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A POWER ARCHITECTURE FOR THE ISECG REFERENCE ARCHITECTURE FOR HUMAN LUNAR EXPLORATION

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Based on the goals of the Global Exploration Strategy (published by 14 space agencies in 2007) the International Space Exploration Coordination Group (ISECG) has been developing an example architecture and notional mission manifest for lunar human exploration, called the ISECG Reference Architecture for Human Lunar Exploration. The mission manifest starts with human lunar return and spans over twelve years, comprising four phases of lunar exploration. The ISECG Reference Architecture advances the principles of programmatic and technical sustainability, affordability, science and Mars forward objectives, and particularly focuses on scientific return and international cooperation for its implementation. Electrical power management plays a critical role in the implementation of each phase. Solutions must be developed that respond to complex concepts of operations for surface elements and at the same time are limited by system constraints as well as transportation and logistics capabilities available.

The exploration phases of the ISECG Reference Architecture are characterised by Polar Exploration and System Validation, Polar Relocateability, Non-Polar Relocateability, and Long Duration; all of which are preceded by a Lunar Precursor Phase. Each phase is notionally planned for a different location on the lunar surface where cargo landers from different international partners deliver elements (e.g. rovers, habitats, power and communication elements) and equipment to the surface. They will be utilised by astronauts during subsequent sortie or extended stay missions of up to 70 days. Astronauts conduct different types of scientific and exploration activities during their stays, some of which include extensive mobility operations during lunar day and night, thus demanding a highly-integrated power and energy capability.

The international Power Function Team of the ISECG has performed an analysis of power system alternatives for the lunar surface architecture and has developed a suite of options for the ISECG architecture. This paper presents the results of the basic analysis of the Team, including the identified key drivers, top-level requirements, sub-functions and resulting architecture. It introduces the chosen parametric classification of power and energy systems and a set of conceptual systems that have been defined in order to implement the power architecture. Using examples of integrated operation profiles for the elements on the lunar surface, possible solutions for power and energy provision in the ISECG Reference Architecture are demonstrated. The inclusion of nuclear systems is discussed and presented as an alternative option.

I. INTRODUCTION

With the release of the Global Exploration Strategy in 2007 (1), and the subsequent formation of the International Space Exploration Coordination Group (ISECG), participating agencies recognized the importance of working together to enable a sustainable human space exploration future. In early 2008, many space agencies were active studying lunar exploration

scenarios which included human and robotic exploration activities. ISECG then invited interested agencies to explore a coordinated approach to human lunar exploration. They were invited to participate in a study of lunar exploration objectives and exploration concepts that could meet common agency objectives. The goal of the study was to develop a common understanding of how humans could best explore the moon, and the partnerships that would enable such an exciting

exploration endeavour. The result of this study has been the ISECG Reference Architecture for Human Lunar Exploration (2, 3).

For the organization of the work 11 international teams and working groups have been set-up, amongst them the Power Function Team (PFT), which was formed by the authors of this paper. Like the other Function Teams its major tasks were to analyze key driving requirements for the various architecture functions, identify innovative concepts responding to these requirements and conceptually define the architecture elements. Many of these element concepts are based on individual agency studies performed earlier or in parallel. Within the architecture development the function teams played a critical role in developing the technical concepts needed to create a viable architecture, and ensured both technical consistency and feasibility of the architecture.

II. GLOBAL POINT OF DEPARTURE (GPOD) CAMPAIGN

The Global Point of Departure (GPoD) campaign is a notional mission manifest for the ISECG Reference Architecture that includes delivery of a specific set of elements to specific set of locations on the lunar surface over a period of time. It is a conceptual study which provides a robust and flexible path to meet the commonly agreed goals for lunar surface exploration

among the participating agencies [4]. These goals are met utilizing a phased architecture, which was chosen after a comparative assessment of different campaign types [5]. The GPoD is a flexible approach to lunar exploration that can accommodate changes in technologies, international priorities and programmatic constraints as necessary. Opportunities for multiple partners and a phased approach that is driven and informed by discoveries and accumulated experience are key to the architecture's robustness. Lessons learned from previous phases and missions can be used to let equipment undergo block upgrades for the next phases. Figure 1 depicts the phases of lunar exploration for the GPoD campaign. Notional exploration locations considered for this campaign are based upon evolving remote observations and studies. A detailed description of the campaign is provided in the related IAC2010 paper [6].

Over the 12 year duration of the GPoD campaign, 24 crew missions are flown giving 96 astronauts opportunity to reach the surface of the Moon. A total of 13 different sites are visited and 660 crew days are available to explore the surface, including 242 crew days of pressurized mobility. Five of the crewed missions can remain on the lunar surface for more than 60 days. A total of 10 large cargo landers and 24 small cargo landers are used to support the GPoD campaign.

