Lunar Fission Surface Power System Design and Implementation Concept

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Abstract. At the request of NASA's Exploration Systems Mission Directorate (ESMD) in May of 2005, a team was assembled within the Prometheus Project to investigate lunar surface nuclear power architectures and provide design and implementation concept inputs to NASA's Exploration Systems Architecture 60-day Study (ESAS) team. System engineering tasks were undertaken to investigate the design and implementation of a Fission Surface Power System (FSPS) that could be launched as early as 2019 as part of a possible initial Lunar Base architecture. As a result of this activity, the Prometheus team evaluated a number of design and implementation concepts as well as a significant number of trades associated with lunar surface power, all culminating in a recommended approach. This paper presents the results of that study, including a recommended FSPS design and implementation concept.

Keywords: Prometheus Project, Fission Power, Lunar Base.
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INTRODUCTION

The goal of sustained human presence on the surface of the moon and other solar system destinations will require the development of reliable high performance surface power systems well beyond the capabilities of any fielded thus far. One potential solution is the application of the technologies and infrastructure developed in the Prometheus Project to a configuration that could support a lunar base architecture. In May of 2005 a team was assembled within Prometheus at the behest of NASA’s Exploration Systems Architecture Study (ESAS) to investigate the design and implementation of a Fission Surface Power System (FSPS) that could be included as part of an initial Lunar Base architecture. Upon completion of work for the ESAS the Prometheus team continued its study to complete a concept for an FSPS that could be integrated into a variety of potential lunar exploration architectures. This paper describes the results of this work from inception through August of 2005.

Trades

The development and implementation of nuclear fission power systems on the lunar surface brings with it many challenges that differ from those in a deep space-based application. The presence of gravity, dust, and surrounding regolith all combine to complicate the design, especially when placed in the context of a crewed lunar base architecture. Constraints and initial assumptions included:

- 2019 flight system availability
- 10 year lifetime
- Maximum lander capability of 15 metric tons down-mass (payload to the surface).
- 50 kWe FSPS total power available to the user

While early in the study these constraints were subject to frequent revision, the above list was established to provide a baseline for the study activities to represent reasonable basic design features for an initial Lunar Base FSPS.

In the course of developing an FSPS design and implementation concept, the team investigated a wide variety of options. Major architecture trades addressed are shown in Table 1. The implementation of an overall lunar base architecture intimately affects the outcome of many of these trades. It may not be possible to finalize an optimum point design for the FSPS independent of final base and exploration architecture decisions.

TABLE 1. FSPS Trades.

Trades	Implementation	Advantages	Disadvantages
Power Plant Placement	On lander	Low risk emplacement	Inhibits use of in-situ shielding Limits lander options
	On surface	Facilitates regolith shielding options	Some separation options are massive or difficult
Power Plant Mobility	Mobile Power Plant	Minimizes constraints on architecture manifesting	Implementation is massive with dubious practicality
	Stationary Power Plant	Lower mass Lower risk	Requires precision landing and site information
Shielding	Manufactured Shield Only	Low risk implementation Minimizes constraints on architecture	Requires massive manufactured shield
	Use Natural Topography without Regolith Reconfiguration	Lowers delivered mass Essentially eliminates dose at base	Limits site selection Substantial manufactured shield still needed
	Regolith shielding	Lowest delivered mass Enables maximum shielding	Requires regolith moving equipment Requires time and risk to emplace
FSPS Phasing	1st Base landing	Power is available for subsequent landings	Uncertainty in landing site characteristics Requires fully autonomous activation
	Landing after minimal Base infrastructure in place	Base assets available for FSPS deployment	Requires base to be energy-sufficient prior to FSPS landing
Crew Assistance	None	Minimizes constraints on architecture	Complicates deployments Increases risk
	Yes	Simplifies deployments Reduces risk	Requires human landing at site prior to commissioning
Radiator Configuration	Horizontal	None identified	Complex deployment Higher mass
	Vertical	Simplest deployment Lowest mass	May be more difficult to deploy at high power levels

Findings

During the course of the study the Team concluded a series of "findings" that help to narrow the trade space and guide the optimization of an FSPS design.

1. Providing mobility to the reactor portion of the FSPS is a mass intensive, operationally risky endeavor due to the reactor's mass and importance to the lunar base architecture. The preferred option in any implementation is to land the reactor directly at its emplacement site, relocating only those electronics elements that need to be located at the lunar base site.

2. Other than mobility, risk is not inherently a discriminator in most implementation options. Most options have at least one low-risk implementation, albeit with additional consequences.

3. Human presence prior to operation during deployment and In-Situ Resource Utilization (ISRU) greatly enhance the practicality of implementing an FSPS. The use of local regolith resources to provide reactor shielding can significantly minimize landed mass when compared to all-manufactured shielding. Likewise, risk to crew from exposure to radiation from the reactor during operation can be minimized by keeping

radiation exclusion zones around the power plant very small through substantial shielding. This can only be accomplished through the use of local materials. Further, the participation of humans in the construction of regolith-based shielding greatly simplifies the shield construction process, increasing robustness and decreasing risk.

