



Power System Concepts for the Lunar Outpost: A Review of the Power Generation, Energy Storage, Power Management and Distribution (PMAD) System Requirements and Potential Technologies for Development of the Lunar Outpost

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Abstract

This paper will review potential power system concepts for the development of the lunar outpost including power generation, energy storage, and power management and distribution (PMAD). In particular, the requirements of the initial robotic missions will be discussed and the technologies considered will include cryogenics and regenerative fuel cells (RFC), AC, and DC transmission line technology, high voltage and low voltage power transmission, conductor materials of construction and power beaming concepts for transmitting power to difficult to access locations such as at the bottom of craters. Operating conditions, component characteristics, reliability, maintainability, constructability, system safety, technology gaps/risk and adaptability for future lunar missions will be discussed for the technologies considered.

Introduction

A power supply system whether terrestrial or space based can be divided into four (4) major sub-systems:

- Power Generation
- Energy Storage
- Power Management and Distribution
- Loads

Prior work published on this subject includes (Cataldo and Bozek, 1993; Kerslake, 2005). This paper will focus on the power requirements of the early development stages of the lunar base. The paper assumes a lunar base sited at the South Pole near the Shackleton crater and that power generation will be based on an initial photovoltaic and regenerative fuel cell (PV/RFC) power source. Figure 1 illustrates a notional Phase 0 base layout. High-level trade studies for energy storage and power management and distribution (PMAD) systems are presented and potential technology gaps/risks are identified.

Lunar power supply systems are optimized primarily on mass, in order to reduce launch costs from earth. The primary quantitative metric used in this paper will be energy density, kWh/kg.

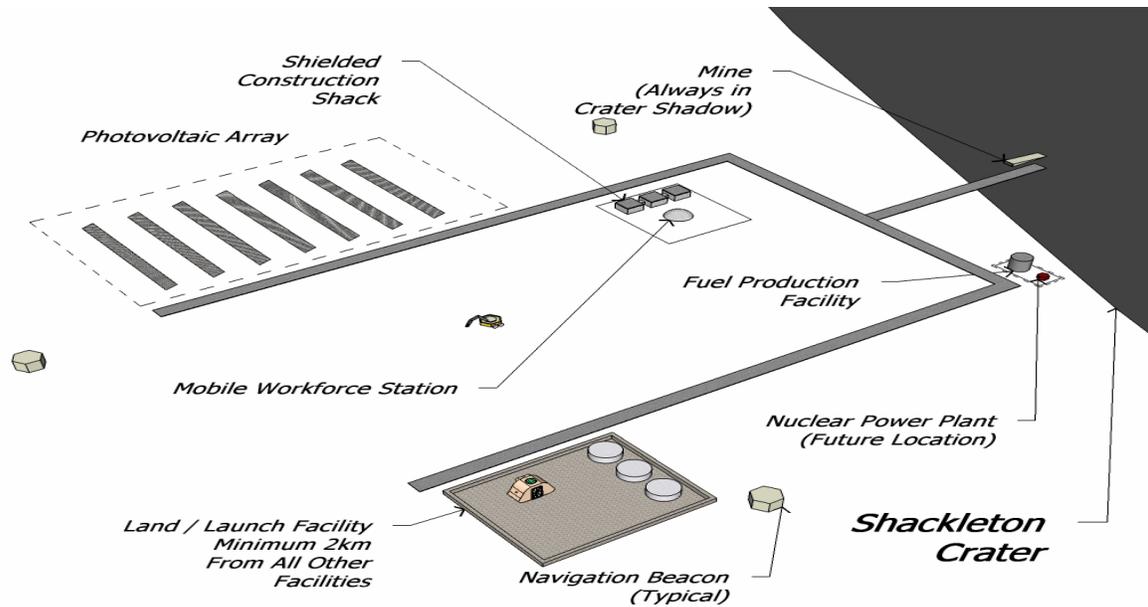


Figure 1.—Notional phase-0 base layout.