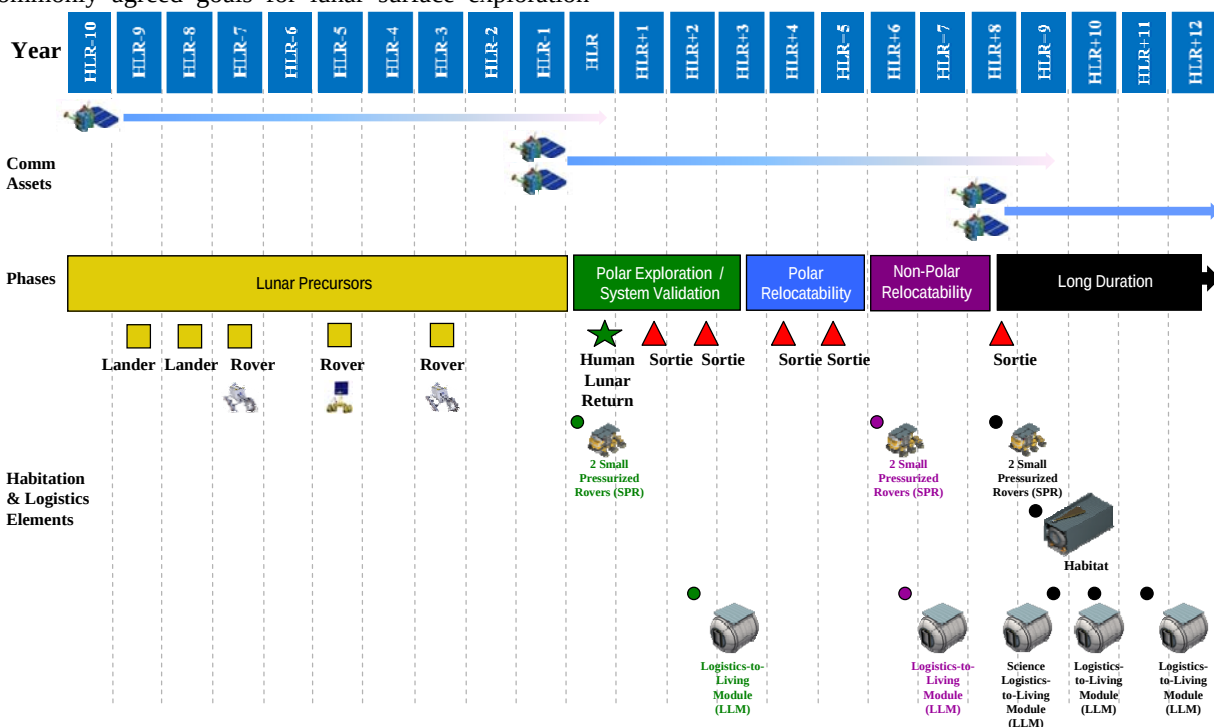


Figure 1: Phases of the Global Point of Departure (GPoD) Campaign, with major elements shown. HLR is the year of human lunar return.

Campaign Phases

In order to be able to understand some trade decisions taken for the power architecture a brief description of each Phase and its specifics is given hereafter. Of particular importance are the locations on the lunar surface and the related illumination conditions, as well as the mobility requirements during surface operations.

Lunar Robotic Precursors

The precursor missions contribute to advancing technologies necessary to support humans for extended durations away from Earth while minimizing the logistics supply chain. They should be used to demonstrate small scale power systems, e.g. fuel cells, and to test power system related technologies and materials. A detailed description of the Robotic Precursor Phase is given in [7].

Polar Exploration and System Validation

This phase occurs at the lunar South Pole, around the rim of Shackleton Crater, due to the favorable solar and thermal conditions, thus not exposing the systems to the harshest operational environment of a full approximately 15 day lunar night until the systems have been deployed and tested.

Before the first crewed mission several small servicing robots are sent to the surface, followed by two Small Pressurized Rovers (SPRs) and supporting power infrastructure (mainly a Power Support Unit, PSU, a large regenerative fuel cell system with solar arrays) on large cargo landers. The water produced from the lander fuel cells is pumped directly into the small pressurized rovers, to provide radiation protection or be used as consumables for the crew later on. The SPRs carry each a Portable Utility Pallet (PUP) with a set of secondary (rechargeable) batteries and a photovoltaic (PV) array. During subsequent crew missions with durations between seven and 28 days, astronauts use the SPRs for excursions of increased range in the South Pole region.

Polar Relocation Phase

During this phase the international collection of robots, rovers and systems begins a ground supervised journey to the next site of interest, the Malapert mountain region, performing science and enabling participatory exploration along the way. The total travel distance along the selected path is 210 km and the maximum slope along the pathway remains within ± 30 deg. Later the crew arrives, meets the robots and explores the region for 28 days. After crew departure the robotic fleet traverses to the next site of interest, Schrodinger crater, where the next crew lands. This time the astronauts can only perform a 14 day mission due to the more severe energy constraining environment at

Schrodinger. After the completion of the mission, the robots traverse back to the South Pole, where they can later be used as supplemental spare systems in support of the Long Duration Phase.

Non-polar Relocation Phase

During this phase several large and small cargo missions are launched to the non-polar region between Copernicus Crater, Marius Hills and Aristarchus Plateau. Non-polar regions have more severe thermal and energy environments due to the ~ 15 days of eclipse / ~ 15 days sunlight cycle. The GPoD campaign includes an additional large cargo lander with a big regenerative fuel cell power system (PSU) and a second ATHLETE system to carry it. This power system enables sufficient energy storage for 28 day crewed missions compared to the polar phase. As before, the international robotic fleet is relocating and exploring before and after crewed visits. There are five crewed missions during this phase with durations from seven days to 14 days, ending in three 28 day crewed missions.

Long Duration Phase

A series of eight crewed missions spanning four years are flown to the South Pole, utilizing the remaining viable infrastructure that exists in the region in combination with new mobility, servicing, power and habitation systems. The mission durations quickly build up to 70 days in length at the same polar location in support of understanding the long term implications of partial gravity and radiation on a statistically significant number of crew. Obviously, more crew missions could follow beyond the given duration requirements applied in the study.

III. POWER FUNCTION AND FUNCTIONALITIES

Approach

The Power Function Team's approach followed three major steps leading to the solution and alternative options for the GPoD architecture:

1. Identification of key function drivers, top-level requirements and power/energy sub-functions. This led to the identification of technological options to be considered.
2. Definition of agency independent conceptual systems, structured in a parametric classification.
3. Analysis of specific requirements on architecture and mission level as well as power/energy related trades. Calculation of alternative options, leading to a baseline solution with alternative options for the ISECG Architecture.

Particular focus has been given on the analysis of nuclear systems as alternative options in future scenarios.

Furthermore, principles and trades of:

- Programmatic and technical sustainability
 - Innovation
 - Mars forward objectives
- have been analyzed on architecture and mission level and have been incorporated in the resulting solution and options.

Power Function Definition and Scope

Power Function Definition

The Function of the Power System is to provide safe and reliable electrical energy to all architecture elements and facilities to enable the robotic and human exploration of the lunar surface. It comprises the generation, storage, distribution and management of electrical energy between all surface assets and the integration with those assets.

Power is crucial to the fulfillment of missions, but is a support function to other systems. It is very important to:

- Understand the requirements and limitations from other systems
- Consider the integration and compatibility with all other assets
- Ensure the safety, protection and robustness of the power architecture

Scope

The scope of the Power Function comprises both Stand-alone and integrated power systems and all related infrastructure as well as operations and interfaces with other functions and elements.

Analysis Process and Products

The process of analysis and its resulting products is shown in Figure 2. On the basis of the initial three Scenarios – Sortie, Extended Stay, Outpost (see e.g. [6]) – the Power Function Team has identified top-level requirements for the power and energy function in lunar human exploration. From both, the initial Scenarios specific requirements and the top-level requirements the PFT then has derived Key Drivers that drive the power functionality. In order to analyze requirements and conceptual systems on lower level it was decided to define sub-functions of the power function, namely Power Generation, Energy Storage, Distribution and Management. For each sub-function a set of generic options on system level has been identified. In order to be able to select systems that respond to scenario specific requirements, those options have been classified through specific parameters such as power range and energy density. The set of options and their parametric classification has enabled the PFT to define Conceptual Elements that respond directly to the specific requirements from different levels of the CIT Campaigns and eventually the GPoD Campaign.