4. Related to human presence, the FSPS design and implementation would benefit from pre-emplacement missions to the lunar base site. These missions could allow early "site surveys", including detailed evaluation of local topography, geology and regolith composition. Pre-emplacement establishment of photovoltaic power and minimal ISRU and transportation assets can also be enabling for the participation of humans in the establishment of the FSPS.

5. Configurations developed in the study are compatible with current Lunar Surface Access Module (LSAM) lander concepts. The FSPS team worked with personnel at Langley Research Center to ensure packaging and deployment compatibility with LSAM concepts being considered by ESAS. Two basic orientations are being considered for the LSAM; vertical and horizontal. It was found that the FSPS concept can be successfully integrated with either concept, however the horizontal lander configuration greatly simplifies FSPS egress and emplacement on the lunar surface in a manner that is compatible with the practical use of regolith shielding.

6. Decommissioning through in-place abandonment appears to be a feasible option, especially in the case of a regolith-shielded FSPS. Radiation dose levels fall off very quickly after reactor shutdown, and in the regolith shielded configuration the post-shutdown radiation exclusion zones would have minimal impact on lunar base operations.

These major findings and the other trades performed during the study have resulted in the identification of potential implementation options as well as a "recommended" concept for an optimal implementation of an FSPS in a lunar base architecture

CONCEPT DESCRIPTION

The Fission Surface Power System (FSPS) is comprised of three major components, based on location (Figure 1). They are the Power Plant, Local Electronics (LE), and the Station Control Electronics (SCE).

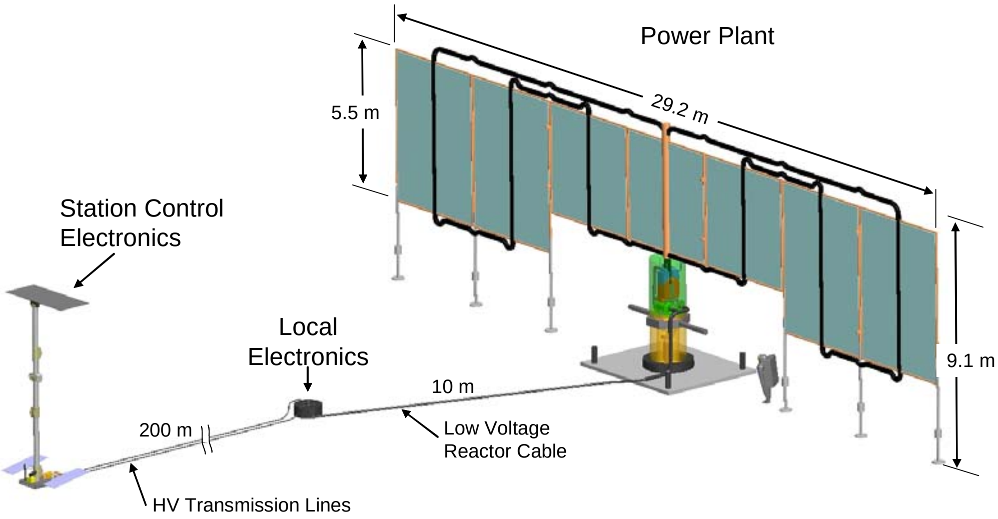


FIGURE 1. FSPS Components – Pre-operational (Regolith Shield Not Shown For Clarity).

The Power Plant is that portion of the FSPS that comprises the Reactor, Shield, Power Conversion, and Heat Rejection Segments. Also included are the structural elements necessary to support the Power Plant through launch, landing, deployment and operations.

The Local Electronics (LE) consists of the reactor controller electronics, signal multiplexer unit and transmission line voltage transformers. The LE is located 10 m from the Power Plant, a distance sufficient to reduce the total dose to Local Electronics from the reactor to less than 100 krad over the planned 10 year operating life of the FSPS. The electronics are connected to the Power Plant by a single cable incorporating redundant power and signal lines.

The bulk of the FSPS electronic subsystems are located at the site of the Lunar Base in an element designated the Station Control Electronics (SCE). The SCE is packaged as a self-contained unit and incorporates the C&DH, Telecom, and Power Conditioning and Distribution electronics which provide the interface with the base power distribution architecture. Also included in the SCE are deployable appendages that support radiators for the PCAD electronics, and the Parasitic Load Radiator, which is used to maintain a constant load on the Power Plant. The Parasitic Load Radiator is elevated on a mast in order to prevent its high temperature radiating elements from presenting a hazard to Lunar Base personnel and equipment. The SCE is connected to the Local Electronics by dual redundant high voltage (7000 Vac) transmission lines.