A qualitative assessment of constructability, maintainability, reliability, adaptability, system safety and technology gaps/risk will also be made and will use the following ranking criteria in table 1:

TABLE 1.—TECHNOLOGY RANKING CRITERIA

Category versus Score	1	2	3
Constructability	Complicated structural requirements	Intermediate structural requirements	Simple structural requirements
Maintainability	High maintenance frequency with earth based logistical support	Intermediate maintenance frequency with earth based logistical support	Relatively low maintenance frequency with earth based logistical support
Reliability	Low reliability with a large number of moving parts	Intermediate reliability with some moving parts	High reliability with a minimum number of moving parts
Adaptability	Low adaptability to Mars and Beyond missions	Intermediate adaptability to Mars and Beyond missions	Good adaptability to Mars and Beyond missions
System Safety	High level of risk for loss of life, equipment or property	Medium level of risk for loss of life, equipment or property	Low level of risk for loss of life, equipment or property
Technology Gaps/Risk	Proof of concept demonstrated	Demonstrated in terrestrial environment	Demonstrated in space environment

The primary trade studies that are investigated in this paper include the following:

- Regenerative Fuel Cell (RFC) versus Batteries versus Flywheel energy storage systems
- AC versus DC transmission
- High voltage versus Low voltage transmission

Transmission frequency, materials of construction, conductor placement, and power transmission into difficult to access areas are also discussed.

The following overview of terrestrial based and space based power systems is provided as a brief summary of the current state of power system technology.

Terrestrial Power Systems

In the United States, power generation is based on a centralized architecture with 3 Phase, 60 Hz AC power being generated at medium voltage, generally between 11 and 25 kV. The generated voltage is then stepped up to high voltage levels (typically 115 and 230 kV) or ultra-high voltage levels (typically 345 kV, 500 kV, and higher) for transmission. The distribution system is split into two categories – primary and secondary. Primary voltages are usually medium voltage systems between 5 and 69 kV. Secondary voltages are usually single phase 120/240 VAC or 3-phase 120/208 VAC or 480 VAC.

Terrestrial power generation is characterized by a wide range of fuels that includes coal, natural gas, nuclear and renewables. This adds diversity to the overall system and results in greater system flexibility and reliability. Recent trends in terrestrial power generation include cogeneration and distributed generation. Cogeneration units generate both electricity and heat and results in a very efficient form of generation. Distributed generation can be defined as locating the generating source near the consumers site and can be integrated or isolated from the main grid. Distributed generation appears to have the ability to provide higher quality and higher reliability power than centralized power stations but still needs additional technology improvements in order to bring costs down.

The transmission system in the U.S. has evolved in to three regional grids interconnected for reliability. Aluminum conductors and buses are the norm for most terrestrial transmission lines, open-air switchyards, switchgear and motor control centers. The operational capacity of the system is determined by thermal constraints, voltage constraints and system operating constraints.

Space Based Power Systems

The International Space Station (ISS) Electrical Power System (EPS) consists of a 120 VDC U.S. built portion and a 28/120 VDC Russian made section. The two sections are interconnected and allow mutual transfer of power. Both systems use PV arrays to generate power during the sunlit portion of the orbit and batteries for the eclipse portion. The U.S. EPS provides approximately 78 kW of power and the Russian EPS provides approximately 29 kW (Gietl et al., 2000). Details of the U.S. EPS follow as this system most closely matches the requirements for the initial Phase 0 PMAD. Figure 2 illustrates the U.S. EPS power flow.