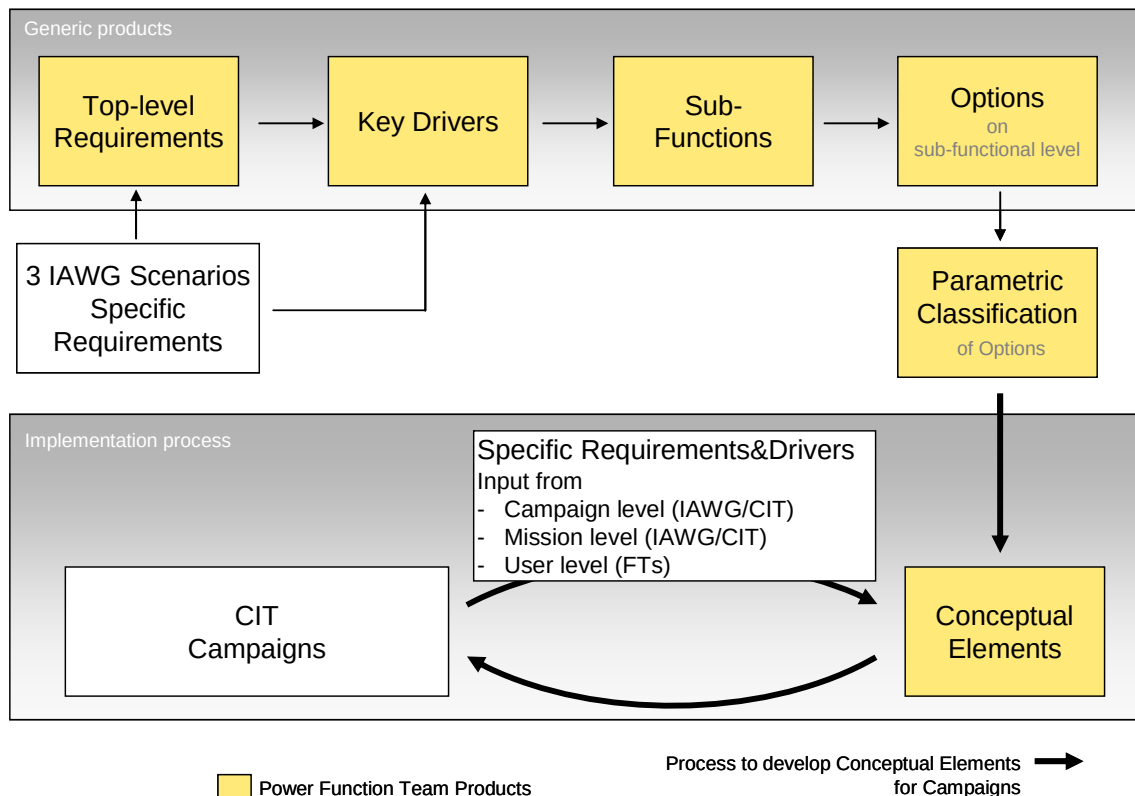


Figure 2: Analysis process and products of the Power Function Team.

The products are described in the following four subsections.

Top-level Requirements

The following top-level requirements have been identified for the power surface infrastructure:

1. Provide the necessary level of power to fixed and mobile client elements on the surface.
2. Provide infrastructure for power distribution (cabling, connections, and interfaces), allowing easy deployment by crew or robotic systems.
3. Provide power formats as required by surface elements (conditioning, conversion)
4. Support compatibility and interoperability between international partner elements. (e.g. standards)
5. Support activities at any given location on the lunar surface.
6. Support operations at any given time during lunar day and/or night for the given mission duration.
7. Support tele-command, control and monitoring.
8. Assure safe and reliable power generation, storage, management and distribution to all surface assets.
9. Allow reusability and extensibility of the power architecture and elements according to scenarios and future exploration missions.

Key Drivers

Based on the definition of the three types of exploration mission scenarios – Sortie, Extended Stay and Outpost – the following related key drivers have been identified:

Power system deployment

The way of deploying a power system to the surface, either pre-deployed on a cargo flight or together with the crew lander, as well as the number of power systems to be deployed are driving the system concept and design that will be used. Furthermore, the necessity for performing maintenance operations is a requirement derived from the scenario.

User / Consumer

The type of consumer and its operational profile is significant for defining the responding power function. Continuous power consumption of fix elements requires different power provision than recharging cycles of mobile elements or the night-survival mode of other elements.

Power Provision

The time periods for which power needs to be provided – lunar day and/or night; overall duration (lifetime) – are driving the requirements on various levels of the power function, such as mission, functional and operational requirements.

Power Grid

Setting up a power grid with different nodes in close or in larger distance from a central location may significantly benefit the efficiency of power distribution and management.

	Sortie Mission	Extended Stay Mission	Outpost
Power system deployment	• Delivery with crew lander (pre-deployment unlikely) • no maintenance	• Pre-deployed power systems • limited / no maintenance	• Pre-deploy power systems • Multiple units following outpost growth
User / consumer		• For habitation elements • For charge-up and night survival of pre-deployed assets	• For outpost and mobility elements • ISRU?
Power provision	• Lunar day only • Limited lifetime (<10 days)	• lunar day and lunar night • Extended lifetime (<180 days), potential reusability	• multiple lunar days and nights • Long lifetime (>several years)
Power grid	• no grid required	• limited number of nodes in close vicinity of landing site	• large number of nodes in a few km distance
Mobility & Autonomy	• fixed on lander • managed by crew, no autonomy required	• fixed for habitation system • mobile element support • tele-operated or autonomous between crew visits	• fixed for outpost main power • support and provision to mobile elements • Limited mobility for power element itself • tele-operated or autonomous between crew visits
Safety	• Radiation protection for SPEs	• Safe operability for crew • Radiation protection for SPEs and extended stay mission duration (longer for pre-deployed systems)	• Safe operability, maintenance, extension for crew • Radiation protection for SPEs and long-term missions
Mars Extensibility	• no growth requirement • no Mars extensibility	• limited growth requirement • no Mars extensibility	• growth with outpost growth expected • Mars demonstration / extensibility

Table 1: Key drivers in the three initial types of lunar exploration scenarios

Its structure and operations depend on the requirements from the mission scenario.

Mobility & Autonomy

The power function must respond to the requirements of fix and mobile consumer elements. Therefore power systems themselves may need to be fix, portable or self-mobile, and able to be tele-operated or to operate autonomously.