Power Plant

A representative Gas-Cooled Reactor concept using Brayton power conversion was adopted for use in the study in the absence of participation by the Naval Reactors Prime Contract Team (NRPCT), whose involvement in work on surface reactors for extraterrestrial applications had not yet been authorized. The concept is consistent with the reactor coolant and power conversion type chosen by the NRPCT for the Prometheus Project NEP application, which was selected in part for extensibility to surface power applications. The specific reactor design used for the study is based on an earlier concept developed by Sandia National Laboratory (Wright and Lipinski, 2003). This reactor, shown in Figure 2, has a relatively favorable geometry for minimization of shield mass associated with the circumferential and axial shielding required in surface systems. The reactor provides an 1144 K turbine inlet temperature to enable high conversion efficiency but is able to maintain a superalloy outer boundary, minimizing concerns of material interactions with the oxidizing lunar regolith. While the gas-cooled reactor was chosen for the study it should be noted that the reactor type, while a very important design consideration, was not found to be a critical driver in the FSPS architecture in this study. Other reactor types designed for operation in this temperature range could be incorporated with minimal impact on the overall configuration.

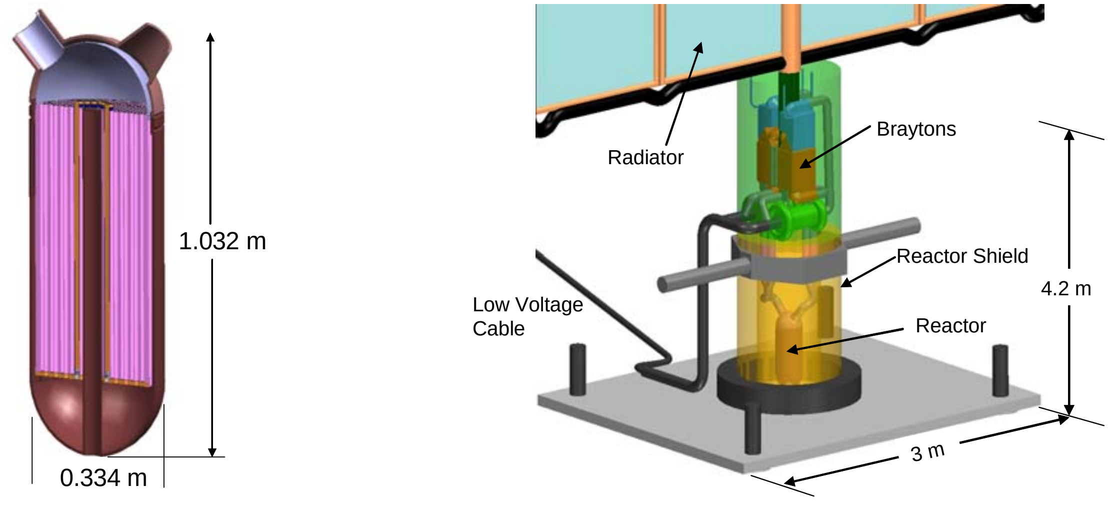


FIGURE 2. Conceptual Reactor and Power Plant Configuration.

The Power Plant configuration is also shown in Figure 2, which illustrates the packaging of the reactor and Brayton power conversion units. This figure illustrates the vertical orientation of the reactor vessel within its manufactured shield. Gas lines run from the reactor vessel in a serpentine fashion to dual, redundant Brayton Turboalternator-Compressor (TAC) units. Each of the two Brayton units is rated at 55 kWe output. Only one Brayton operates at a time, the second serves as a redundant spare. The Braytons reject heat through a gas cooler to the heat rejection system radiators.

The Heat Rejection Segment (HRS) contains the main radiator panels, secondary fluid lines, pumps, and the radiator support jacks. These radiators, shown deployed in Figure 3, employ a pumped water secondary cooling loop to distribute heat to water heat pipes embedded in Carbon-Carbon radiator panels. Secondary loop piping is provided with foam micrometeoroid protection along its entire length. The radiator area provided for the 50 kWe FSPS is ~230 m^2, sized to support continuous full power operation at maximum insolation and IR backload at any latitude. It should be noted that radiator area is a driving consideration in the FSPS design. The combination of the gas cooled Brayton power system operating at high temperature and a vertical radiator orientation enables a relatively compact HRS design that is compatible with projected lander and payload fairing envelopes in its stowed configuration. The use of lower temperature power system designs, while potentially attractive from a reactor development standpoint, generally results in significantly larger radiator area requirements which serve to greatly complicate issues associated with deployment and packaging.

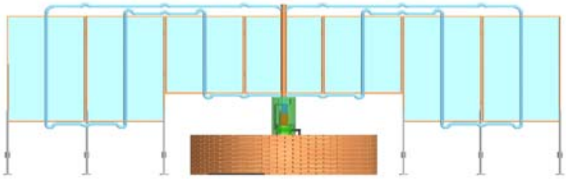


FIGURE 3. Radiators Deployed (Power Plant Shown With Regolith Shield In Place).

Local Electronics

The items in this section include the Reactor Cable and Reel as well as the Local Electronics. These items are attached to the Base Plate in the launch and landing configurations and are deployed by the astronauts when they arrive. The Reactor Cable is attached to the output of the Brayton turbo alternators on one end and the Local Electronics at the other. It is deployed by having it unreel from a spool. The astronauts would move it from the Base Plate to its final location, approximately 10 m from the reactor.