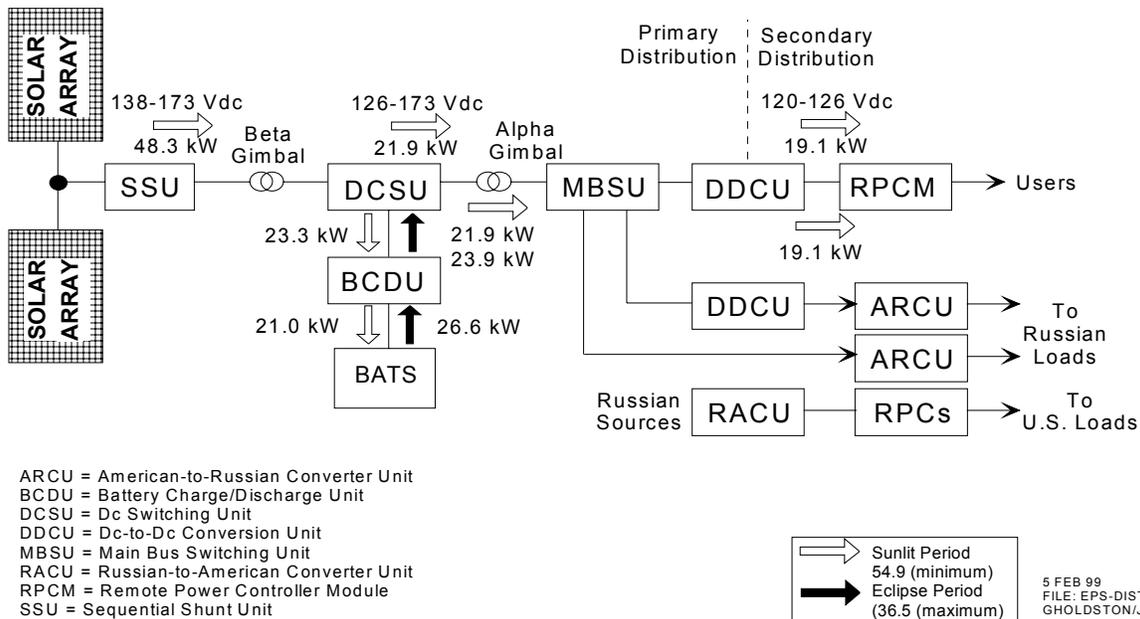


Figure 2.—ISS single channel power flow diagram (Gietl et al., 2000).

The U.S. EPS provides 78 kWe of power generated by four photovoltaic array modules. Each Array consists of two flexible deployable array wings of silicon solar cells supported by an extendable mast. This results in a total of eight (8) solar array panels. During an eclipse Nickel-Hydrogen batteries provides station power. The PMAD system distributes power at 160 VDC using DC contactor switchgear. This voltage is then stepped down to 120 V DC by DC-DC converter units that condition the voltage for use by end users through solid-state switchgear (Ianculescu, 1999).

In the sunlit portion of the orbit, power flows from the solar array through the Sequential Shunt Unit (SSU) to the DC Switching Unit (DCSU). Power then flows downstream to loads connected to the DC-DC Converter Units (DDCU) and to the batteries through the Battery Charge Discharge Unit (BCDU). During eclipse periods and during sun periods with low solar array output, power flows out of the batteries through the BCDU to the DCSU which routes power to the connected loads. The station uses two redundant channels for power distribution. The temperatures of the batteries and electronics are maintained via an active thermal control system.

General Design Considerations for a Polar Site

This paper assumes a lunar base sited at the South Pole near the Shackleton crater. The relatively constant thermal and illumination conditions along with the potential of water at the South Pole makes this area an attractive site for a manned lunar base. Preliminary data indicates that regions located near the Shackleton crater receive sunlight for much of the lunar day (Cook et al., 2000).

Estimated lunar temperatures at polar sites averages 40 K in shadowed polar craters and approximately 220 K in other polar areas with a monthly range of 10 K. The thermal conductivity of the sub-surface lunar soil is on the order of 1.4 to 3.0×10^{-4} W/cm /K. The electrical properties of the lunar soil are characterized by extremely low electrical conductivity. In the absence of water and in darkness, the DC electrical conductivity is in the range of 10^{-09} to 10^{-14} mho/m. The low conductivity of the lunar soil also contributes to the fact lunar materials are chargeable and remains charged for long periods of time. Charged surface soil particles can levitate and move and coat solar arrays or radiators (Eckart, 1999). This may result in a decrease in power system performance.