Safety

Two different aspects of safety are driving the power function: power systems need to be protected against the radiation environment and in particular SPEs; and they also need to be designed in a way that enables their safe operability and maintenance by crew.

Mars Extensibility

Power belongs to the functions for which extensibility to applications on Mars is desirable. This effects the selection of technologies to be demonstrated as well as the capability of the power infrastructure to grow in the long-term over several missions.

Each Key Driver may relate to the three mission scenarios in different ways as shown in Table 1.

Functional Decomposition

Power provision can be subdivided into four sub-functions, which usually are combined to design the complete power provision service on component, element or architecture level:

- Generation
Options: Photovoltaic, Solar Dynamics, Primary Fuel Cell, Nuclear Fission, Radioisotope System, Space Based Solar Power
- Storage
Options: Batteries, Regenerative Fuel Cells, Thermal Storage Tanks, Flywheels
- Distribution (comprising conversion, conditioning and transmission)
Options: Cables, Wireless Transmission, Interchangeable power systems
- Management (design and operation of power infrastructure)
Options: Centralized, Independent

Parametric Classification

The power infrastructure for different mission types at different lunar locations will need to respond to a wide range of demands. As the design of a power system strongly depends on the required power level, power density, size and other needs, the power

infrastructure has to be a combination of different power systems. Accordingly, parametric classification was developed, which classifies each power option according to its current or foreseeable capacity in power range, power density, and size. Together with technology trade discussions, this classification was used as a tool for the selection and implementation of power systems.

IV. POWER ANALYSIS AND TRADES FOR THE GPOD CAMPAIGN

One of the Power Function Team objectives was to provide power systems concepts that support the integrated campaign manifest and associated concepts of operations. In order to verify that these systems meet the needs of the campaign, power analyses were conducted whose breadth spans the duration of the campaign. The variables associated with this analysis have been distilled to element loads, eclipse duration, and power system capabilities including generation, storage, and charge rates.

Element Loads

Element loads were provided by the other Function Teams without a growth factor. The Power Function Team then worked to determine both a mobility and utilization load value with the appropriate function teams. The three classes of loads were increased by allowing for 30% growth and an additional 10% for contingency reserve. Once growth and contingency were applied to the element hotel loads, the final loads that had to be accounted for were utilization and mobility. The utilization load was determined to be 4kW-hr per day before growth and contingency. This was derived from the loads for usage of the small robots, EVA suits, mobility tool kit winch and science kit drills over expected nominal durations. The mobility loads were calculated to be approximately 500 W-hr/km for the SPR and 1 kW-hr/km for the ATHLETE carrying a PSU, Logistics-to-Living-Module, and other smaller elements up a 5 degree slope. This calculation takes into account vehicle mass, regolith compaction, and total drivetrain efficiency. The assumed average distance traveled each day is 5 km for periods of eclipse and 10 km for periods of illumination.

Initial Power Systems

Based on initial load estimates, concept of surface operations and technology trade considerations the Power Function Team did a pre-selection of possible power systems from the parametric classification tool. They include:

- Fuel cell system with solar arrays (integrated in the Power Support Unit, PSU)

- Portable photovoltaic system with secondary batteries (primarily carried on the Small Pressurised Rovers, integrated in the Portable Utility Pallet, PUP)

Additionally, nuclear power systems were considered as alternatives. Further discussion is located in the Campaign Power Trades – Nuclear Systems section below.

Power Solutions for the GPoD Campaign

For each notional mission the power performance was assessed for closure based on daily averages for loads, equipment utilization, and mobility generation for both illuminated and eclipse periods with and/or without crew.

Power analysis of campaign phases

The analysis was performed for each change of state in the campaign, either element delivery, crew arrival, or change of location. The results are aggregated together in the following bar graphs that depict the

deployment and use of the systems on the lunar surface. Element delivery can be seen in increasing generation, energy storage, and element loads; crewed missions in particular have higher loads mainly due to the ascent stage keep-alive loads and to a small degree, to crew life support. The apparent decreases in the energy available during eclipse in the polar exploration graph are the result of increasing eclipse durations with unchanged power system capabilities.

Figure 3 to Figure 5 below show that for all missions in the three phases, a power closure has been achieved. This is the case when the available energy (green line) is always above the cumulated element loads. The element loads during illumination (left graph) are either with fully charged PSUs (red bars) or with PSU charging (blue bars). The loads during eclipse (right graph, blue bars) are smaller generally since there is no possibility for recharging and crew often do not stay through the eclipse period. In cases when the crew stay through eclipse the blue bars on the right graph should match the red bars on the left graph for that mission.

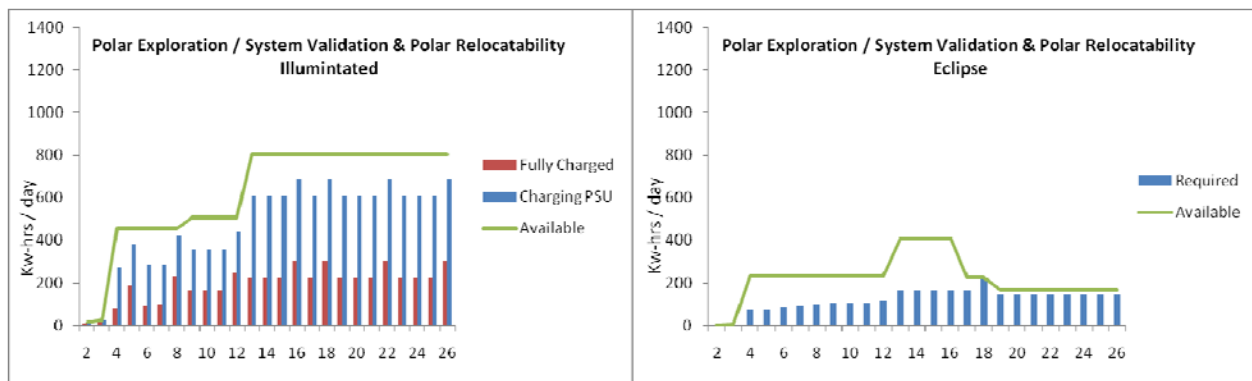


Figure 3: Power Analysis of Polar Exploration / System Validation & Polar Relocatability Phases