Station Control Electronics

The Station Control Electronics (SCE) contains the PCAD subsystem, High Voltage Distribution, C&DH Subsystem, Telecom Subsystem, Two Boxes of Cable, Trencher, Shunt Radiator, and Electronics Radiator. All these components are placed on a pallet near one end of the base plate in the landed configuration. It is intended for the astronauts to remove the pallet before the Power System begins the standup operation. The pallet is relocated to the Base area for use. Baseline is to have the SCE delivered with the FSPS, but its relatively small size and mass would allow it to be carried and pre-emplaced on an earlier landing if desired. Figure 4 shows the SCE deployed with all the components labeled.

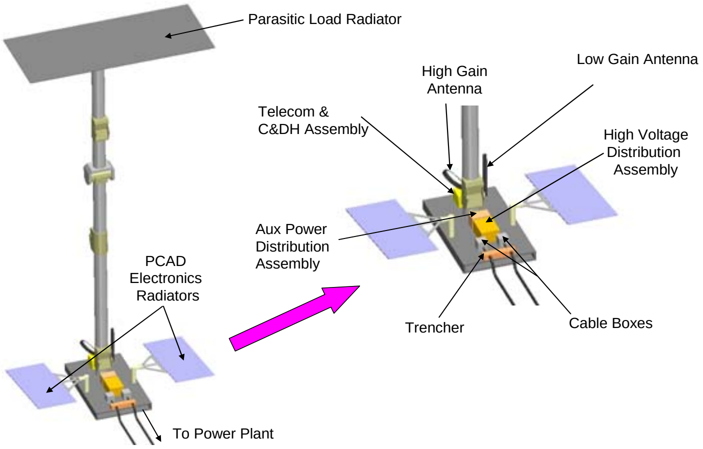


FIGURE 4. SCE Components.

Mass Summary

The Master Equipment List (MEL) for the FSPS is shown in Table 2. Note that masses are shown with values for current best estimate (CBE), with 20% contingency (1.2 x CBE), and with the standard JPL mass margin of 30%, which equates to CBE/0.7.

TABLE 2. FSPS Mass Summary.

Element Mass	CBE (kg)	1.2 x CBE (kg)	CBE/0.7 (kg)
Power Plant Elements			
Reactor	1060	1272	1514
Reactor Shield	2402	2882	3431
Power Conversion	442	530	631
Heat Rejection	722	866	1031
Mechanical/Thermal/EIS	833	1000	1190
Power Plant Total	5459	6551	7799
Other FSPS Elements			
SCE (w/o Transmission Line)	216	259	308
LE	122	146	174
HV Cable and Transformers	164	197	234
Cable Deployment	70	84	100
Bag Filler and Bags	450	540	643
FSPS Total	6481	7777	9258

SHIELDING ISSUES

Shielding is a central concern for any reactor design, particularly those which must operate in proximity to humans. It is critical that reactor shielding be capable of attenuating the radiation dose to an appropriate level for the crewed lunar base. While definitive requirements have not been developed for all environmental components of radiation exposure to base inhabitants, a maximum allowable dose rate contribution from the FSPS at the lunar base has been assumed for this study to be 5 rem/yr. Shielding concepts developed in the course of the study have been designed to assure a reactor-generated dose rate of less than 5 rem/yr at the lunar base, and results presented herein are based on this assumption.

The salient feature of the recommended FSPS design is the use of In-Situ Resource Utilization (ISRU) assets to support construction of the power plant radiation shield. In most concepts investigated in the course of the studies, the implementation of radiation shielding was found to be, by far, the largest mass contributor to the power system. By using a minimal circumferential shield and maintaining a full top shield the total system mass can be vastly reduced while ensuring a tolerable lifetime radiation dose to components of the Brayton power conversion system and reactor control drives. Lunar regolith gathered locally from the area surrounding the reactor emplacement site may be used to provide the additional circumferential radiation protection needed to lower radiation dose levels from the operating reactor to less than 5 rem/year at the base. The thickness of the regolith shield determines at what distance this dose rate can be achieved, but given the ready availability of shielding material in this implementation and relative ease of shield construction, a distance of 200 m from the FSPS was chosen as a baseline for the study. This distance is sufficiently small that it should not significantly impede exploration activities, and entails a reasonable thickness of regolith shielding that does not impose overly strenuous work-hour requirements on the crew. One of the major features of the use of regolith for shielding is that the shielding design is no longer driven only by providing a tolerable dose rate at the lunar base, but can also consider minimizing impact of the FSPS on base exploration and future plans for power plant augmentation or replacement.

The reference design for the FSPS uses 3.5 m effective thickness of regolith shield to attenuate the reactor dose rate to 5 rem/year at 200 m distance from the reactor, as seen in Figure 5. This significantly eases implementation relative to options that only use manufactured shielding. Use of manufactured shielding (without regolith augmentation) results in a requirement for the reactor to be placed 2-3 km away from the lunar base to achieve a comparable dose rate with acceptable mass. The regolith shield is built using “sandbags” filled with lunar regolith gathered from the local area surrounding the FSPS emplacement site. The sandbag shield 2 m high and 3.5 m thick around the reactor can achieve the dose rates shown in the figure.

