



An Overview of Power Capability Requirements for Exploration Missions

José M. Davis, Robert L. Cataldo, James F. Soeder, Michelle A. Manzo,
and Roshanak Hakimzadeh
Glenn Research Center, Cleveland, Ohio

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301-621-0134
- Telephone the NASA Access Help Desk at 301-621-0390
- Write to:
NASA Access Help Desk
NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076



An Overview of Power Capability Requirements for Exploration Missions

José M. Davis, Robert L. Cataldo, James F. Soeder, Michelle A. Manzo,
and Roshanak Hakimzadeh
Glenn Research Center, Cleveland, Ohio

Prepared for the
First Space Exploration Conference: Continuing the Voyage of Discovery
sponsored by the American Institute of Aeronautics and Astronautics
Orlando, Florida, January 30–February 1, 2005

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

The authors wish to acknowledge all the NASA personnel that participated in the development of the white papers and presentations that are summarized here, as well as those that supported the Advanced Power team of the Capability Requirements Analysis and Integration (CRAI) activity.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at <http://gltrs.grc.nasa.gov>

An Overview of Power Capability Requirements for Exploration Missions

José M. Davis, Robert L. Cataldo, James F. Soeder, Michelle A. Manzo, and Roshanak Hakimzadeh
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Advanced power is one of the key capabilities that will be needed to achieve NASA's missions of exploration and scientific advancement. Significant gaps exist in advanced power capabilities that are on the critical path to enabling human exploration beyond Earth orbit and advanced robotic exploration of the solar system. Focused studies and investment are needed to answer key development issues for all candidate technologies before down-selection. The viability of candidate power technology alternatives will be a major factor in determining what exploration mission architectures are possible. Achieving the capabilities needed to enable the CEV, Moon and Mars missions is dependent on adequate funding. Focused investment in advanced power technologies for human and robotic exploration missions is imperative now to reduce risk and to make informed decisions on potential exploration mission decisions beginning in 2008. This investment would begin the long lead-time needed to develop capabilities for human exploration missions in the 2015 to 2030 timeframe. This paper identifies some of the key technologies that will be needed to fill these power capability gaps. Recommendations are offered to address capability gaps in advanced power for Crew Exploration Vehicle (CEV) power, surface nuclear power systems, surface mobile power systems, high efficiency power systems, and space transportation power systems. These capabilities fill gaps that are on the critical path to enabling robotic and human exploration missions. The recommendations address the following critical technology areas: Energy Conversion, Energy Storage, and Power Management and Distribution.

Introduction

Advanced power technologies lead to improvements in specific mass, specific energy, radiator and array area, and overall power management efficiency. Such technologies reduce the mass and size of deployed systems, and can also reduce the launch mass and volume of the overall system. Low specific mass power systems also reduce trip times for electric propulsion. In some cases, advanced power technologies enable missions not otherwise possible, such as surface mobility or nighttime operations. Further, future exploration missions will require power systems that are able to operate in extreme environments. These benefits will be attained with a broad effort across a range of power technologies.

For the exploration missions, power production requirements can range from milliwatts for some robotic exploration components, to watts for human-portable energy storage devices, to kilowatts for surface mobility, to hundreds of kilowatts for surface habitats and operations, and up to multi-megawatts for Nuclear Electric Propulsion (NEP) dependent architectures. Other advanced power requirements will include low specific mass power production, high capacity/low mass energy storage, advanced materials and components, and flexible and intelligent power management. Advanced power systems must also address operational environment issues for space and surface applications.

The key power technology areas, capability gaps, and how they address the critical capabilities are discussed in the following sections. Table 1 shows which of the critical capabilities will be impacted by developments in each of the technologies.

TABLE 1.—TECHNOLOGIES NEEDED FOR CRITICAL CAPABILITIES

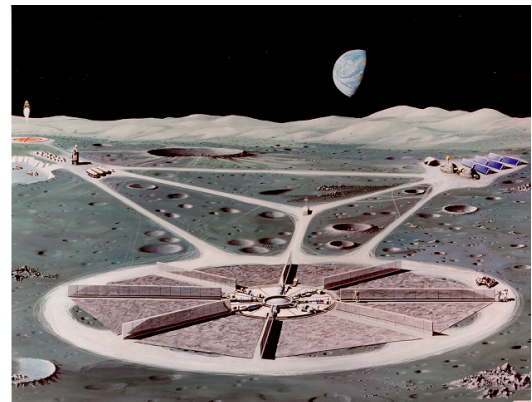
Technology	Critical Capability					
	Power Generation (for CEV)	Surface Nuclear Power Systems	Surface Mobile Power Systems	High Efficiency Power Systems	Space Transportation Power Systems	Survivability —Long Life Components
Solar Power Generation	X		X	X	X	
Nuclear Power Generation		X	X	X	X	
Energy Storage	X		X	X	X	
Intelligent PMAD	X	X	X	X	X	
Advanced Electrical Components	X	X	X	X	X	
Environmental Durability/Survivability	X	X	X	X	X	X

Technology Areas

Nuclear Power Generation

Capability Gaps.—Although Radioisotope Thermoelectric Generators (RTGs) are commonly used in deep-space missions, there are no flight-qualified nuclear fission power systems capable of supporting the types of exploration missions currently being planned. These missions will require higher power levels for longer periods of time under challenging environments. Previous designers developed elements and components over the past 30 years, but program cancellations and restarts have caused discontinuity of expertise, thus, the technology remains at TRL 3-5. Elements have been ground tested—reactors, power conversion systems, electric propulsion systems, and breadboards. The technology still needs system integration testing and has not flown in space environments. Development costs to TRL 6 are predicted to be in the \$100M to \$1B range depending on the technologies ultimately selected, schedules, and applications.

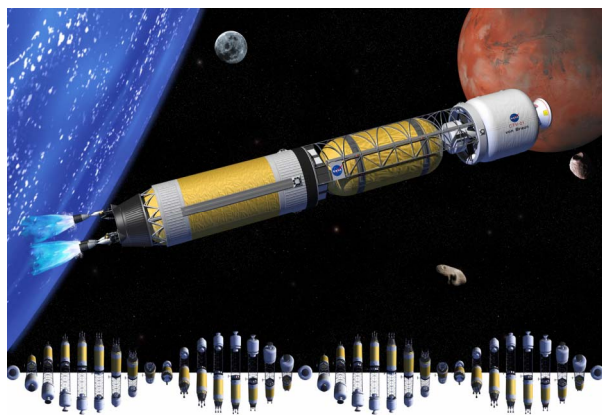
All exploration activities, robotic or human, require planetary-surface electrical power (i.e., Moon or Mars). Requirements for robotic missions will vary from 10s of watts up to a few kilowatts. Radioisotope power systems (RPS) may be used in these applications—they offer a mass and development cost advantage relative to fission systems in this power range. In addition, the combination of RPS and electric propulsion (EP) technologies enables a new class of space exploration missions; for example, RPS provides power beyond the practical range of solar arrays in deep space, powers EP during outbound cruise, provides power to Science and Communications at target, and offers the option of separating RPS units for landers/rovers. The issue here is availability/cost of Pu – 238 isotopes, especially if many missions are planned. For human missions, power requirements may vary from 10s of kWe to support initial human visits to 100s of kWe for permanent lunar/Mars bases, especially if In-Situ Resource Utilization (ISRU) processes are required. For these power ranges, fission power systems are advisable. A key issue is whether one reactor power system design can cover increases in lunar or Mars base requirements. A potential solution is to place modular fission power systems on the surface as the base grows (would need a study to determine the power level of the modular unit).



Lunar Base, circa 20xx

Another issue is that the environments on the Moon and Mars may require different reactor design approaches, introducing uncertainty as to whether the same fission power system would work on both

surfaces. Mars, with its CO₂ atmosphere, will react with refractory alloys that would be used in high temperature reactor materials. The Moon, not having an atmosphere, does not present the same challenge for a reactor. Having a lower temperature reactor that negates the need for refractory alloys might be one solution. However, that would result in higher fission power system mass and larger volumes. One solution is to isolate the reactor core from the CO₂ atmosphere by placing the reactor in a sealed container, which may or may not be practical.



Artificial-g BNTR CTV for
Mars/NEA Missions

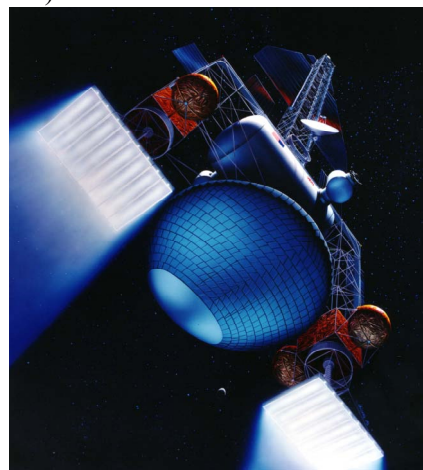
extra electric propulsion for maneuvers at planetary destinations. Previous NTP development activities include the Rover and NERVA reactor programs (1960s and early 1970s).