Lunar Base Phased Construction

We are assuming that the construction of a lunar base and its supporting infrastructure will undergo an evolutionary development. The infrastructure must allow for increased power, mobility and research capability at each stage. The construction of the lunar base may be undertaken in five (5) phases over a period of 15 to 20 years. The final phase, Phase 4, will involve self-sufficient scientific and commercial projects with only discretionary links to the earth (Duke and Freid, 2004).

- Phase 0—Robotic Site Preparation (minimum or no human presence)
- Phase 1—Deployment and initial operations (3 to 4 personnel for 4 to 6 months)
- Phase 2—Growth Phase (approximately 10 personnel for a year)
- Phase 3—Self Sufficiency (ten to 100 personnel for extended periods)
- Phase 4—Science and Commercial (greater than 100 personnel for unlimited durations)

Lunar Surface Power Supply Requirements

Phase 0 mission requirements includes robotic exploration with landers and rovers with minimum or no initial human presence. The landers and rovers will survey the lunar terrain, test accessibility to permanently shadowed areas, demonstrate basic construction techniques, demonstrate propellant production, confirm the existence of water, and establish and demonstrate power system operations.

An estimate of the array peak power requirements for Phase 0 is listed in table 2. The highest expected load of 43 kWe is for In-Situ Resource Utilization (ISRU) mining activities for water, hydrogen and oxygen (Blair, 2005). Additional loads are included for general science activities and rover recharging. Parasitic loads for the RFC electrolyzer are based on 65 percent sunlight and 50 percent nighttime power. Emergency power for equipment health monitoring and thermal control may be provided by an independent power source such as batteries. Additional base power requirements for subsequent phases can be added in a modular fashion.

TABLE 2.—ESTIMATED ARRAY PEAK POWER REQUIREMENTS FOR PHASE-0

Loads	Phase 0 kWe
ISRU mining (Blair, 2005)	43
General Science (Cataldo and Bozek, 1993)	1
Rover Recharging (Catadalo and Bozek, 1993)	5
RFC Parasitic Load	25
10 percent margin	7
Total	81

Power Generation

Portable power in the 1-2 kWe range for rovers and landers can be provided by a number of different options. Power may be provided by Radioisotope Thermal Generators (RTG) with batteries for peaking power or an RFC system (Kerslake, 2005).

The proposed PMAD architecture would be a hybrid design with centralized power from a PV/RFC source for initial ISRU loads and emergency power provided by batteries. This would also provide dissimilar redundancy. Power could be generated at the array panels at relatively low voltages (200 VDC) for better PV component reliability and then conditioned to higher voltages for transmission.

PV technology is used extensively in space-based systems and is currently being used for power generation on the ISS. PV power generation takes advantage of the relatively constant illumination at the Shackleton crater to convert free solar energy into electricity. However, like all solar powered systems an energy storage system will be required for nighttime power. This can be provided by an RFC system.

In order to meet future multi-MWe power requirements, a nuclear fission reactor may be required for later stages. The trade between PV and Nuclear Reactor power is not considered here.

Energy Storage

Energy storage options include RFC's and batteries. Energy storage using flywheels, thermal reservoirs, supercapacitors and gravitational fields is also possible although they are not as mass efficient. Flywheel energy storage systems do have the potential for a high lifetime, improved energy density, power and voltage levels.

Fuel cells combine hydrogen and oxygen to produce electrical energy, water and waste heat. A fuel cell can be coupled with an electrolyzer in an RFC arrangement in order to regenerate the reactants. This system would function as a fuel cell at nighttime and regenerate the reactants during the day. The additional power requirements needed to run the electrolyzer during the day needs to be included in the base load power requirements.

Cryogenic RFC systems store the reactants as liquids in tanks. Cryogenic reactant storage increases the energy density of the overall system by reducing the volume of the stored reactants and the mass of the storage tanks. Permanently shadowed areas exist in certain craters at the South Pole and may allow for cryogenic storage of reactants at these locations. This would result in reduced liquefaction equipment load although additional equipment (pumps and/or transfer rovers) would be needed to transport the fuel to the land and leave area.