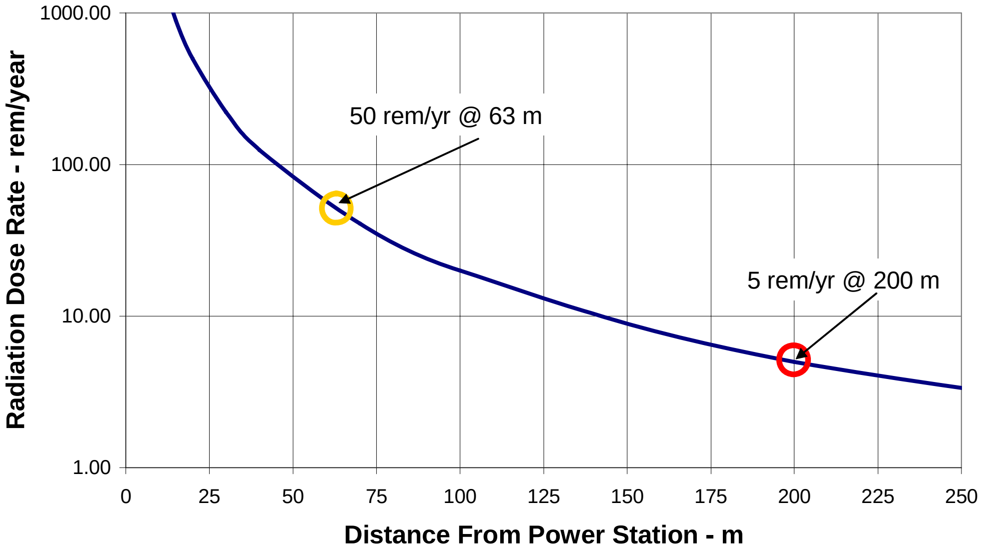


FIGURE 5. Radiation Dose during Operation Using 3.5 m (Effective Thickness) Regolith Shield.

Due to the radiation field of the FSPS, manned operations would be restricted by the size and geometry of the "exclusion zone", or region surrounding the reactor where the radiation dose is greater than 5 rem/yr. Areas between the 5 rem/year boundary and the 50 rem/year exclusion zone could be entered for short periods of time such as traverses which pass through the area. It is desirable to keep the exclusion zone as small as possible in order to limit restrictions on lunar exploration. The regolith shielding implementation recommended for the FSPS design dramatically reduces this zone when compared to all-manufactured shielding designs.

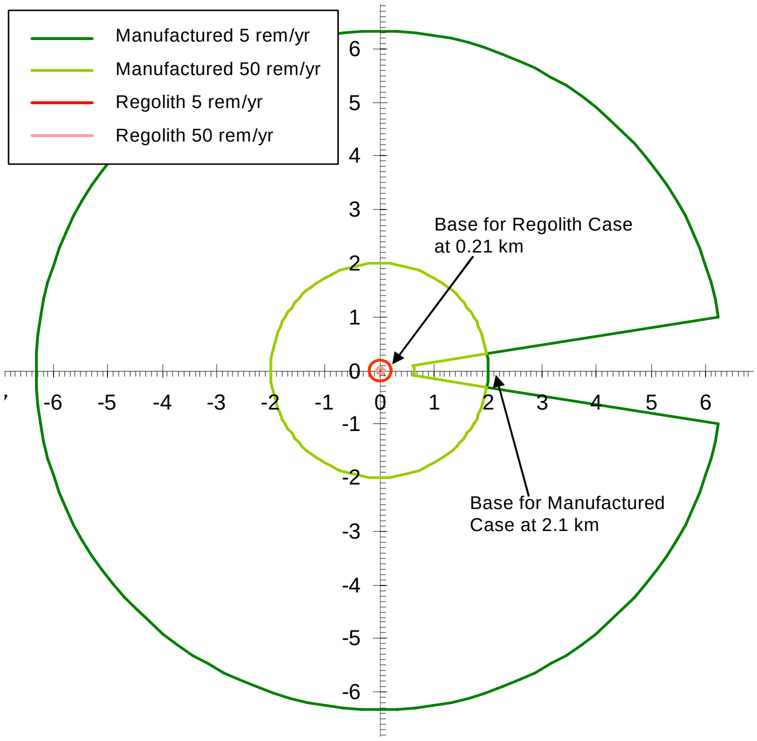


FIGURE 6. Radiation Dose Contours During Operation.

During operation of the reactor, the radiation field limits the astronaut's access to the surrounding area. Figure 6 shows the affected area resulting from the regolith shielding implementation with a 3.5 m effective thickness regolith shield located 200 m from the lunar base habitat compared to the all-manufactured shield implementation placed 2000 m from the habitat.

In order to reduce the mass of the manufactured shield implementation to acceptable levels it was necessary to design a tailored shield which exhibits preferential shielding in the direction of the habitat. This shield design, developed and evaluated earlier in the study, provides a 5 rem/yr dose rate at a habitat separation distance of 2 km in the direction of the habitat, and 50 rem/yr at 2 km in all other directions. It is clear that the regolith shielding implementation results in dramatically less restriction on overall lunar base operations. With the all-manufactured shield case the exclusion zone covers 11.5 km2 compared to the recommended FSPS's 0.0125 km2. The recommended FSPS opens up over 920 times more area for operations than the all-manufactured shield implementation. The notched shape for the all-manufactured shield case minimizes the mass needed to shield down to the 5 rem/year level at the base, but would have a significant impact on operations around the FSPS due to limited access corridor produced by the notch. Traverses past the FSPS would have to follow a path around the high radiation portion of the zone adding significant time to exploration trips. Conversely the small radiation exclusion zone for the regolith shielded case makes bypassing its footprint a relatively simple task for astronauts.