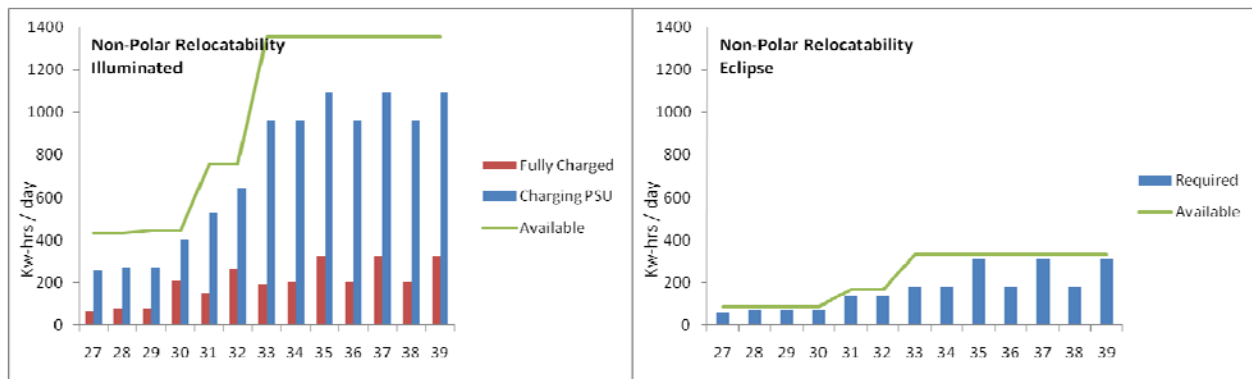


Figure 4: Non- Polar Relocatability Phase Power analysis

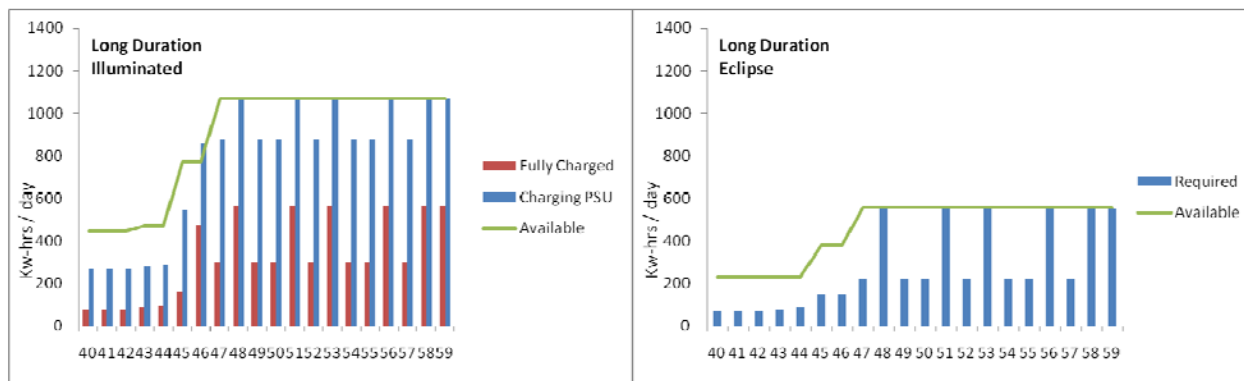


Figure 5: Long Duration Phase Power analysis

Campaign Power Trades – Nuclear Systems

Alternative options for power systems were assessed for feasibility and performance against the baseline GPoD campaign that includes regenerative fuel cells, batteries, and solar arrays in order to understand the implications of utilizing different technologies for power generation and energy storage.

One option chosen was to include Large Scale ASRG (Advanced Stirling Radioisotope Generator) units rather than Portable Utility Pallets to support extended SPR excursions. The L-ASRG generation of 2kW was enough to allow for significant increased capabilities over the solar and battery system of the Portable Utility Pallet. However, the size of the L-ASRG and the generally agreed upon challenges involved in developing systems that require large amounts of plutonium (multiple kgs) are significant drawbacks.

As another option a Mobile Fission Power System (M-FPS) concept was developed that produces 10 kW of power when deployed. It could be leveraged in the non-polar relocation phase to reduce the number of cargo landers by one, but the short duration of that phase does not take advantage of the life of a fission system.

The most promising trade that was performed was the assessment of a fission power system for the Long

Duration Phase, a Fixed Nuclear Power System (F-NPS). This option would allow the long duration phase to be located at any location on the lunar surface. Initially, this analysis was performed with the 10 kW output M-FPS system, however the final data sets for the element power loads were of a magnitude that requires closer to 20 kW output to support them. Fission systems offer favorable scaling to high power because the reactor heat source mass doesn't change much with increasing power. A mobile 10 kW system would weigh about 3300 kg, while a fixed 40 kW system would weigh about 5800 kg and provide considerable growth capacity for the long duration outpost.

Figure 6 shows an option for a non-polar Long Duration Phase with a 20 kW fission power system. The variability of the illuminated loads is less as there are fewer energy storage systems to recharge after eclipse.

More detailed information about fission surface power systems can be found in [8].

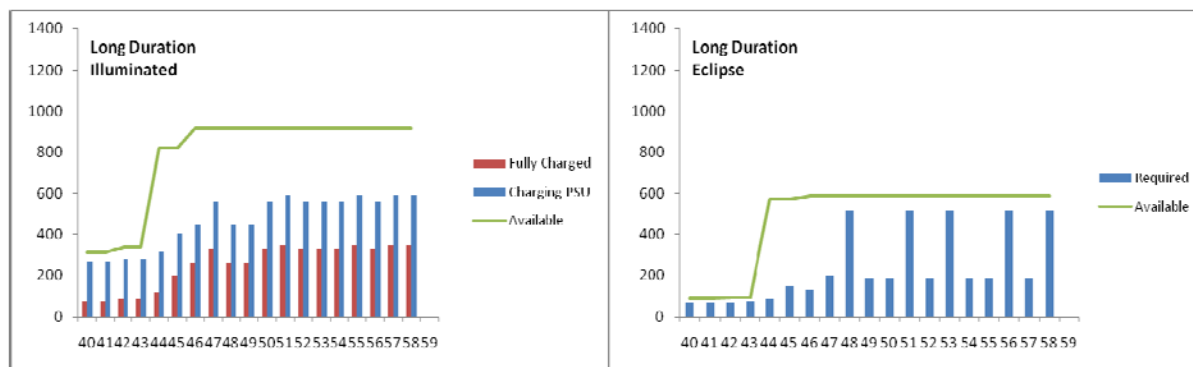


Figure 6: Non-Polar Long Duration phase trade with fission power system

Detailed analysis of Malapert Mountain mission

In the case of the Malapert Mountain mission, (mission 18 in the GPoD campaign), the daily average generation and load analysis as described above does not provide enough granularity to determine mission closure. Mission 18 in Figure 3 shows the eclipse required energy storage to be equal to the loads. The eclipse durations for Malapert Mountain change based on element location with respect to local topography. The concept of operations for this mission was iterated and refined between the Power Function Team and the Campaign Integration Team.