The other nuclear power/propulsion need is robotic/cargo vehicles. For robotic missions beyond Mars, high Isp NEP propulsion systems are desirable because of the large delta Vs required to escape Earth's gravity and the long interplanetary distances for missions to Jupiter and the outer reaches of the solar system, e.g., PROMETHEUS I. Nuclear fission power levels of 75 to 100s of kWe are typical for these missions. NEP systems can maneuver to multiple destinations (as with PROMETHEUS I), provide copious quantities of electrical power at those destinations for science investigations, and transmit the science data back to Earth. Human mission cargo vehicles might transfer high-mass support cargo to planetary destinations—using multi-megawatt NEP vehicles where transit time is a lower priority; NEP's high Isp propulsion could minimize fuel consumption. NTP could also work for cargo missions, but it has a lower Isp and so requires more fuel for a given mass transfer.

The nuclear fission power and propulsion needs discussed above point to the need for trade studies to determine nuclear fission power/propulsion characteristics that best meet exploration requirements from early robotic precursor missions to later human missions to the Moon and Mars. Characteristics include nuclear fission power output, thrust for NTP systems, modularity, potential for growth, and low-cost reproducibility. A key objective would be to minimize the number and types of nuclear fission systems for a combined robotic/human exploration scenario.

Capability Benefits.—Nuclear power is the preferred option for surface power needs based on its high power capability at reduced mass and volume, fewer deployment issues and its insensitivity to changes in operating environment, i.e., latitude, atmospheric sunlight attenuation, and seasonal variation of day/night ratio. The selection of nuclear power for any mission poses concerns due to its inherent nature, and therefore, safety to public, crew, and equipment will be paramount in the design requirements. The use of nuclear power for a sustained human presence addresses several important needs, such as

Another application for nuclear power/propulsion is piloted vehicle propulsion. Though detailed requirements are lacking here, too, a primary requirement is minimizing human transit times to/from planetary destinations. One nuclear propulsion candidate would be nuclear thermal propulsion (NTP), although several piloted vehicle concepts using nuclear electric propulsion (NEP) with 10's of megawatt fission power systems have been postulated, with some penalties in trip time and operational complexity. Included in this propulsion category are bimodal NTP (where the nuclear fission reactor also provides on-board power for the human habitat, negating the need for a separate power source) and hybrid NTP, in which the same reactor generates



NEP System

saving significant launch mass, increasing overall life cycle affordability, increasing reliability from benign operation issues with the lunar environment and providing a single, robust design that provides the same power regardless of latitude and local topographical features. While this discussion is specific for a human lunar mission, the underlying strategy of scalability/evolvability and technology/hardware commonality would also apply to a human Mars mission, albeit, certain design aspects would be different to accommodate different requirements and the planetary environment. It is estimated that a significant portion of the development effort and resources can be shared across the in-space, lunar and Mars surface designs. For example, common power conversion technology, reactor fuels, and radiator and power distribution systems can follow concurrent engineering practices to further reduce costs. A core systems development program would be established at the start improving schedule, costs and programmatic risk. This core development would be augmented for specific application/hardware products, e.g., vacuum operations for lunar surface and carbon dioxide atmosphere for Mars.

Technology Assessment.—A preliminary study was completed to derive lunar surface system technology options in order to identify leading candidate technologies that will accomplish the mission scenario, identify current technology readiness levels (TRLs), identify the potential to advance to TRL 6 by 2014, and identify programmatic cost and risk metrics to help direct the Code T investment strategy. Prior to selecting the candidate power system technologies for the lunar surface applications, many elements were evaluated. This study determined the effectiveness of the technology to meet the mission requirements in the specified time, the technology readiness levels, mass, safety, redundancy, extensibility to Mars missions and other figures of merit (FOMs) which helped in screening applicable technologies.

Although some deliverables can be assumed based on the capability gaps and R&D priorities, it is premature to establish schedules and major milestones without lower level exploration requirements, design reference missions, and architectures. There are several approaches to developing nuclear power/propulsion capability for robotic and human exploration missions. This section describes development scenarios from 2005 to 2050 to meet potential exploration requirements. These scenarios will evolve as detailed budgets and requirements emerge. Table 2 summarizes the scenarios.

TABLE 2.—STRATEGIC GOALS AND AN ACTION PLAN FOR THE NEXT 45 YEARS.

Time Frame	Development Activity	Reactor Fission Development	Power Systems Development
2005-06	Power systems technology development	Develop nuclear fuels and cladding for 1300 K reactor	Develop Brayton, TE, Rankine, Stirling technologies; develop 400 to 500 K radiator suitable for all conversion concepts
2006-12	Early NEP flight demo	Develop 1300 K 1 MWt reactor	Develop 25 to 50 kWe power system modules
2005-15	PROMETHEUS I Mission	Use 1300 K 1 MWt reactor	Use 25 to 50 kWe power system modules. Start developing 1300 K power converters, 500 to 600 K radiators
2010-15	Lunar/Mars surface power	Re-use 1300 K 1 MWt reactor; mitigate CO ₂ Mars atmosphere issue; increase man-rated reactor shielding	Use 25 to 50 kWe power system modules Develop 500 to 600 K surface radiator
2010-25	Mars Cargo NEP for both cargo and humans	Develop nuclear fuels and cladding for 1500 K reactor; develop 20 to 40 MWt reactor	Develop materials to increase power systems peak temperature to 1500 K and heat rejection radiators to 600 to 700 K Develop multi-megawatt power converters up to 2.5 Mwe
2010-30	Mars piloted NTP	Develop fuel/claddings for NTP reactor; develop NTP reactor	Use 25 to 50 kWe power system modules
2025-50	MMWt NEP and/or NEP/NTR nuclear propulsion system	Use multi-megawatt NEP or NTP fission reactor	Use multi-megawatt conversion from Mars Cargo NEP

Notes on table 2.

2005-06 Power System Technology Development: Prometheus is now addressing all options except Stirling through NRA efforts managed at NASA GRC.

2006-12 Early NEP Flight Demonstration: Carry out flight demonstration of an NEP system, fission reactor, power conversion, power management and distribution, heat rejection, and electric propulsion subsystems—for experience in navigating and operating an NEP craft.

2005-15 PROMETHEUS I Mission: The nuclear fission power system power level is ~100 kWe, though NASA may opt to build an initial capability of a few hundred kWe so the vehicle could accomplish space science robotic missions beyond Jupiter. Along with development of the required electric propulsion subsystem, the same spacecraft could be used about every five years for follow-on science missions to Saturn, Neptune, and other outer solar system destinations.

2010-15 Lunar and Mars Surface Power System: If a surface power system design and development activity paralleled the PROMETHEUS I mission, taking advantage of common fission reactor and power system development, that nuclear surface power capability could be available in the 2015 to 2020 time frame. Developers would have to redesign radiator and power distribution systems to accommodate being used on a planetary surface rather than on a space vehicle. If designers predict that surface power needs will grow, they could add multiple nuclear fission surface power systems.

2010-25 Mars Cargo NEP: Power conversion systems in the multi-megawatt power range would be needed, as would on-orbit assembly approaches for the resultant large heat rejection radiators. Much technology development in power conversion and heat rejection would focus on high performance and low mass to reduce the NEP vehicle specific mass (kg/kWe or alpha).

2015-30 Mars Piloted NTP: For NTP, the nuclear fission reactor heats and expands hydrogen gas through a nozzle creating thrust. These high-thrust devices create several thousand of pounds of thrust. In a bi-modal NTP system, the same reactor produces heat for high thrust propulsion and for generating electrical power. The He/Xe working fluid in a closed cycle Brayton would flow through a separate set of coolant passages in the NTP fission reactor. When generating power, the fission reactor would run at a lower thermal power and temperature level for long periods (many weeks). In comparison, when it is generating high thrust it would be operating at high thermal power levels and temperatures for several *minutes*. A key reactor fission development issue would be finding the right combination of nuclear fuel and cladding that could operate for relatively short periods (several minutes) for high-thrust propulsion maneuvers *and* operate at lower thermal power and temperature levels for many months when producing electrical power during transit to Mars.