REGOLITH SHIELD IMPLEMENTATION

The implementation recommended by the study team would utilize telerobotically controlled equipment that is pre-emplaced for In-Situ Resource Utilization (ISRU). These assets are used to harvest loose surface regolith and collect it in bags so that it can be easily transported and positioned as shielding material. The filled and sealed regolith bags would be stockpiled at the site where shielding is needed, all remotely controlled by operators on Earth. The final emplacement of the regolith bags to form the desired shield would be performed by astronauts who would arrive at a later time.

This implementation is considered to be a minimum risk approach for ISRU shielding, since it can largely be performed by lightweight equipment which is teleoperated from Earth. It is also an approach which is easily testable on Earth prior to deployment on the Moon. Robust radiation shielding (i.e. thick shielding) can be constructed since the available ISRU resources are effectively limitless. The necessary infrastructure could be put in place with a relatively minimal landed mass.

The collection and filling of the regolith bags could be performed on a timescale of weeks and does not require the presence of astronauts on the Moon. The final emplacement of the bags to form the shield is estimated to entail only a moderate construction time, depending on level of robotic assistance that is available to the astronauts.

In order to establish an acceptable location for the FSPS, and to reduce risk, it is recommended that the FSPS landing be preceded by a site evaluation mission. This would allow for topographic mapping and regolith characterization. Photovoltaic (PV) and ISRU infrastructure elements could be pre-emplaced by the site evaluation mission, or could be delivered with the FSPS landing mission, depending on the down-mass availability on these missions.

Figure 7 depicts a baseline scenario for delivery, deployment, and commissioning of the FSPS. This approach has been designed to minimize the work time required of the astronauts and to maximize the efficiency of their time.

The regolith shielding concept has been quantified by estimates of the driving parameters and appears to be a feasible approach. This quantification is preliminary, but believed reasonably conservative. The regolith bag concept for ISRU is robust to changes in estimates of the key parameters and there are many feasible fallback approaches available. The details of this implementation may change after further study, and the design margins need to be reviewed and assessed. The option suggested here is only representative of a larger trade space.

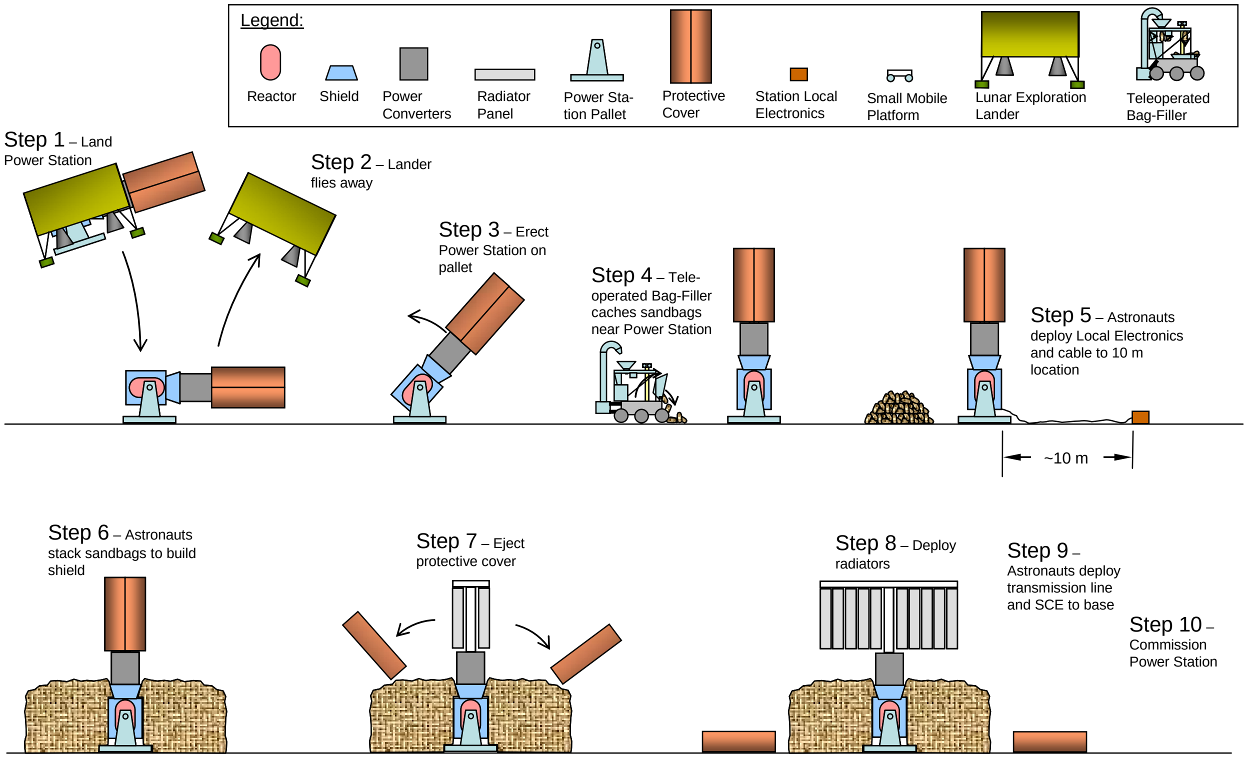
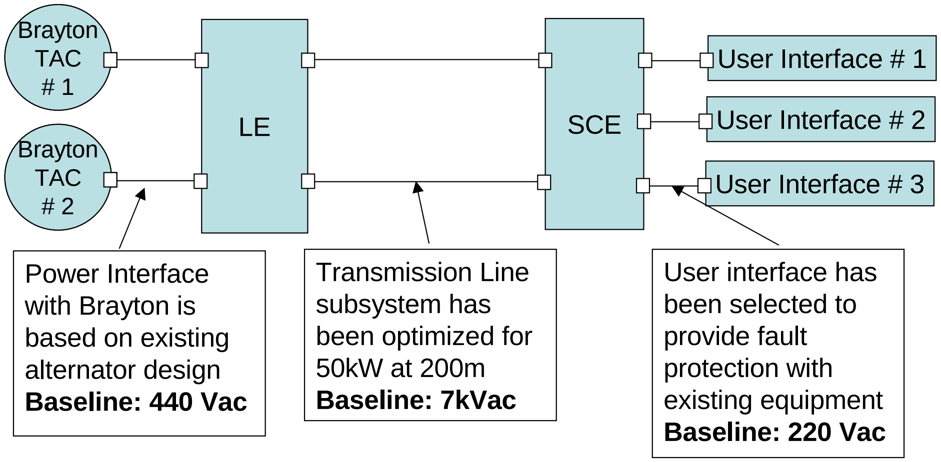