Primary batteries are defined as non-rechargeable and do not have sufficient energy density to be considered for lunar base use. Secondary batteries are defined as rechargeable and can be used in a variety of space-based applications including lunar landers, rovers, human outposts and astronaut equipment. Nickel-hydrogen secondary batteries are currently in use on the ISS. However these batteries have limited storage capacity and are not suitable for lunar base application. Lithium-ion battery technology offers higher specific energy with the capability of operating at higher voltages over a wide range of temperatures.

Table 3 summarizes the basic characteristics of RFC, battery and flywheel energy storage. Battery depth of discharge is assumed as 80 percent. Energy density values are representative of current technology (Eckart, 1999). RFC energy density is based on cryogenic storage.

TABLE 3.—RFC VERSUS BATTERIES VERSUS FLYWHEELS

Criteria	RFC (cryogenic)	Batteries	Flywheels
Nighttime Stored Energy, kWh	6,449	8,062	6,449
Energy Storage Mass, kg	4,300	80,617	214,978
Energy Density, kWh/kg	1.5	0.1	0.03
Constructability	3	3	2
Maintainability	2	2	2
Reliability	3	3	2
Adaptability	3	2	2
System Safety	3	2	2
Technology Gaps/Risk	2	2	1
Total	16	14	11

Power Management and Distribution

The PMAD consists of power conditioning equipment, switchgear and high voltage transmission lines. The PMAD system mass is governed by the PMAD architecture, the output power demands, the power source, transmission voltages, operating frequencies, stage efficiencies, transmission line design, and materials of construction.

Space based power supply systems have evolved from the small satellite requirements of less than 1 kWe, where power consumption is in close proximity to the power consumers, to systems like that of the ISS where multiple sources, multiple loads and large physical size make the ISS power system more like a terrestrial utility system than a traditional spacecraft power system.

The requirements of the Phase 0 lunar surface PMAD are very similar to the ISS EPS. Both systems are characterized by multiple sources, multiple users, similar power generation levels and similar secondary distribution voltages. Important differences include transmission distances in the 10's of km's and that loads will be mobile and fixed for the initial Phase 0 lunar base. It should also be noted that during the development of the lunar base the power supply system will have to evolve from the relatively low power requirements (multi-kWe) of the initial stages to the much higher power requirements (multi-MWe) of the later stages along with the possibility of even greater transmission distances. This may require a nuclear reactor power source for later stages.

AC versus DC transmission.—DC power transmission is typically more efficient than AC because DC line losses are primarily due to conductor resistance. For AC transmission, “skin effects” (uneven current density resulting in greater effective resistance) plus reactance terms must be added to the conductor resistance. Because of these differences AC and DC transmission need different cable configurations. DC lines are simpler to fabricate. AC conductors require specialized construction in order to minimize reactance terms and skin effects. AC has the advantages of simpler voltage transformations and the ability to switch on zero current which simplifies power conditioning component design. The trade between AC and DC transmission is not clear cut and more detailed trade studies need to be done that take into account safety and life cycle costs.

As noted in the previous section, the power supply requirements of the Phase 0 lunar base PMAD are similar to the ISS PMAD except for longer transmission distances. It may be possible to install an ISS derived, DC based PMAD for Phase 0 that could be adapted for the relatively short distance of high voltage transmission. This would take advantage of the ISS EPS's developmental work and allow for quicker flight testing of new high voltage components. Initial PMAD designs must be able to evolve and adapt to future requirements that may include AC power generation. If a DC based system is selected for the initial Phase 0 PMAD this system could be adapted to interface with an AC system with solid-state inverters. Additional trade off studies will have to be performed to assess the mass and cost penalty associated with this.

Table 4 summarizes the trade between AC and DC transmission. DC transmission systems are expected to be relatively easy to install and maintain. DC systems are given a slightly lower ranking for system safety because of the greater potential of arcing at switchgear. This may be addressed with DC PMAD architectures involving low voltage DC switchgear and high voltage side current limiting protective devices. Additional studies involving analysis, testing and prototyping of suitable DC switchgear technology for reducing arcing and high fault currents need to be undertaken. Although terrestrial transmission is based on AC transmission, there are currently no space based applications. All existing space based electrical power systems are DC.