2025-50 Multi-megawatt NEP and/or NEP/NTR nuclear propulsion system: During this time, a hybrid NEP/NTR nuclear propulsion system or a multi-megawatt NEP system could be developed. The NEP/NTR concept would be similar to the bimodal NTP propulsion system except that electrical power produced by heat of the NTR fission reactor would be many times that of bi-modal—perhaps up to 1.5 MWe. This energy could run high-power electric propulsion thrusters, possibly the same designs used for NEP cargo vehicles. This propulsion capability would combine high NTP thrust with high NEP Isp, resulting in science missions to the edge of the solar system and into interstellar space with the potential for human missions beyond Mars. Likewise, the multi-megawatt NEP propulsion system described above for Mars cargo transfer could also be used for grand science missions to outer planets. For human missions beyond Mars, more power would be needed, but designers could use the same power conversion modules developed for Mars cargo transfer in a building block fashion. Multiple modules of the reactor and the power conversion systems could be used for the piloted vehicles

Exploration Goals/Requirements vs. Nuclear Power/Propulsion Strategies.—The ultimate goals and resulting requirements for exploration will significantly affect the path chosen for nuclear power/propulsion development. For example, if the goal is to establish a permanent human base on Mars with ISRU plants and massive planetary infrastructure, large multi-megawatt NEP vehicles would be needed to move the large amount of mass efficiently from Earth to Mars. However, if the goal were only to conduct “sortie” missions to Mars, with relatively short surface stays (45 days) and round trips of one

year to 18 months with little infrastructure and relatively low mass transfers, both cargo and humans could be transported using bi-modal NTP propulsion vehicles, possibly eliminating the need for multi-megawatt NEP.

Strategies Given the Uncertainties.—Developing space nuclear power/propulsion systems is *very* challenging and time consuming (many years) given their technical sophistication and complexity. Sustaining political and budget support over several congresses and presidential terms is crucial, leading to these suggestions:

- *Minimize the number of new developments:* Each new nuclear fission reactor power conversion development costs *billions* of dollars over many years. For the wide range of robotic to human exploration missions being contemplated, no one nuclear fission reactor-power conversion system will satisfy all needs. However, early nuclear fission-power conversion developments that employ flexible design will minimize risk, cost, and time. For instance, with the fission reactor-power conversion scenario mentioned above, it is reasonable to use the same fission reactor-power conversion system for the early NEP demonstration mission, the PROMETHEUS I class vehicle, and surface power applications—minimizing development cost and risk and making concurrent development feasible.
- *Determine fission reactor size:* When developing a new fission reactor power system, designers must decide how big to make that reactor. In the scenario above, 1 MWt was chosen to accommodate an early demo, PROMETHEUS I class mission, and surface power requirement. Make sure the fission-reactor is “big enough” to accommodate a wide range of needs.
- *Maximize technology development leverage:* Especially in nuclear fission fuels and cladding. Where feasible, using the same fuels for multiple fission reactor applications will again minimize costs and risks.
- *Build power system capability in modular blocks:* Combine them in different numbers for different applications, again minimizing the number of developments.
- *Engage technologists/developers early:* Involve the fission reactor-power conversion technologists and developers in early requirements sessions for both robotic and human exploration missions. Power system architecture decisions significantly affect program costs and risks, so those types of impacts need careful scrutiny. Also, develop capabilities and tools to ensure that power/propulsion input parameters to trade studies result in correct perspectives.

Energy Conversion—Solar Photovoltaic

Capability Gaps.—In general, for all applications, improvements in the typical solar cell and array figures of merit are highly desirable, as long as the cost to achieve these improvements does not outweigh the benefit. The typical figures of merit for solar cells are the following: Efficiency (AM0), normally reported at 25 °C but even more important at the expected operating temperature, cost (\$/W), and radiation tolerance. The typical figures of merit for solar arrays include the following: Mass Specific Power (W/kg), calculated at Beginning of Life (BOL) at 25 °C but more important at End of Life (EOL) at operating temperature, as this is typically the design point for sizing; Areal Density (W/m²); Cost (\$/W); stowability (within payload shroud); reliable deployability and reliable operation in the space environment.

Specifically for exploration missions, past systems studies have shown that solar photovoltaic (PV) systems are applicable to Solar Electric Propulsion (SEP) vehicles, especially “cargo tugs” and surface systems (lunar and Mars). Even if nuclear systems are developed and used in both vehicle and surface systems, there will probably always be the need for PV systems to provide start-up power, redundant power in the event of a nuclear system shutdown, or a cost-effective alternative to nuclear options for ancillary surface systems (rovers, ISRU plants, etc.)

Solar arrays operating under high power/high voltage conditions, as expected for a Solar Electric Propulsion application, will require high specific power and the ability to survive in the space

environment (i.e., preclude arcing). Solar arrays operating on lunar and planetary surfaces will need to mitigate the loss of power due to dust deposition on the surface.

Finally, to minimize cost, modular and scalable solar arrays that obviate the need for unique designs for every application are highly desirable.

Technology Assessment

Current State-of-the-Art and TRL: The current state of the art for solar cells and arrays is summarized in table 3.

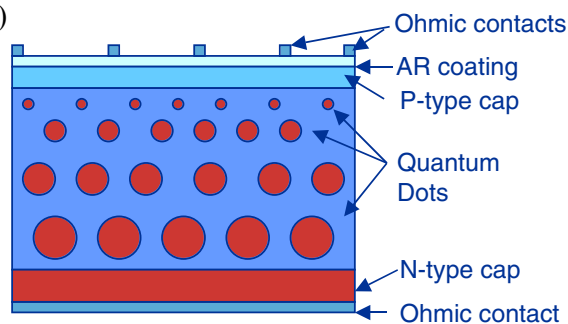
TABLE 3.—CURRENT STATE OF THE ART FOR SOLAR CELLS AND ARRAYS

	State-of-the-Art	Goals
Multi Junction Cell Solar Arrays	50 to 70 W/kg Cell efficiencies: 28% lot average (Honeycomb Planar and DS-1 SCARLET)	180 to 500 W/kg (with Adv. Concepts) Cell efficiencies: 35 to 40%
Thin Film Cell Solar Arrays	No qualified thin film arrays/blankets Cell efficiencies: 8 to 10% (Si) 6 to 9% (CIGS) Large area amorphous Si production	300 to 500 W/kg Cell efficiencies: >20% Small stowed volume
High Voltage Solar Arrays	<100 volts typical 160 volts, Space Station	>1000 volts with no adverse space plasma interactions
Advanced Concepts Light Weight Cell Substrates Quantum Dot Solar Cells High Temperature Cells Low Temperature Cells	Lattice-matched Germanium (Ge) QDs reliably synthesized; cells N/A 8% efficiency at 150 °C 29% efficiency at –20 °C (Mars)	Lattice mismatched Si: Poly-GaAs on Ge 60% theoretical efficiency 30% efficiency at 450 °C 20% efficiency at –180 °C

For solar arrays operating on planetary surfaces and on the Moon, technology to mitigate the effects of dust deposition is desired. The figure of merit for dust deposition is the fractional loss of power per day (or sol) of operation. The Mars Exploration Rover mission and the Pathfinder mission measured losses ranging from 0.20 to 0.28 percent decrease in performance per sol. Technology readiness for dust mitigation measures is 2-3. For solar arrays operating under extreme high voltages, technology is needed that will enable the reliable operation of multi-kilovolt photovoltaic systems that are free from arcing, sputtering, Paschen discharge, corona, and other identifiable high voltage phenomena. Current practice deploys systems in the range of 100 to 200 volts.

R&D Priorities: It is impossible to set priorities without lower level exploration requirements and design reference architectures and until missions are established. So until further requirement definition, it should be assumed that the following objectives for solar cell and array R&D have equal priority.