FIGURE 7. Establishment Scenario.

TRANSMISSION LINE AND POWER CONDITIONING AND DISTRIBUTION SUBSYSTEM (PCAD) SUBSYSTEM

The key trade drivers in the Transmission Line and PCAD subsystem architecture are the distance to the Lunar Base, power level, fault tolerance and deployment. The recommended architecture was developed to reduce mass, enhance deployability and enable future trades for optimization as the requirements mature. A Power Transfer Block Diagram of the recommended architecture is shown in Figure 8.



Power Interface with Brayton is based on existing alternator design **Baseline: 440 Vac**

Transmission Line subsystem has been optimized for 50kW at 200m **Baseline: 7kVac**

User interface has been selected to provide fault protection with existing equipment **Baseline: 220 Vac**

FIGURE 8. Power Transfer Block Diagram.

The Power Transfer Block Diagram displays how the power delivery function was broken up into segments that can be optimized based on the requirements. The Lunar Surface Power Plant requires two closed Brayton engines (one operating, one in standby) to be single fault tolerant. A Local Electronics (LE) function was added to separate the output of the Brayton alternators from the transmission line function. The separation of the alternator voltage from the transmission line voltage enables the transmission line voltage level to be optimized for power and distance, and the alternator voltage can be optimized for performance. The LE also provides isolated fault containment regions for the Brayton alternators and the transmission line function. The alternator voltage was selected at 440Vac based on the information from Prometheus and the model of the alternator that was used on Prometheus. The transmission line function is block redundant in order to accommodate the single fault tolerant design of the Brayton alternators, and allow for delivery of power from either alternator. The LE and Station Control Electronics (SCE) provide cross strapping of the two transmission lines. The transmission line fault containment region includes the step up and step down transformers.

With the fault containment and redundancy approach defined, the next trade was to determine the optimum transmission line voltage for the delivery of power to the base habitat. The key drivers in the transmission line voltage trade are the power level, line length and deployment approach. As depicted in Figure 9, the transmission line length quickly becomes a driver in the FSPS architecture as the distance increases beyond a few hundred meters even at relatively high voltages. This non-linearity in growth of transmission line mass reflects a significant growth in cable diameter to support the greater transmission distances with acceptable losses. The growth in cable diameter itself represents a major issue in terms of deployment, whether autonomous or crew-assisted, as cable mass and minimum bend radius complicate transportation and line-laying operations.

