produces DC electricity while most habitat components use AC. Habitat voltage levels are arbitrary and could be standardized between Lunar and Mars missions. Also, step-up and down transformers will be needed in both situations if solar power systems are used, since they are low voltage systems. For power distribution itself, there is a 500 volt transmission limit on Mars due to atmosphere, whereas lunar distribution systems can operate in the kilovolts range. This may be an area of non-commonality, as high transmission voltages on the Moon would give lower transmission losses over distances. Therefore, distribution cables would probably not be in common for the two locations. Low transmission voltage on Mars gives solar another advantage over nuclear, as the generation arrays can be distributed closer to the systems that need power and thus lower loss would be experienced than for architectures based on nuclear power, where the reactor may need to be placed up to one kilometer away from human activities. Lastly, components such as transformers, switchgear, and human interfaces can be common without being identical designs, as the Mars versions can be block upgrades that take advantage of testing and lessons learned on the moon.

7. Conclusions

7.1 Summary

A systematic comparison of surface power system concepts for human Mars missions was carried out, including nuclear fission, radioisotope, and solar power generation technologies. The quantitative analysis was carried out on the basis of equal energy provision to the power system user over one Martian day (including day and night periods); this means that the total amount of energy available to the user will be the same in all cases, but the power profile over the course of the day may be different from concept to concept. The main metrics considered were mass-specific average system power and volume-specific average system power; both were calculated based on an equal-energy analysis for each of the architecture options considered. Another consideration was the ease and feasibility of deployment of large solar array fields.

7.2 Findings and Recommendations

The analysis results indicate that over the entire range of average surface power levels considered (≤ 200kW), solar-power systems based on thin-film arrays with batteries or regenerative fuel cells are comparable to and actually better in performance than nuclear-fission-based architectures. Thin-film-based solar architectures provide sufficient power for crew habitation and operations even during contingency situations such as global dust storms, and they appear to require only very limited time to deploy and maintain on the surface of Mars. Also, initial provision of sufficient stay-alive power can be accomplished with 14 man-hours of EVA work. Maintenance which includes dust mitigation is most simply performed by brushing the arrays off. This and deployment can either be done by crew members on EVA or by a robotic system. The technology level necessary for robotic deployment and dust mitigation has been demonstrated, however, actual flight hardware does not exist. Potential areas of commonality between lunar and Mars surface power systems were found and could positively lead to early development of Mars mission components. Commonality can also lead to reduced development costs for Mars missions and operations experience.

It is important to note that significant development and associated performance increase of photovoltaic power generation and energy storage capabilities can be expected in the next decades for Earth-based applications in the energy sector, which would be available virtually free of NASA investment into technology development for human Mars missions in the 2030s or 2040s. It is also important to note that technology development for photovoltaic power generation and high-performance energy storage technologies will occur independently outside NASA, while small (50-500 kW) nuclear reactor technology will not. The associated performance gains will make solar surface power even more competitive with nuclear fission systems. Also, public opinion may not favor nuclear options, and in fact the public's demand for clean energy technology development is pushing the use of solar power in many areas. Another nuclear drawback is that the reactor must be placed far from the base or have larger, heavier shielding.

Also, maintenance on the reactor itself will require robotic systems, adding complexity and risk to the overall power system. This indicates that solar-based Mars surface power systems should be seriously considered as an alternative to nuclear surface power.

7.3 Future Work

The analysis done for this thesis was based mainly on currently available technologies. This is especially the case for the energy storage technologies, which dominate the mass of the system when light weight solar arrays are employed. There are significant current research and development investments into energy storage technologies being made, and it is likely that new technologies and systems with improved energy storage density will soon become available and in turn increase the performance of photovoltaic power architectures. It has been observed that energy storage, like many technologies, demonstrates an exponential increase in performance over time. Figure 27 is based on a study of performance of energy technologies over time, taken from Koh and Magee [25]. It illustrates that energy-density/Kg is increasing at a low exponential rate.

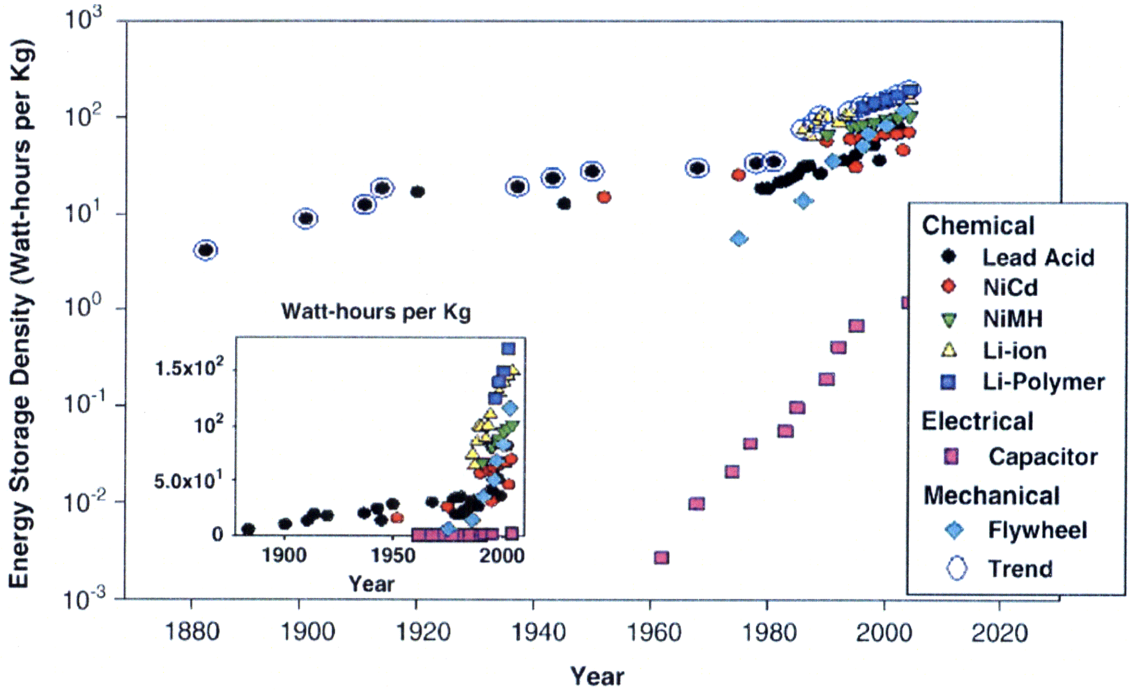

Figure 27. Trends in energy storage density for various energy storage technologies

These forecasts of improvements in energy storage technologies are paralleled by forecast improvements in the performance of photovoltaic power generation. This means that significant improvement of system mass and volume may be expected for power systems based on photovoltaics. Again, most developments are also occurring outside the aerospace sector. Therefore, this comparative analysis of power system architectures for human Mars exploration would greatly benefit from consideration of future performance increases in architectural elements. One approach could be to develop a predictive model for the performance of energy storage mechanisms and solar arrays, and then to analyze architectures that employ these future technologies as was done in this study. Another approach would be to update this analysis as the technology developments occur.

In addition to future development in solar architecture elements, nuclear reactor designs for space exploration applications may improve. The designs used in this analysis are not far along in development and lack fidelity. Additional progress in nuclear reactor designs for human exploration could also be added to this analysis as it becomes available. However, development of a small scale reactor, on the order of hundreds of kilowatts, will most likely fall solely on NASA as there are no obvious applications outside of space exploration.

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