- Improve solar cell figures of merit in expected exploration mission environments (near Earth, lunar orbit, lunar surface, Mars orbit, Mars surface)
- Improve solar array figures of merit in expected exploration mission environments (near Earth, lunar orbit, lunar surface, Mars orbit, Mars surface)
- Improve survivability in expected exploration mission environments (near Earth, lunar orbit, lunar surface, Mars orbit, Mars surface)
- Develop High Voltage Solar Arrays (e.g., Solar Electric Propulsion)
- Mitigate effects of dust disposition for surface systems



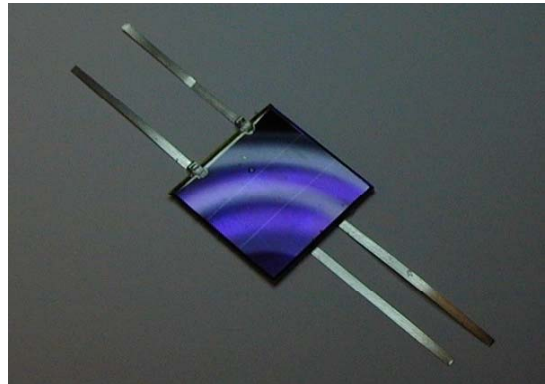
Quantum Dot Solar Cell Schematic

- Develop modular, scalable arrays capable of operating in as many expected exploration mission environments as possible (near Earth, lunar orbit, lunar surface, Mars orbit, Mars surface)

Deliverables, Schedule and Major Milestones:

Although some deliverables can be assumed based on the capability gaps and R&D priorities, it is premature to establish schedules and major milestones without lower level exploration requirements, design reference architectures and missions. Example deliverables are provided below:

- High Voltage, High Performance Solar Array for Solar Electric Propulsion Applications
- Polycrystalline III-V dual junction cell on a thin metal foil substrate enabling a high-efficiency, flexible “roll-out” solar array
- Lightweight, High Specific Power, Modular, Scalable, Deployable Solar Array for Surface Power



III-V solar cell grown on a silicon substrate

Energy Storage

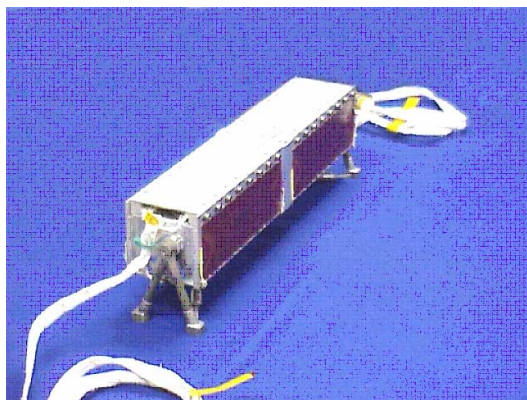
Capability Gaps.—Future robotic and human exploration missions require advanced primary and rechargeable energy storage devices that can provide 3 to 6 times mass and volume savings compared to state of the practice (SOP) devices. The other requirements include long life capability, high rate capability, and the ability to function at temperature extremes. The classes of missions that require these advanced energy storage technologies include: crew exploration vehicles, spacesuits, astronaut life support systems, astronaut equipment, orbiters, landers, rovers, human outposts, in-situ resource utilization systems, and sensor networks. The energy storage requirements vary significantly from a few watt-hours (astronaut equipment) to hundreds of kilowatt-hours (human outposts), depending on the mission. Similarly power requirements also vary from a few watts (astronaut equipment) to several kilowatts, depending on the mission (human rovers, human outposts, crew exploration vehicles).

Several types of advanced energy storage devices, such as primary batteries, rechargeable batteries, fuel cells, regenerative fuel cells, capacitors, and flywheels, are potentially available to enable future robotic and human exploration missions. Advanced primary batteries are required for applications such as astronaut equipment, communication devices, sensor networks etc. Advanced rechargeable batteries are required for solar or nuclear powered landers and rovers, solar powered electric propulsion missions, solar powered human outposts, and astronaut equipment. Primary fuel cells are required for crew exploration vehicles and rovers. Regenerative fuel cells provide an enabling, mass-efficient solution for surface electrical energy storage for future long duration human exploration of the Lunar and Mars surface. Aerospace flywheel technology can enhance the performance of a crew exploration vehicle and orbiting platforms by providing long life, high efficiency energy storage and attitude control, especially for those orbits which require many discharge cycles. For surface power systems, flywheel technology can provide critical load uninterruptible power supply capability, power utility voltage support, peak power load management and life enhancement capability by managing charge/discharge rates on chemical energy storage assets. Hybrid systems that combine two or more of the energy storage systems can also offer improvements in efficiency, weight and volume for a wide range of applications.

The primary batteries used in early spacecraft were largely aqueous alkaline batteries such as Zn-AgO. These batteries exhibit high specific power, moderate specific energy and energy density, relatively low voltage, limited life and a limited operating temperature range. More recent missions have used lithium based systems, Li-SO₂ and Li-SOCl₂, which operate at higher voltages and possess similar or

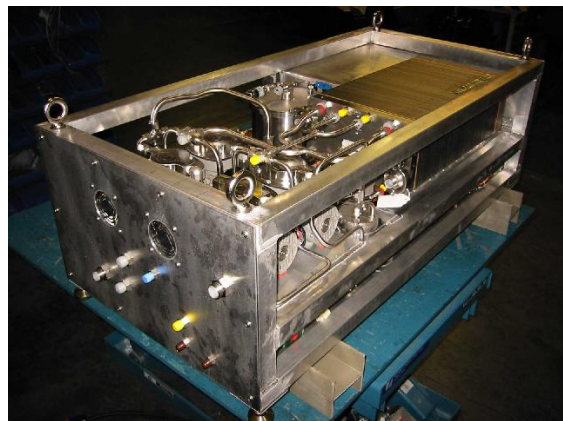
higher specific energy and energy densities and exhibit longer shelf life and a wider operating temperature range than the aqueous systems. The lithium based primaries deliver moderate to high specific energies (200 to 500 Wh/kg), can operate over a temperature range of -40 to 60 °C and have proven lifetimes up to 10 years. However these systems have lower specific power, exhibit voltage delays and are less abuse tolerant than the alkaline batteries.

Among secondary (rechargeable) batteries, Ni-Cd and nickel-hydrogen (Ni-H₂) batteries are in wide usage. Currently, Ni-H₂ batteries are the most widely used chemistry for large scale energy storage systems for space applications. However, Ni-H₂ systems have several characteristics that limit their applicability to orbiting spacecraft, rovers, and landers with capacity requirements in excess of 15 A-hr. Lithium-ion (li-ion) technology offers many advantages over these vintage systems. Currently, aerospace-design li-ion batteries offer over twice the specific energy and over three times the energy density of SOA individual pressure vessel Ni-H₂ batteries (see table 4). They are capable of discharging at higher rates than Ni-H₂, so they can more effectively address higher power applications. Additionally, they operate at higher voltages, over a wider range of temperatures, and at greater energy efficiencies than Ni-H₂ batteries. Li-Ion batteries are also scalable, and cells can be configured to store from a fraction of an ampere-hour to hundreds of ampere-hours. These advantages contribute to the rapid acceptance and assimilation of li-ion technology for aerospace applications. Advanced lithium-based batteries are the chemistry of choice for enhancing and enabling exploration missions. To date, li-ion battery capabilities have been demonstrated to the levels required for some select, relatively low-cycle-requirement aerospace applications. Continued development is critical in order to advance the technology to meet the rigors of the upcoming exploration missions.



Mars Exploration Rover Li-Ion Battery

Although the SOP alkaline fuel cell (AFC) technology presently used on the Shuttle has been highly effective and reliable, it faces serious obsolescence issues in the near future. The asbestos material used in the separator for the AFC is expected to become unavailable in the 2010 to 2015 time frame. AFC technology has no widespread commercial applications, has seen little development over the past 20 years, and is supported for space applications by a single vendor. Advanced fuel cell systems that may enhance future space missions include: Polymer electrolyte membrane (PEM) fuel cells, Direct Methanol fuel cells, solid oxide fuel cells and regenerative fuel cells. Proton Exchange Membrane Fuel Cell (PEMFC) technology has seen extensive development for automotive and residential applications by numerous vendors, and of the newer fuel cell technologies, is the most advanced and capable of supporting near-term space vehicle applications. Development of PEMFC technology for aerospace applications can leverage off of the commercial developments and offers advantages that include enhanced safety, increased robustness, modularity, 2 to 3 times higher power levels, 2 times longer life, equal or lower weight, improved reliability and maintainability, 2 to 5 times higher peak-to-nominal power capability, compatibility with propulsion-grade reactants, 30 to 50 percent reduction in ground and mission operations support requirements, and 50 percent lower recurring costs. The PEMFC can be coupled with an electrolyzer to provide a fuel cell based secondary energy storage system. Both primary and secondary (regenerative)



PEM Fuel Cell Breadboard
Powerplant (TRL 5)

PEM fuel cell technology can enable multiple exploration missions. One of the key technical challenges to the eventual implementation of PEMFC in space include water management in a 0-g environment.

Presently flywheels are not in use in any space missions, however, flywheels do offer potential benefits for various exploration applications such as the Crew Exploration Vehicles (potential to enhance the performance of CEV power and attitude control systems by providing capability to perform the multiple functions of energy storage, power peaking and attitude torque in an efficient, long life package); surface power (provide critical load UPS, power utility voltage support, peak power load management); rovers (long life, high efficiency energy storage capability to meet the requirements for high numbers of charge/discharge cycles and for rapid charge or discharge); space transportation power (MagLev launch assist, Pulsed Inductive Thruster power load leveling).