TABLE 4.—AC VERSUS DC TRANSMISSION

Criteria	AC	DC
Advantages (Metcalf, Harty, and Robin, 2001)	<ul style="list-style-type: none"> • Voltage transformations less complex • Switching on zero current eases fault current interruption • Switching on zero current reduces switching losses, transients and EMI 	<ul style="list-style-type: none"> • Transmission lines are more efficient • Easier to parallel DC lines • Low voltage DC used developed for SSF
Disadvantages (Metcalf, Harty, and Robin, 2001)	<ul style="list-style-type: none"> • Increased transmission line losses due to skin effect • Further R&D in paralleling sources • AC to AC frequency conversion requires 2 steps 	<ul style="list-style-type: none"> • Voltage transformations require 3 steps • High fault currents, difficult to interrupt, damaging arc • Channelized approach probably necessary to handle fault currents, reduces power utilization efficiency
Constructability	3	3
Maintainability	2	3
Reliability	2	3
Adaptability	3	3
System Safety	3	2
Technology Gaps/Risk	2	3
Total	15	17

It may be noted that for terrestrial applications, there has been a recent trend in the electric power transmission industry to utilize high voltage DC (HVDC) transmission lines at different voltage levels for bulk power transmission over long distances. There are numerous HVDC projects with voltage levels up to 500 kV already installed and operating around the world presently, which provide valuable field lessons learned to the industry. In addition, large HVDC transmission schemes over distances between 1000 and 2000 km are currently being planned for various hydroelectric power stations. It appears that ultra high DC voltage in the range of 800 kV is the preferred voltage for this application. This planned ultra high DC voltage scheme is being designed to be bipolar, unidirectional (although power reversal shall be also possible), with ratings exceeding 6000 MW. In general, with the HVDC technology in terrestrial applications, the installed systems presently are being used not only to transmit power over extremely long distances, but to also connect to AC asynchronous grid systems, i.e., AC systems operating at different frequencies.

High voltage versus low voltage transmission.—High voltage transmission is defined in this paper as voltages greater than 300 V. Transmission line voltage affects component sizing in two ways. Increasing the voltage level reduces the amount of current a line must carry. This reduces the conductor mass and increases transmission line efficiency. A higher voltage also requires more insulation and greater separation distances which increases hardware volume and mass. On a system level, previous studies have shown that power system mass approaches a minimum value of 5000 V for both AC and DC systems (Metcalf, Harty, and Robin, 2001).

ISS transmission voltages are approximately 160 VDC and would not be optimum for transmitting power over 10's of km's. It would be necessary to step up the voltage to a higher voltage level in order to minimize I^2R losses and increase transmission efficiency. This transmission voltage would be the result of another more detailed trade study.

Table 5 summarizes the trade between high and low voltage transmission. High voltage transmission is expected to be relatively easy to install due to its lower overall system mass, have a low maintenance frequency based on terrestrial experience, and a high adaptability to other surface based power systems. Although terrestrial transmission is based on high voltage transmission, there are currently no space based applications above approximately 160 V. High voltage systems are considered to pose a greater safety hazard than low voltage systems, and this will need to be addressed with additional analysis, testing and prototyping.