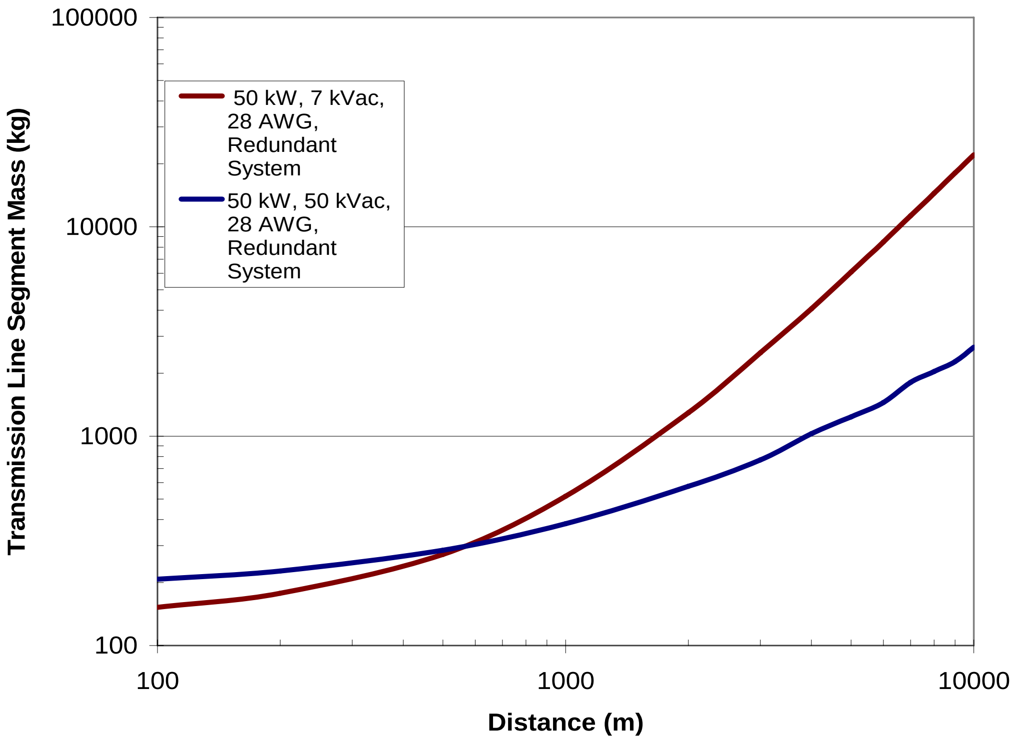


FIGURE 9. Transmission Line Mass.

Previous trades determined that the power level and the distance are a result of the user needs and regolith shielding. It was assumed that 2.5% power losses were acceptable in the transmission line based on thermal and overall power delivery capability. To enhance deployability and determine the optimum voltage, the lowest allowable gauge wire was selected (28 AWG) and multiple conductors were added for current density based on voltage. Insulation thickness was varied as a function of voltage to determine the area and volume of the cable. The results of this trade are shown in Figure 10.

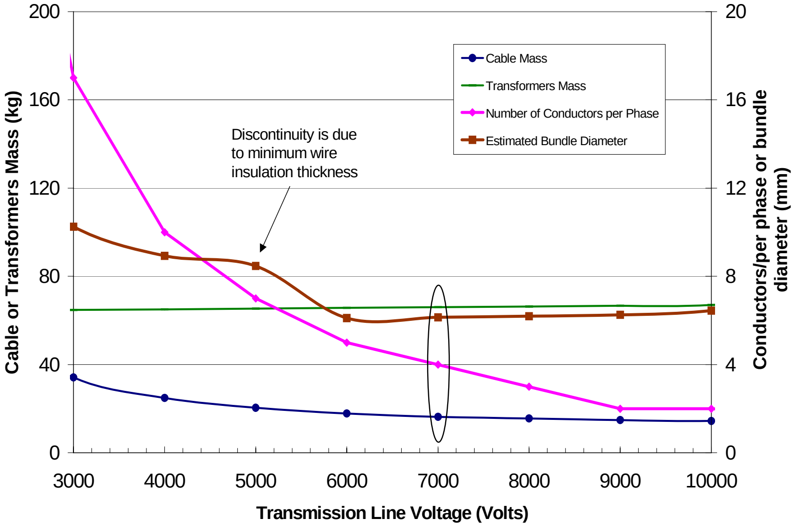


FIGURE 10. Transmission Line Voltage Trade (50 kW, 2.5% Loss, 200m, 28 AWG, Single Line).

The figure shows the mass of the cable including signal lines, the mass of the transformers, the number of 28 AWG conductors required per phase and the diameter of the wire bundle. The transformer mass and cable mass are relatively insensitive to voltages greater than 3000 volts. The number of conductors and insulation thickness determines the bundle diameter, which drives the deployment function. There is a manufacturing constraint for minimum thickness of about 5 mils of Kapton, which is shown in the figure as a discontinuity around 5000 volts. A 7000-volt transmission line with four conductors per phase was selected as the recommended approach based on mass and bundle diameter.

CONCLUSIONS

The Prometheus FSPS study provided an in-depth assessment of the systems engineering challenges associated with practical incorporation of fission power into a sustained lunar base architecture. Major conclusions reached in the study include the realization that shielding design for a long-life Lunar Base is driven by radiation dose rate constraints on lunar exploration accessibility, rather than simply by dose rate constraints at the base. Following from this, it was found that the practical achievement of satisfactory radiation dose rate constraints requires the employment of regolith for shielding. The most practical means of using regolith would necessitate some pre-emplaced infrastructure, as well as astronaut support. As an additional benefit of this robust shielding approach, the practical implementation of power transmission from the FSPS to the users is greatly facilitated.

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