Technology Assessment.—A number of advanced energy storage devices are under development under the DoD, DOE and NASA sponsored programs. These technologies are projected to provide significant mass and performance advantages to stationary power systems, mobile power systems, distributed power, stationary power, sensor networks, and astronautic/robotic devices of future exploration missions. Many of these technologies are in early stages of development and some are in fairly advanced stage of development. A brief overview of the status of the advanced energy storage technologies is provided below.

Advanced lithium-primary systems under development include improved Li-SOCl₂, Li-CF_x, Li-MnO₂, Li-air/oxygen, and Li-interhalogen. These advanced primary batteries are projected to offer one or more of the following advantages: a) significantly higher specific energy and energy density with adequate specific power, b) minimal voltage delay, c) longer life, and d) improved low temperature performance compared to SOP Li-SO₂ batteries. Among these advanced systems, Li-SOCl₂ and Li-CF_x are projected to be the most attractive candidates for future space science missions, because they appear to have potential for improved performance characteristics and they have greater maturity.

Advanced rechargeable lithium systems presently under development include: Li-Ion batteries, solid polymer electrolyte lithium batteries, and solid-state inorganic electrolyte lithium batteries. These batteries are projected to offer one or more of the following advantages: a) higher specific energy and energy density, b) long cycle life and calendar life, c) improved low temperature performance, d) low self-discharge, e) high charge/discharge efficiency, f) lower cost compared to SOP rechargeable batteries g) improved safety, and h) conformability. Among these systems, the Li-Ion system has the highest potential to meet the near- to mid-term needs of space exploration missions in view of its high level of technical maturity, its low temperature performance capability, and its potential for improved cycle life. The lithium solid polymer electrolyte (SPE) system offers packaging advantages compared to the lithium-ion system, however, it is in the early stages of development (TRL ~2). This technology is projected to be available for missions beyond 2015. The Li-solid inorganic electrolyte system has the intrinsic capability of providing very long shelf and operational life compared to the other lithium systems, but it is also in very early stages of development (TRL 1-2). Table 4 summarizes the characteristics of rechargeable batteries.

TABLE 4.—CHARACTERISTICS OF ADVANCED RECHARGEABLE BATTERIES**

Characteristic	SOP Ni-H ₂	Li-ion with Liquid Electrolyte	Li-Solid Polymer Electrolyte*	Li-Solid Inorganic Electrolyte*
Technology Readiness Level	9	5 to 9	3	1 to 2
Specific energy (Wh/kg)*	30 to 40	100 to 150	>200	> 200
Energy density (Wh/l)*	40 to 50	200 to 300	300 to 450	> 300
Cycle life*	60,000	1500	1500	>10,000
	(at 30% DOD)	(at 100% DOD)	(at 100% DOD)	at 100% DOD
Operating temperature	–5 to 30 °C	–40 to 65 °C	0 to 80 °C	0 to 80 °C

*Projected values based on analysis (not data). Specific energy figures are at the battery level and 100% DOD and do not include power electronics

**Not all characteristics are achievable in the same cell—values reflect the technology capabilities

Advanced fuel cell systems that may enhance future space missions include: Polymer electrolyte membrane fuel cells, direct methanol fuel cells, solid oxide fuel cells (SOFC) and regenerative systems based on PEM and solid oxide fuel cells. Among various fuel cell technologies, PEM fuel cell technology is in the advanced stage of development (TRL 4-5). Projected specific power of the PEM is now 250 W/kg or 2.5 times the specific power of the existing alkaline fuel cells (100 W/kg). Basic regenerative fuel cell configurations use discrete electrolyzers and fuel cell stacks. Also, early versions focused on using alkaline electrolyte because of the proven flight history with this type of technology. PEM electrolyzer and a PEM fuel cell have replaced the alkaline cell technology. Table 5 summarizes PEM fuel cell advantages and applications for exploration systems. More recently, advanced versions that combine the fuel cell and electrolyzer functions, called “unitized regenerative fuel cells,” are under development. A regenerative system based on discrete PEM fuel cell and electrolyzer stacks is the breadboard stage. Direct methanol fuel cells are in early stages of development, compared to other fuel cell technologies (TRL 2-4). SOFC, like PEMFC are commercially available technology but are only at a TRL of 2-3 for aerospace applications. SOFC’s have the potential for in-situ resource utilization for exploration missions.

TABLE 5.—SUMMARY OF PEMFC TECHNOLOGY ADVANTAGES

Technology Goal	PEMFC Characteristics and Goals
Improve Safety	<ul style="list-style-type: none"> - Reduces hazardous and corrosive materials/fluids <ul style="list-style-type: none"> o No KOH o No asbestos - Allows greater delta pressure across solid membrane than asbestos matrix - Eliminates hazard of KOH electrolyte contaminating potable water supply
Improve Mission Supportability and Operability	<ul style="list-style-type: none"> - Can reverse fuel cell flooding with no hardware damage; alkaline is irreversible - Is not sensitive to air exposure (can run on air as reactant instead of O₂) - Has potential for greater operational life supports longer missions (2 times longer) - Has potential for greater power to increase payload/vehicle capability (2 to 3 times) - Offers higher peak-to-nominal power capacity (2 to 5 times)
Reduce Cost	<ul style="list-style-type: none"> - Changes from high purity to propellant-grade reactants - Reduces number of working fluids for launch processing <ul style="list-style-type: none"> o No FC-40 for cooling - Provides modernized instrumentation and components - Reduces ground and mission operation support (30 to 50%) - Reduces life cycle costs in logistics with longer life power plants (10,000 hr goal vs. 5,000 hr LLAFC) - Provides multiple vendors/commercial competition to reduce production and recurring costs (50%)
Applicability Across Exploration Missions	<ul style="list-style-type: none"> - Supports the following programs: <ul style="list-style-type: none"> o Crew Exploration Vehicle Power Systems o Portable fuel cells for space suits, EMUs, and equipment o Lunar/Mars transportation and surface-based power systems

Aerospace flywheel systems provide storage of energy and momentum using high speed, rotating masses. They offer the potential to operate at deep depth of discharge levels making them an attractive high specific energy option. Arrays of flywheels can be used to provide both power and torque control for spacecraft. They provide an opportunity to combine functions previously supplied by separate subsystems (i.e., energy storage and attitude control) in a single system with significantly (up to ten times) less mass. Flywheels inherently provide regulated power during discharge and higher efficiencies than chemical energy storage (i.e., lower losses). Flywheels are long life systems, including both high-cycle charge/discharge and long dormant periods. The energy/momentum storage capability of a flywheel can be sized separately from its power/torque capability giving the technology a wide range of potential applications. This feature of the technology makes it an ideal candidate for peak power, pulse power and load leveling applications. Flywheel systems also offer the potential for operation over a wider

temperature range and in high radiation environments. Table 6 summarizes flywheel system characteristics and performance in the short/long term.

TABLE 6.—FLYWHEEL CHARACTERISTICS AND GOALS

Flywheel Size	Flywheel System TRL	Specific Energy,* Whr/Kg	Round Trip efficiency	Life, cycles at 90% DoD	Specific Power, w/Kg	Rotor Tip Speed, m/s
Large, >1000whr	3/2	25/100	85/90	75,000/90,000	40/500	1100/1300
Medium, 250 to 1000 whr	4/2	25/50	85/90	75,000/90,000	40/500	1100/1300
Small, <250whr	3/2	20/50	85/90	75,000/90,000	40/500	1100/1300

Note: Metrics provided for Near term(<6 years)/Far Term (>10 years) capability

*Specific Energy at the systems level, including power electronics

R&D Priorities.—It is impossible to set priorities without first establishing lower level exploration requirements and design reference architectures for missions. So until further requirement definition, it should be assumed that the following objectives for energy storage R&D have equal priority.

- Develop high specific energy (500 Wh/kg) and long-life (>10 years) lithium primary batteries that can function over a wide temperature range (–80 to 60 °C)
- Develop high specific energy (150 to 200 Wh/kg) and long-life (30,000 to 50,000 cycles at 30 percent DOD) rechargeable batteries that can function over a wide temperature range (–80 to 60 °C)
- Develop high specific power primary fuel cells (250 W/kg) and demonstrate performance at system level
- Develop regenerative fuel cells that can provide high specific energy (>300 W/kg), high efficiency and demonstrate long life capability at system level
- Develop Flywheel Systems that can provide high usable specific energy (50 to 100 Wh/kg) and high efficiency (90 percent round trip) with long life capabilities (90,000 cycles at 90 percent DOD).
- Develop advanced capacitors that can provide high specific power as well as high specific energy

Although some deliverables can be assumed based on the capability gaps and R&D priorities, it is premature to establish schedules and major milestones without first establishing lower level exploration requirements and design reference architectures for missions. Examples of deliverables are suggested below. However, delivery dates are dependent on requirements, architectures, and ultimately, funding levels.