TABLE 5.—TRANSMISSION VOLTAGE

Criteria	High Voltage (Greater than 300 V)	Low Voltage (Less than 300 V)
Advantages (Metcalf, Harty, and Robin, 2001)	<ul style="list-style-type: none"> • Reduced Transmission Line Mass • Increased Efficiency 	<ul style="list-style-type: none"> • Existing Space Based Designs • DC to DC converters easier to manufacture and probably more reliable • Minimal Electrical Insulation for Power Conditioning
Disadvantages (Metcalf, Harty, and Robin, 2001)	<ul style="list-style-type: none"> • At equivalent efficiencies line temperatures rise • Power Conditioning requires more insulation • Additional testing of high voltage switches 	<ul style="list-style-type: none"> • DC to DC conversions less efficient • High I² losses • High switching losses
Constructability	3	2
Maintainability	3	2
Reliability	3	2
Adaptability	3	2
System Safety	2	3
Technology Gaps/Risk	2	3
Total	16	14

PMAD frequency.—In an AC system, as frequency increases the mass of the power conditioning components decrease, and the transmission line mass increases. The mass of the power conditioning equipment decreases with frequency because of a decrease in the required flux density for a specified voltage. Transmission line mass increases with frequency as skin effect and inductive reactance increase with frequency. Previous studies indicate that the reduction in mass of the PMAD system due to increasing frequency has a relatively minor effect as the power source mass dominates the overall system (Metcalf, Harty, and Robin, 2001).

Equipment and conductor materials of construction, conductor placement, and grounding.—Temperatures expected in shadowed areas at the poles are approximately 40 K. This increases to approximately 220 K in other polar areas. This will require material of construction for equipment and wiring to be qualified to operate throughout this wide temperature range. Materials used in cryogenic service on earth in this temperature range include stainless steels and aluminum. Composite materials have also been used in cryogenic service but will need further testing and analysis to see if they can be used at these temperatures.

As the mass of an aluminum conductor is approximately half that of an equivalent Copper conductor, Aluminum is more suitable for external conductors. Aluminum is used extensively in terrestrial power systems for this reason. Copper has a smaller volume and better ductility than Aluminum and is more suitable for use in power conditioning components. Power conditioning components will be in thermally controlled environments and will not be expected to see wide variations in temperature during normal operation.

For Phase 0, surface placement of cables is considered preferable to suspended or buried placement. Suspended cable placement will require additional installation complexity and buried placement of transmission lines may be difficult because of potentially rocky polar terrain. During Phase 0 with minimum or no human presence surface placement of cabling provides the advantages of relative ease of installation and increased cable routing flexibility. Road crossings will be protected with suitable reinforcing to allow equipment to cross. High voltage cabling run on the surface of the moon may be a safety hazard to humans during the later phases of base development and additional analysis, testing and prototyping of conductor design, trenching and cable laying technology along with additional data on regolith properties will be needed in order to mitigate the risks associated with buried placement of cabling. Current carrying density of all lunar cabling will be designed to take into account the lunar environment.

A grounding system will also have to be established in order to provide a safe path for fault currents and static discharge to travel. Due to the poor conductivity of the lunar soil and the possibility of charged clouds of dust moving along the surface of the moon, additional fault protection relays and/or separate grounding wells may have to be installed at each piece of equipment. Additional studies involving analysis, testing and prototyping of suitable grounding technology for the surface of the moon needs to be undertaken as very little experience in this area exists.

Beamed power for access to difficult to access areas.—Access to the interior of the Shackleton crater will be very important for ISRU operations for propellant and water production. Independently powered rovers will be

designed for access to the interior of the Shackleton crater for these mining operations. Additional material testing and equipment prototyping will be required to mitigate the risk associated with operating at these low temperatures. Power for rover locomotion may be provided by RTGs, but this will not be sufficient power for mining and processing operations. This additional power would need to be transmitted into the crater. Communication into and out of the crater will also need to be addressed as crater topography would prevent line of sight communication.

The simplest way to transmit power and maintain communication with the rover in the crater would be to lay power and control cabling into the crater. Cable laying operations may be complicated by the steep slope of the Shackleton crater walls and may require the rover to be either winched down or for the rover to follow a mining haul road with multiple switchbacks into the crater. An alternative might be to install relay communication/power antennae on the crater rim or suspended over the crater. This would establish a communication link with the rover in the crater and may allow the use of beamed power between the rover and a base station just outside of the crater. Another option is the use of fiber optics to transmit light to power solar arrays either on the rover or to waypoints along the way that would allow the rover to recharge without having to come out of the crater. Additional analysis, testing and prototyping will be required to address technology gaps in transmitting power via lasers and/or microwaves and transmitting solar energy through fiber optics in order to mitigate the risks associated with operating within crater structures (Kerslake, 2005).