It leverages this idiosyncrasy and utilizes topography to provide additional illumination during critical periods of the mission.

Figure 7 shows the results of analysis of the final Malapert Mountain Mission concept of operations. The total system state of charge can be seen on the far left. The time periods during which the elements are in eclipse are illustrated by the system charge decreasing. Over periods where the elements are illuminated, the total system charge increases as the energy storage systems are replenished. For this mission, the PSU 2 graph in Figure 7 represents the state of charge of the system at the lander supporting the Ascent Stage.

It should be noted that contingency drive-back required power was not taken into account when developing the Malapert mission operations plan, therefore this only represents a notional mission and is not how the mission would actually be performed.

Defined PFT Elements

The following is a summary of the Power FT elements which meet these functional allocations and enable the GPoD architecture.

Standard Battery (Standard Battery 10kW-hr)

Description: A common, swappable 10 kW-hr battery.

Primary Functions: Energy Storage

Power and Support Unit - 2500 kW-hrs Fuel Cells with Solar Arrays (PSU-2500kW-hr)

Description

The PSU provides launch support structure for payloads up to 14 t. The PSU works with ATHLETE to transport payloads on lunar surface and can carry additional tanks for ECLSS. The PSU contains two sets of fuel cells and electrolyzer are triple redundant and run at 6 kW with the electrolyzer being approximately 0.625 efficient. The PSU's fuel cells can store up to 2500kW-hrs. The PSU provides 28 kW (beginning of life, BOL) of solar power generation.

Primary Functions

The PSU interfaces with ATHLETE for offloading and surface transport of pressure vessels, logistics payloads, robots, PUPs and communications systems. The PSU interfaces with SPRs and other surface elements to provide power and Environmental Control and Life Support System (ECLSS) consumables. The PSU interfaces with a lander to provide power and can be configured with additional equipment to scavenge and store water from the lander.

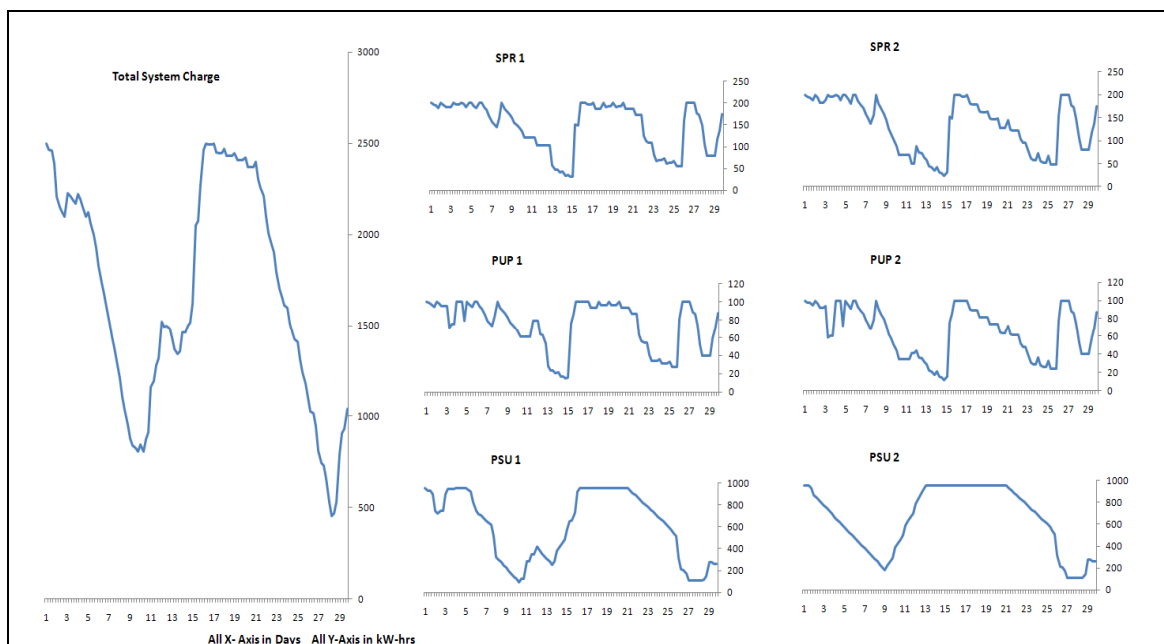


Figure 7: Detailed Malapert Mountain Crewed Mission Power Analysis results

The PSU provides power to SPRs during night traverses, and it carries and provides power for small rovers during convoy operations between locations.

Power and Support Unit - 950 kW-hrs Fuel Cells with Solar Arrays (PSU-950kW-hr)

Description

The PSU provides launch support structure for payloads up to 14 t. The set of fuel cells and electrolyzer are triple redundant and nominally run at 6 kW for discharge and re-charge. The system has been estimated to be approximately 0.625 efficient round trip. Reactants stored in the PSU allow the fuel cells to store up to 950kWhrs of energy. The PSU solar array also provides 14 kW (BOL) of solar power generation.

Primary Functions

The PSU interfaces with ATHLETE for offloading and surface transport of pressure vessels, logistics payloads, robots, PUPs and communications systems. The PSU interfaces with SPRs to provide power and ECLSS consumables. The PSU interfaces with a lander to provide power and can be configured with additional equipment to scavenge and store water from the lander. The PSU provides power to SPRs during night traverses. The PSU carries and provides power for small rovers during convoy operations between locations.

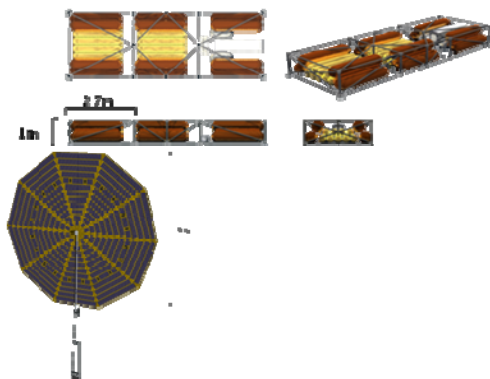


Figure 8: PSU Stand Alone Views and Solar Array

Portable Utility Pallet – Secondary Battery with Solar Arrays (PUP)

Description

The Portable Utility Pallet (PUP) is primarily designed to extend the duration of Small Pressurized Rover operations by providing power and consumables recharge and carrying additional logistics, communications equipment, and science payloads as necessary to facilitate operations. The PUP provides power generation (2.2 kW BOL) and logistics support to supplement pressurized rover operations to enable up to extended excursions away from the lander or habitat. The PUP is designed to be carried by a Small Pressurized Rover and to be emplaced on or picked up from the lunar surface without crew intervention.