- PEM fuel cells for Crew Exploration Vehicles
- First generation high specific energy (150 Wh/kg) and long life (30,000 cycles) energy storage technologies (rechargeable Li-Ion Batteries)
- High specific energy (600 Wh/kg) primary lithium batteries
- 50 Wh/kg and long life flywheel systems
- Second generation high specific energy (>200 Wh/kg) high efficiency and long life rechargeable energy storage technologies (Lithium Polymer batteries, Lithium solid state inorganic electrolyte batteries,. regenerative fuel cells, flywheels)

Advanced Power Management and Distribution Technology: Modular, Intelligent Electrical Power Systems

A critical system in any space vehicle or surface asset is the electrical power system. Almost every critical subsystem needs a reliable source of electricity to function. The electrical power system is really made up of three primary subsystems—energy generation, energy storage, and power distribution. Energy

generation and energy storage work hand-in-hand to provide the critical source of electricity, but simply generating the electricity will not ensure that it is delivered to the subsystems and loads that require it. Without a reliable method of controlling, conditioning, and distributing electricity all the generation and storage capability could be for naught.

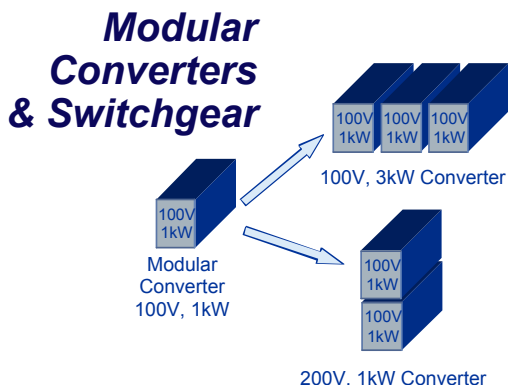
Since the PMAD system is really the “interface” between the power sources and the power users, the design of the PMAD subsystem is often highly dependent on the sources and the loads chosen for the specific vehicle or mission. In the past, this has led to “point designs” for PMAD systems where the system is designed specifically for a single application. However, this standard business model will hamper the exploration systems mission from delivering an affordable and sustainable program.

What is needed instead are: 1) the ability to re-use PMAD components in many applications 2) and systems that can be built by connecting common, “building block” modules together in various ways. Whether those “building blocks” are common switches, modular converters, modular switches, or even complete modular systems, it is clear that a more modular and intelligent PMAD system is necessary for an affordable exploration program that features “systems” interacting intelligently with other “systems.”

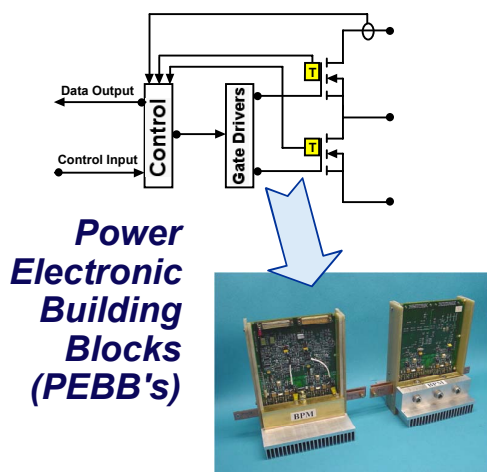
Capability Description and Benefits.—The power management and distribution (PMAD) system can be modularized at three distinct levels: 1) power electronic building blocks (PEBBs), 2) modular converters and switchgear, and 3) modular systems. Each of these levels is independent of the others, meaning that modular converters do not depend on PEBBs, and modular systems do not require that modular converters or switchgear be developed first. The modular PMAD system can be worked at any one of these levels depending on the technology development maturity, the expected benefits, or the specific needs of the exploration systems.

At the lowest level, power electronic building blocks (PEBBs) are common power electronic switches integrated with all the supporting circuitry they require for operation— isolation, drivers, sensors, and control. Power electronic switches are the most common building blocks in any PMAD system because all regulators, converters, motor drives, protective switches, etc., can be built using them. With the inclusion of a flexible digital controller, new PMAD elements can be developed very quickly using common PEBBs, thereby reducing design and hardware costs. Also, if all PMAD elements are constructed using common PEBBs, then the need for large numbers of spare elements for long duration missions is greatly reduced.

At the next level of modularity are the modular converters and switchgear elements that make up a PMAD system. The idea here is to build common elements that can be connected in series and parallel combinations to meet the needs of more than one application. By employing a modular power system vision from the start, the number of dissimilar hardware developments can be greatly reduced. This



modular approach also increases reliability as it makes it very easy to implement N+1 redundancy schemes while limiting the negative mass penalty. While some amount of modularity exists in the power electronics industry today, all solutions rely on a central controller to coordinate the operation between the interconnected modules. What is needed for a truly modular solution is to develop the ability of modules to function independently while also being able to coordinate with their interconnected neighbor in a “master-less” collaboration. This distributed, coordinated control can only be achieved using digital control and a local communication capability.



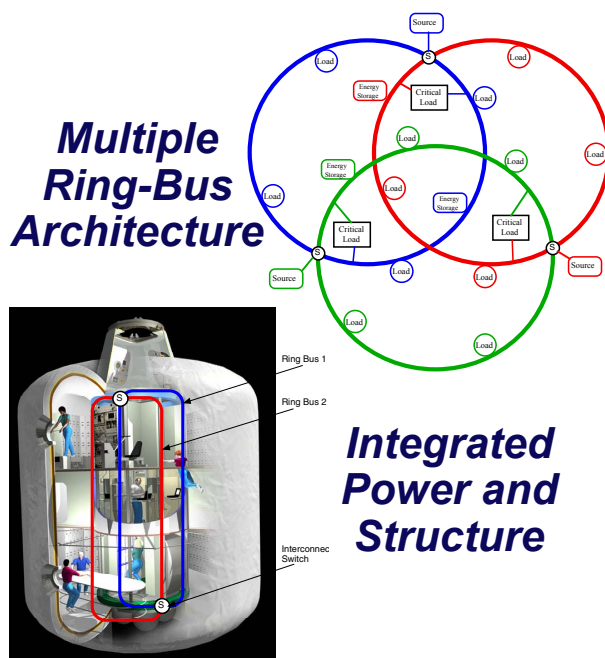
Once digital control exists in the modular converters and switchgear, additional capabilities that improve upon the system performance, reliability, and safety can be implemented. These include active stability control, hidden fault detection (arcing and leakage faults), and component health monitoring. Active stability control is the ability of a PMAD element to adjust its control in response to internal or external changes so that local and system instabilities can be avoided. Hidden faults such as arcing faults and leakage faults pose dangers to mission success and human occupants and are currently uncovered in today's PMAD systems. The data processing and communications capability inherent in a modular, digitally controlled power system now offers the ability to implement algorithms that can detect these uncovered faults.

Ultimately, the PMAD system can be modularized at the system level by breaking the entire system into smaller subsystems—much as the International Space Station does today. However, these modular systems for long duration exploration missions and “systems-of-systems” will have to be more collaborative than the ISS “channelized” approach. They must be able to readily share power resource (sources) and power burdens (loads), and they must be able to collaborate across dissimilar vehicles and platforms. For instance, it would be very desirable if the power system of the Crew Exploration Vehicle (CEV) could collaborate with the power system of the lunar lander, and the lunar lander power system collaborate with the lunar habitat modules.

An example of such a modular power system is that of the multi-ring bus distribution system. This system is comprised of three (3) subsystems, each with its own energy generation, storage, distribution, and control. Each ring is able to cross-tie and parallel with the other rings by coordinating the control of each ring bus. This technology also would allow for integrating the power distribution system into the space vehicle structure—thereby saving mass. Finally, because all three rings are distributed throughout the space vehicle, it is very easy to take high priority and critical loads and connect them to multiple power subsystems—thereby further increasing the reliability of the electrical power system. These are exactly the type of power system technologies needed for the “system-of-systems” approach being taken by the space exploration program as space vehicles and assets will be expected to “interoperate” and collaborate with one another.

Finally, it is desirable to develop technologies that enable autonomous operation of the electrical power system. Autonomy reduces the mission life support costs and communication requirements by eliminating the need for “24/7” monitoring of the electrical power system by engineers on Earth. Autonomy also can provide higher levels of reliability by sensing hidden faults in the system, and quickly responding and reconfiguring the power system following a failure. An autonomous power system can also actively manage its own “health,” thereby increasing reliability, decreasing maintenance operations, and extending the life of the mission.