Conclusion and Recommendations

The proposed PMAD architecture would be a hybrid design with centralized and distributed power. Centralized power would be from a PV/RFC source for initial ISRU loads, rover recharging and general science activities. Distributed power for emergency use could be provided by batteries. This design would allow for dissimilar redundancy.

During Phase 0 with minimum or no human presence and mobile loads, surface placement of cabling provides the advantages of relative ease of installation and increased cable routing flexibility.

Difficult to access areas, such as the interior of craters, may be accessed with tethered rovers. Other options for transmitting power into the crater might include power beaming using lasers and/or microwaves and the possibility of transmitting solar power via fiber optics.

Both AC and DC systems are expected to be relatively easy to install and maintain due to lower system masses with good adaptability to other surface power applications. Safety is considered better for an AC system because of potentially reduced arcing in AC switchgear although the technology gaps/risk for AC are considered greater as all existing space based applications are DC based. A DC based system is recommended as the technology gaps/risk are lower and safety issues can be addressed with additional analysis, testing and prototyping of HVDC switchgear. Technology gaps in the following areas have been identified:

- 1) AC-DC conversions
- 2) High voltage DC switchgear technology
- 3) Optimum DC transmission voltage
- 4) High voltage transmission system safety
- 5) Materials for low temperature service
- 6) Surface cable laying technology
- 7) Lunar grounding technology with respect to lunar regolith and environment
- 8) Laser or microwave power beaming technology
- 9) Fiber optic technology for power and control

These areas will need more detailed trades studies to be conducted and additional analysis, testing and prototyping of power supply components for lunar surface application.

References

1. Blair, B., "Configuration of Polar ISRU (Water Ice) Plant," Colorado School of Mines, personal communication, 2005.
2. Cook, A.C., Watters, T.R., Robinson, M.S., Spudis P.D., and Bussey, D.B.J., "Lunar polar topography derived from Clementine Stereoimages," *Geophysical Research Letters* 105, 12,023–12,034 (2000).

3. Cataldo, R.L., and Bozek, J.M., "Power Requirements for the First Lunar Outpost (FLO)," NASA/TM—105925, 1993.
4. Duke, M., and Freid, S., "Manned Lunar Base Construction Strategy," Bechtel National, Bechtel Nevada, Colorado School of Mines, NASA Space Operations Mission Directorate, personal communication, 2004.
5. Eckart, P., *The Lunar Base Handbook*, McGraw-Hill, New York, 1999, pp. 137–139.
6. Gietl, E.B., Gholdston, E.W., Manners, B.A., and Delventhal, K., "The Electric Power System of the International Space Station-A Platform for Power Technology Development," NASA/TM—2000-210209, 2000.
7. Ianculescu, A., "Overview of ISS Electric Power System," Boeing Canoga Park, Space Operations & Flight Experiments Group, personal communication, 1999.
8. Kerslake, T.W., "Electric Power System Technology Options for Lunar Surface Missions," NASA/TM—2005-213629, 2005.
9. Metcalf, K.J., Harty, R.B., and Robin, J.F., "Issues Concerning Centralized Versus Decentralized Power Development," NASA/CR—2001-210763, 2001.

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13. ABSTRACT (<i>Maximum 200 words</i>) This paper will review potential power system concepts for the development of the lunar outpost including power generation, energy storage, and power management and distribution (PMAD). In particular, the requirements of the initial robotic missions will be discussed and the technologies considered will include cryogenics and regenerative fuel cells (RFC), AC and DC transmission line technology, high voltage and low voltage power transmission, conductor materials of construction and power beaming concepts for transmitting power to difficult to access locations such as at the bottom of craters. Operating conditions, component characteristics, reliability, maintainability, constructability, system safety, technology gaps/risk and adaptability for future lunar missions will be discussed for the technologies considered.				
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