Furthermore, the PUP can provide keep-alive power for landers. The PUP can scavenge water from the lander and supply that water to pressurized rovers, habitats, and other water storage tanks. The PUP can also receive O₂ from ISRU oxygen production plants for use with the pressurized rover and for transfer to other O₂ storage tanks.

Primary Functions

The PUPs primary functions are power generation, energy storage, water scavenging, water storage and transfer, oxygen storage and transfer.

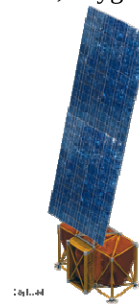


Figure 9: PUP Deployed

The following chapters present additional considerations related to the Power Function within the GPoD Architecture. They are at the same time of generic nature and therefore are valid for alternative lunar surface exploration scenarios.

V. INTERFACES AND STANDARDS

Common power interfaces and standards enable lunar surface missions. They are necessary if power sharing between elements is desired. Common international power standards are needed only if the overall impact is considered beneficial (scientific or mission enabling) to the international program. It should be clear that there is a hardware cost to implement common power standards. It is also recognized that partner elements may exist and missions may be conducted without the need for connecting power between partner elements.

The following examples are shown as possible beneficial situations when common power transfer standards may be utilized.

- International cooperation for joint lunar exploration. Multiple client rovers can connect to any other client rover to provide/receive power for extended exploration missions.
- Flexibility of charging locations. Rover elements can connect to any client power generating source for battery charging. Thus providing power at sites which may be some distance apart.
- Emergency situations. Any power element(s) can provide keep-alive power to crew, ascent stage, or

other critical infrastructure, thus reducing risk by providing redundant sources.

General approach to defining standards:

As much as possible, utilization of the electrical system standards already formulated under the international partner activity of the International Space Station should be incorporated. It provides a guide and a starting point for a lunar systems standard to be created and may be adapted as needed. The ISS international partners have agreed signed and put into practice the power source/user document. It also references related (non-NASA) space agency power standards indicating a correlation has been made assuring the standard meets individual expected levels of performance. The Power Quality documents SSP 30482/52051 Vols. I and II provide for specification of interfaces between the primary power system and elements, and also between the elements and components. Some of the major areas of definition include

- Source and load requirements
- Voltage level control
- Electrical noise limits
- Ripple limits
- Current inrush limits
- Impedance limits
- Fault protection
- System stability

Power transfer specifications for connectors and wiring exist within each space agency but no common standard. These specifications are important for the protection of wire, crew and of mobile assets (assuming wire deployed on surface). The same situation applies to wire material specifications for thermal, radiation, insulation and abrasion conditions. The possible use of wireless power transfer, by induction, microwave or laser transfer exists thus eliminating the need for a mechanical connection is possible but no current standard exists for these types of technologies.

VI. SUSTAINABILITY

Approach for a sustainable power system

As much as is known about the lunar environment from the Apollo missions, later robotic activity and probes, still much more is needed for a series of successful surface exploration missions like in the GPoD campaign. Dust accumulation, radiation levels and solar availability while in motion on the lunar surface all need to be quantified to a greater extent. The lunar precursor missions will provide early input to design decisions for later missions. Incorporating this knowledge into designs and adapting through a gradual

buildup of hardware as we learn, will result in a more sustainable power architecture.

One of the most important design characteristics of a sustainable system is the capability to modify, upgrade and adapt over a longer time period, e.g. a campaign phase, as both conditions are better defined and as needs change. There is usually added cost and mass associated with such a flexible system. This factor will have to be taken into account when trade analyses are performed to determine how adaptable the system should be. At this early stage of system definition, only a cursory look can be performed and broad statements made indicating the intention. For example, a characteristic of a sustainable system is one with minimal operation, low maintenance and repair needs. Although some features may be discussed such as modularity to allow component interchangeability, it is difficult to develop other important items such as the prediction of failure and repair levels without having defined the exact hardware to be used. Therefore, it should become a future requirement but does not show up as a designable feature at this stage.

Other top level sustainable attributes include: managing environmental hazards; protecting the crew; minimize failures; design in fail soft mode; reduce waste; limit contamination of the local environment and minimizing the impact or “footprint” left on planetary surfaces.

Some of the more specific features which may be incorporated into the power architecture are categorized and identified specifically below.

Improve performance and capability

In general, as performance increases, fewer resources are also needed per operation. The following discusses some of the power system factors which can contribute to sustainability.

- Longer lived batteries.
Batteries with longer lives will not only provide energy for a longer period, but will also provide the energy at a higher level over its lifetime.
- Reliable and longer lived primary fuel cells.
Similar to batteries, having fuel cells which can perform longer enables supported systems to maintain their capability longer or at a higher level.
- Utilize Fission Technology.
By the nature of their design, fission power systems considered for operation on the lunar surface have advantages over solar systems for long or intensive nighttime activity. Higher levels of daytime power are also available. Elimination of arrays, reduced energy storage needs along with reduced replacement units and the long life of components makes fission power a major benefit for sustainability.
- Continually assess current and new technologies as the mission changes.

The current lunar campaign is estimated to take place over twenty years and therefore offers many opportunities to inject new technologies that can respond to changed mission requirements.

- Planning for technology updates
Building flexibility into systems will allow (periodic) technology updates and system revisions during the mission at appropriate times is one way to assure the power system will be performing at the highest technology development level at all times.

Reduce risk to mission and crew

- Utilization of different types of power technologies within a system
It may provide redundancy but also improves overall system availability and reliability thereby reducing mission and crew risk.
- Maximizing the use of self diagnostics
It relieves the crew of the possibility of injecting a fault or error into the system during standard operations and allows faster corrections.
- Common battery design.
Having a common battery type which is able to be exchanged easily between elements will prove valuable in the event of failure, particularly of a crewed mobile system.

Reduce cost for performing missions and operations

- Reliable and longer lived primary and regenerative fuel cells.
Reliable and longer lived fuel cells are essential for advanced energy storage, particularly for lunar night survival, and will reduce the need for replacements and the amount of disposed equipment on the lunar surface.
- Common battery for interchange between elements.
Having a common battery used by many elements may reduce the amount of development costs.
- Create common international power transmission standard.
A common power transmission standard will reduce costs by allowing power to be shared between elements, preferably using a central energy storage system.

Reduce dependence on Earth supplied logistics and infrastructure

- Longer lived batteries to reduce replacement and disposal on the lunar surface.
- Reliable and longer lived primary fuel cells.
Fuel cells which have a lower failure rate and last longer will reduce the number of replacements and the disposal on the lunar surface.
- Utilize Fission Technology.