Gap Analysis.—Reliable, robust power distribution systems are needed for all conceivable exploration missions—vehicles, landers, lunar and Mars surface elements, and large robotic platforms. The difficulty with PMAD systems are that their requirements vary across a large range of variables—power levels, distribution voltage, and distribution frequency, protection features. What this means is that extra attention must be provided early in the “systems-of-systems” planning phase so that commonality among systems can be achieved and exploited. For example, deciding on a standard distribution voltage and



frequency (ac or dc) for all exploration platforms may not provide ideal point designs for each “system,” but may be optimal for the entire “systems-of-systems” exploration program.

CEV Power: While advanced PMAD technologies are not enabling for the CEV, including some level of component and system modularity in the early stages could greatly enhance reliability. Multiple power sources and some storage will be employed to increase fault tolerance of the vehicle, so providing a channelized, modular distribution architecture is a natural extension that will further increase fault tolerance. These modular component and system technologies will also set the stage for later capabilities in interoperable “systems-of-systems” when the CEV is expected to work together with transfer vehicles and surface landers.

Surface Nuclear Power: Surface nuclear power challenges include the distribution of high levels of power over long distances. To minimize cable mass, high voltages will be required. Modular converter technologies that allow series “stacking” of lower voltage converters would be useful in lowering the costs and mass of this distribution system. Additionally, expected surface assets such as habitat, laboratory, and logistic modules will each include their own self-contained power distribution system and be connected together physically. Modular power system technologies would enable the interoperation of these surface assets to greatly increase reliability and fault tolerance.

Surface Mobile Power: While surface mobile power is expected to be much smaller in scale to other surface assets, if the power system components are modularized, many of them can be used “as is” in smaller mobile power assets such as robotic platforms.

High Efficiency Power Systems: It has been demonstrated that modular power converters are able to achieve higher total power efficiency by shutting down modules under light load. In a system such as ISS where the total connected load is much higher than the average total power, the ability to optimize efficiency at low power levels could improve power availability by 5 to 10 percent.

The modular power system technologies described above are not used in any aerospace vehicle at this time. While some amount of modularity at the converter level can be seen in commercial power converters and even the commercial satellite market, the concept of master-less, distributed modularity that is necessary for true modularity and extended fault tolerance is not found anywhere. Additionally, there is currently no technology deployed today that will reliably detect arc, leakage, or connector faults in large distributed power systems.

The ability of a large power system to be broken down into smaller subsystems yet still be able to share resources and easily reconfigure following faults is not available anywhere today. The International Space Station is an example of a “modularized” power system, but the power system has been broken up due to limitations in fault current capability, not as a means to achieve higher levels of fault tolerance. If one subsystem on the ISS experiences a failure, the other subsystems are not able to help mitigate the fault. Finally, there is almost no application of automation or health monitoring on any aerospace electrical power systems. For the Space Exploration Initiative to be successful, automation and health management technologies are essential if manned and unmanned vehicles are to operate far from Earth for long periods of time.

Current technology readiness levels are described below.

Modular power converters and switchgear—TRL 3/4: Digital control of DC-DC converters and switchgear has been demonstrated in breadboard hardware. Distributed, master-less control algorithms are close to being demonstrated in breadboard hardware, and initial development of rudimentary digital control for a commercial DC-DC converter is underway. Additional modular functionality is just starting to be developed, including active stability control, health monitoring, and input series control.

Modular, ring-bus distribution systems—TRL 2: Initial concepts have been developed and breadboard hardware is being assembled.

Autonomous electrical power systems—TRL 2: Initial concepts have been developed and breadboard hardware is being assembled. Modeling and algorithm development has yet to start. However, power system autonomy literature exists from the late 1980s (Space Station program) and terrestrial power systems.

Power Management and Distribution: Advanced Power Electronics Components

All Aerospace Power Systems require Power Management and Distribution (PMAD) between the energy/power source and the loads. The PMAD subsystem can be broadly described as the conditioning and control of unregulated power from the energy source and its transmission to a power bus for distribution to the intended electrical loads. The foundation and fundamental principles of PMAD are based on the engineering discipline known in the industrial/academic community as power electronics.

All power and control circuits for PMAD require power electronics components for switching, rectification, energy storage, voltage/current transformation, filtering, regulation, protection, and isolation. Advances in present power electronics component technology are required to increase the energy/power density, efficiency, operating temperature, radiation hardness, voltage, and reliability of the PMAD subsystem. The primary means to achieve advanced power electronic components is to develop new or significantly improved present day materials for semiconductor switches and diodes, capacitors, and magnetic components such as transformers and inductors.

Development of new or significantly improved wide bandgap (WBG) semiconductor, dielectric, insulating, and magnetic materials is the key to developing advanced electronic components. Technology development will be focused on significantly increasing the performance levels through the use of the figures of merit to be discussed later. Development of these new/improved materials and subsequent development of the advanced power electronics components using these materials will enable or strongly enhance exploration missions. Failure to develop these advanced power electronics components could impact the schedule for presently planned exploration missions.

Capability Description and Benefits.—The primary space exploration applications for advanced power electronics components are the space power PMAD subsystem and the instrument and control subsystem in nuclear reactor systems. Specific applications within the PMAD system include DC/DC converters and DC/AC inverters, which are used to control and regulate the spacecraft power bus and to drive the spacecraft's control surface actuators. Other PMAD applications include DC power supplies for driving electric thrust engines, telemetry, radar, computers, radio transmitters and receivers.

Other exploration applications include high speed performance aircraft and launch vehicle propulsion systems, and in general, any spacecraft requiring advanced PMAD technology.

The specific benefits of developing advanced power electronics materials and component technology for space exploration systems are:

- *Higher PMAD Power Density*—High operating frequency components increase PMAD power density by reducing the mass and volume of the passive components (transformers, inductors, and filter capacitors).
- *Higher Operating Temperatures*—High temperature power electronics components reduce cooling requirements and thus reduce the complexity, size and mass of the thermal transport and radiator subsystem.
- *Higher Efficiency*—High efficiency components not only reduce cooling requirements but also reduce the power generation and storage needs for a given output power.
- *Higher Radiation Tolerance*—High radiation resistant components reduce mass and volume of shielding materials.
- *Higher Voltage*—High voltage components provide higher power systems and also reduce power transmission cable mass and volume.

Taken all together, the above benefits would enhance/enable increased payload capability, decrease spacecraft mass/volume/cost and increase design flexibility.

Gap Analysis.—The efficiency (percent) and radiation tolerance (total integrated dose and fluence) are two figures of merit common to all the power electronics components. The power losses in these components determine their efficiency. The losses in WBG semiconductor switches and diodes include conduction and switching losses in magnetic components (transformers, inductors, motors, generators);

core and winding loss; and in power capacitors, the losses expressed in the dissipation factor. These semiconductor, magnetic and capacitor losses are dependent on the operating temperature, frequency, and voltage. The radiation tolerance is dependent on the semiconductor, magnetic, dielectric, and insulating materials used in the components. For switches and diodes, the level of radiation resistance is very dependent on the type of switch (BJT, IGBT, MOSFET, thyristor, etc) and diode (Schottky, PiN, etc.)

In addition, a figure of merit for magnetic components is the power density (W/kg) or its inverse; specific mass (kg/W) for transformers, motors, and generators; and energy density (J/cm³) for inductors. For power capacitors, the figures of merit are volumetric efficiency (μF/cm³), i.e., capacitance per unit volume, and energy density (J/cm³). Again, these figures of merit are dependent on operating temperature, frequency, and voltage.

It should be noted that the figure of merit of highest importance in a particular PMAD spacecraft application will be dependent on the spacecraft's requirements. For example, if low mass/volume is necessary, then power density, energy density, and volumetric efficiency are the figures of merit of highest importance; consequently, the efficiency figure of merit would be of lesser concern. Thus, PMAD trade-off analysis would need to be performed, and the spacecraft's requirements would determine the priority of applying these figures of merit.

Current State of the Art: Technology Readiness Level (TRL): The specific technology goals for the power electronics components are listed in table 7 along with the Metric, SOA, and Program Goals.

TABLE 7.—GOALS FOR POWER ELECTRONICS COMPONENTS

Technology	Metric	State of the Art	Exploration Goals
Power Capacitors	Volumetric Efficiency	0.2 to 0.3 μF/cm ³	1 μF/cm ³
	Energy Density	1 J/cm ³	4 to 5 J/cm ³
	Operating Temperatures	85 to 105 °C	250 to 300 °C
Power Transformers	Power density	1.5 kVA/kg	5 kVA/kg
	Switching Frequency	100 to 200 kHz	500 kHz
	Operating Temperatures	100 to 125 °C	250 to 300 °C
	Efficiency	95 to 97%	98 to 99%
Power Switches	Current Density	50 to 100 A/cm ²	500 A/cm ²
	Operating Frequency	100 to 200 kHz	500 kHz
	Operating Temperatures	125 to 175 °C	250 to 300 °C
DC/DC Converter	Operating Frequency	100 to 200 kHz	500 kHz
	Operating Temperatures	100 °C	250 to 300 °C

As previously noted, the main barrier associated with the development of advanced power electronics components is the limitations imposed by presently available semiconductor, magnetic, dielectric, and insulating materials, particularly for high temperature and high radiation resistant components. Thus, the focus on advanced power electronics components needs to be on the identification, investigation, and development of either new or significantly improved present day WBG semiconductor, magnetic, dielectric, and insulating materials.

For the very high temperature, high efficiency, and high radiation resistant power electronic components the key will be, as previously noted, the development of new and/or significantly improved present day WBG semiconductor, dielectric, and insulating materials.

Major Technology Deliverables: The purpose of developing advanced power electronic components is to use them in advanced PMAD subsystems for Space Exploration space power systems. The components will be tested and characterized on an individual basis but the true test of their performance will be their incorporation into a power electronics circuit, for example, a DC/DC converter. The major deliverables then are DC/DC converters which demonstrate TRL levels 4 to 6 using these advanced power electronics components. Deliverables include:

- Demonstration of 250 °C, Radiation Resistant (TIG = 0.5 Mrad, fluence = 10^{13} n/cm²), 5 kW Modular, DC/DC Converter (TRL 5)
- Demonstration of 200 to 250 °C, Radiation Resistant (TIG = 0.5 Mrad, fluence = 10^{13} n/cm²), 5 kW, Modular DC/DC Converter (TRL 6)
- Demonstration of 300 °C Radiation Resistant (TIG=1-5 Mrad, fluence= 10^{15} n/cm²), 25 kW Modular, DC/DC Converter (TRL 6)

Specific delivery dates are dependent on funding profiles.

Environmental Durability/Survivability

Human and robotic exploration missions will be subjected to a wide range of hostile space and surface environments that will demand that mitigation measures and new materials be developed and implemented. NASA has been working on technologies to address space power system durability and reliability. The focus has been on technologies such as light-weight, wide temperature, radiation tolerant power systems, and space power arcing and radiation mitigation.

To address lunar and Martian durability with a focus on power system operation in dusty wide temperature swing environments, several applicable technologies have been developed to TRL 1-3:

- Light-weight radiation-tolerant intercalated graphite shielding for electronics to reduce the weight of electronics enclosures and still provide adequate EMI shielding but with radiation shielding exceeding aluminum
- Radiation tolerant wiring insulation needed for nuclear power systems and Jovian environment operation
- Dust control and abatement technology critically needed for lunar and Martian surface power system
- Surface charge control through conductive abrasion-resistant and transparent coatings for lunar and Martian surface power systems
- Wide temperature electronics to allow lunar and Martian surface power systems to survive the wide temperature extremes of these environments
- Radiation acceleration testing technologies to validate power system durability to assure power system durability through short term accelerated radiation testing
- Passive thermal shunt using highly organized graphite fibers for heat rejection in power electronics by reliable, high performance high conductivity graphite fibers
- High emittance radiator surfaces for lunar nuclear power systems to minimize the mass of radiator by using the world's highest known emittance surfaces
- Lunar and Martian dust effects simulation to evaluate power system durability in those environments

Summary and Recommendations

The following technology needs have been identified in order to support the exploration missions by lowering mass and cost, function in extreme environments, provide modularity and scalability, and increase reliability and safety:

- Human-rated nuclear systems implementations
- Advanced electrical components
- Advanced energy-storage technologies
- Modular, “building block” technologies

- Autonomous electrical power systems
- Solar arrays that can operate at high power/high voltage conditions
- Environmental durability and survivability techniques

Nuclear power generation technologies and their associated technologies (power management and distribution, thermal control, autonomous operation) require immediate attention, since no human-rated applications exist. Additional power capability gaps exist in advanced development of high specific power solar arrays and high specific energy storage system technologies, which will not reach the needed levels of performance with current funding profiles.

Within these needs, some of the key technology issues to be addressed include (but are not limited to):

- Implementation issues for surface nuclear power on the Moon and Mars
- Commonality of nuclear fission technologies among lunar, Mars, and space transportation implementations.
- High voltage capability systems, intelligent power management, advanced electrical components
- Accelerated development of Regenerative Fuel Cells (RFCs) and advanced primary and secondary batteries
- Feasibility of 500 to 10000 kWe SEP, including low specific mass solar array systems
- Deployment systems for large arrays and radiators
- Space and planetary environment/materials interaction
- Feasibility of 6,000 to 20,000 kWe space power reactors with specific mass lower than 30kg/kWe
- Feasibility of Nuclear Thermal Propulsion, including bimodal operation
- Ground test facilities for multi-megawatt NEP, NTP, and BNTP, including development cost and schedule
- Power conversion technology risk and reliability analysis for high power systems

Finally, in terms of strategy, sustaining the political and budgetary support for the exploration missions over time will be critical, thus, the following are important:

- Minimize the number of new developments
- Maximize technology development leverage
- Build power system capability in modular blocks
- Engage technologists/developers early
- Conduct trade studies throughout the developments

Bibliography

NASA Report of the 90-Day Study on Human Exploration of the Moon and Mars, November 1989.
Hoffman, S.J. and Kaplan, D.I. (eds). Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team. NASA Special Publication 6107, July 1997.
Jet Propulsion Laboratory, Energy Storage Technology for Future Space Missions, JPL D-30268, November 2004.
Jet Propulsion Laboratory, Solar Cell and Array Technology for Future Space Science Missions, JPL D-24454A, December 2003.
Hoffman, David J., "A Parametric Assessment of the Mission Applicability of Thin-Film Solar Arrays," presented at the 2002 Space Power Workshop, NASA/TM—2002-211720.

Hoffman, David J., Kerslake, Thomas W., Hepp, Aloysius F. and Raffaele, Ryne P., “Thin-Film Solar Array Earth Orbit Mission Applicability Assessment,” presented at the 17th Space Photovoltaic research and Technology Conference, Sept. 2001.

Hoffman, David J., Kerslake, Thomas W., Hepp, Aloysius F., Jacobs, Mark K., Ponnusamy, Deva, “Thin-Film Photovoltaic Solar Array Parametric Assessment,” presented at the 35th IECEC, July 2000, AIAA-2000-2919 and NASA/TM—2000-210342.

Aerospace Flywheel Technology Website: <http://space-power.grc.nasa.gov/ppo/projects/flywheel/index.html>.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 2005		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE An Overview of Power Capability Requirements for Exploration Missions			5. FUNDING NUMBERS WBS-22-612-10-04-11	
6. AUTHOR(S) José M. Davis, Robert L. Cataldo, James F. Soeder, Michelle A. Manzo, and Roshanak Hakimzadeh				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-15067	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2005-213600 AIAA-2005-2786	
11. SUPPLEMENTARY NOTES Prepared for the First Space Exploration Conference: Continuing the Voyage of Discovery sponsored by the American Institute of Aeronautics and Astronautics, Orlando, Florida, January 30-February 1, 2005. Responsible person, José M. Davis, organization code PTE, 216-433-5407.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 20 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Advanced power is one of the key capabilities that will be needed to achieve NASA's missions of exploration and scientific advancement. Significant gaps exist in advanced power capabilities that are on the critical path to enabling human exploration beyond Earth orbit and advanced robotic exploration of the solar system. Focused studies and investment are needed to answer key development issues for all candidate technologies before down-selection. The viability of candidate power technology alternatives will be a major factor in determining what exploration mission architectures are possible. Achieving the capabilities needed to enable the CEV, Moon, and Mars missions is dependent on adequate funding. Focused investment in advanced power technologies for human and robotic exploration missions is imperative now to reduce risk and to make informed decisions on potential exploration mission decisions beginning in 2008. This investment would begin the long lead-time needed to develop capabilities for human exploration missions in the 2015 to 2030 timeframe. This paper identifies some of the key technologies that will be needed to fill these power capability gaps. Recommendations are offered to address capability gaps in advanced power for Crew Exploration Vehicle (CEV) power, surface nuclear power systems, surface mobile power systems, high efficiency power systems, and space transportation power systems. These capabilities fill gaps that are on the critical path to enabling robotic and human exploration missions. The recommendations address the following critical technology areas: Energy Conversion, Energy Storage, and Power Management and Distribution.				
14. SUBJECT TERMS Power systems; Electric propulsion; Nuclear electric propulsion; Energy storage; Power management; Photovoltaic power systems			15. NUMBER OF PAGES 26	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