Current fission systems intended for operation on the lunar surface have an intended lifetime of eight to ten years without maintenance and little ground support.

VII. INNOVATION

Once surface stays reach 28 days (in non-polar locations) the total energy storage required is at the maximum. In the GPoD campaign, a minimally satisfactory power supply could be achieved through a refined concept of mobility operations that involves locations of longer illumination, which are being used for recharging. A simple solution, but at much higher costs and delay of subsequent missions, would have been to bring more energy storage units to the lunar surface with additional cargo landers. An alternative way to providing improved energy storage performance without additional cargo delivery are innovative technologies. There are a number of factors which need to be evaluated when considering low level technology development. The cost for development must be traded against the launch costs for a true evaluation. The technology advancement must also be achievable within budget and ready for launch date.

Listed below are some of the high risk / high payoff power technologies which were not considered for the baseline missions.

Advanced batteries.

In practice, battery chemistries typically plateau below 40% of their theoretical specific energy, which is 240W-hr/kg for Lithium-Ion (Li-I) batteries. For Lithium Sulphur (Li-S) batteries this value is 1020 W-hr/kg, thereby making the technology of great interest. Li-S batteries have been in the development stage for approximately 15 years waiting for other technologies to be developed to solve some of the tough design issues. However, some recent investments and breakthroughs pressured by great commercial interest in the automotive industry may also be beneficial for space exploration.

Flywheels for energy storage

The advantages of flywheels include long life as compared to batteries and fuel cells and high discharge capabilities to meet user needs.

A future flywheel design could include using high strength fibers made of glass with imbedded carbon nanotube whiskers to fabricate the rotor, and a superconducting magnetic bearing suspension. This would enable high specific energy due to increased rotor speed and low parasitic loss due to the superconducting suspension system, and low lunar operating temperature. This would result in improved performance levels in the order of specific energy of

800Whr/kg, low parasitic loss, and high turn-around efficiency (>93%).



Figure 10: Notional Flywheel

A phased series of hardware developments could demonstrate the gradual technology improvements. The first phase would focus on a superconducting magnetic bearing suspension system at an operational speed of 250krpm with an integral cryogenic cooling system. The second phase could develop and demonstrate an integrated flywheel system with superconducting suspension system from phase 1, a rotor system utilizing T1000 fibers, and tests to demonstrate life, parasitic loss and efficiency. Phase 3 could develop the rotor system, using the advanced glass fibers, and demonstrate the ultimate goal of an 800Whr/kg specific energy lunar flywheel energy storage system.

Advanced Power Management and Distribution (PMAD) technology – Smart Grid

Autonomous control ring bus architecture has been identified as critical for deployment of surface power systems as well as power systems for exploration vehicles. In addition to being highly reliable, these systems can provide robust power availability along with rapid fault detection and reconfiguration capabilities. Studies have been performed and test beds have been developed which utilized ring bus technology and associated controls to study and demonstrate utility type power systems for the exploration applications. However, additional work needs to be done to support their long term operation with minimal operator interaction, detect component failures using prognostics and provide optimal load scheduling under constrained resources. To achieve those latter goals, additional technology must be developed in the areas of automation technologies, embedded decision support tools, component fault diagnostics, power system modeling and simulation, intelligent controls for power components, and wireless sensors.

Wireless power transfer (Power Beaming)

Power beaming for surface-to-surface energy transfer could be worthwhile for local operations up to the limitations of the curvature of the moon (~15km).

Beaming power from lunar orbit to the surface is technologically possible but comes with serious technology challenges and high cost as previous studies have indicated.

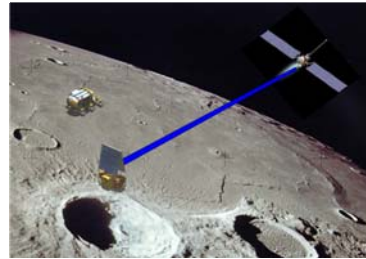


Figure 11: Illustration of wireless power transfer

Two redundant orbiting spacecraft to give reasonable surface coverage have been estimated to cost \$900M plus the cost for continuous ground control. Surface receivers and converters would be additional cost. Microwave transmission requires a large diameter receiver, not easily made mobile. Laser transmission requires highly accurate target location and tracking as well as a large moveable receiver. Yet, there is no existing space system to confirm the technology. Therefore, an extensive amount of development time and investment will be needed to bring this technology to a demonstration stage.

VIII. CRITICAL FUNCTIONS AND TECHNOLOGIES

Critical Functions

Two power sub-functions have been identified as critical for the implementation of the GPOD campaign:

- Power generation
- Energy storage

Power and energy provision are enabling the operations of all surface elements during lunar day, and operations or survival through eclipse periods.

Critical Technologies

In an initial analysis the following technologies and related aspects have been identified as critical for the power elements:

- Power elements (PV with fuel cells)
 - energy density
 - storage technology
 - reliability/safety
 - space qualification
- ASRG, fission system
 - system technology development required
 - Pu availability (ASRG)
 - reliability/safety
 - space qualification

Regarding the portable power system (PV with batteries) an increase of energy density would be beneficial, because it would increase capabilities for surface ops, like independent operations of small pressurized rovers.

IX. CONCLUSION

On the basis of the ISECG lunar reference campaign the Power Function Team has developed a consolidated understanding of the power function in lunar mission scenarios. Emerging technologies have been evaluated and a selection of conceptual elements was defined, which provided the basis for the detailed campaign analysis spanning four distinct phases over 20 years. An iterative analysis process with close cooperation with other Teams on campaign, element and function level made it possible to develop tailored power and energy solutions for the intended campaign. The process resulted in a configuration of power elements which will support both robotic and human exploration at various sites, of various durations and with high mobility demands.

The Malapert relocation scenario needed to be adapted to illumination conditions due to limited power and energy storage capacities. The scenario could have been conducted in a much more flexible and safer way, if higher energy storage capacity was available. This has demonstrated the significance of sufficient power and energy provision for robotic and human operations on the lunar surface. Given the drawback of high transportation costs for simply bringing more power mass to the surface, the study underlined the importance to develop advanced and innovative technologies for future mission scenarios.

The study work of the Power Function Team has demonstrated the importance and usefulness of early coordination and consolidation between different agencies in planning future international mission scenarios. Multilateral assessment of related technology requirements and technology readiness is indispensable for preparing long-term cooperation in space exploration (for more details see also [9]).

X. REFERENCES

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