



A Summary of NASA Architecture Studies Utilizing Fission Surface Power Technology

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Abstract

Beginning with the Exploration Systems Architecture Study in 2005, NASA has conducted various mission architecture studies to evaluate implementation options for the U.S. Space Policy. Several of the studies examined the use of Fission Surface Power (FSP) systems for human missions to the lunar and Martian surface. This paper summarizes the FSP concepts developed under four different NASA-sponsored architecture studies: Lunar Architecture Team, Mars Architecture Team, Lunar Surface Systems/Constellation Architecture Team, and International Architecture Working Group-Power Function Team.

Introduction

Under the NASA Exploration Technology Development Program (ETDP) and in partnership with the Department of Energy (DOE), NASA has an ongoing project to develop Fission Surface Power (FSP) technology. The primary goals of the project are 1) develop FSP concepts that meet expected surface power requirements at reasonable cost with added benefits over other options, 2) establish a hardware-based technical foundation for FSP design concepts and reduce overall development risk, 3) reduce the cost uncertainties for FSP and establish greater credibility for flight system cost estimates, and 4) generate the key products to allow NASA decision makers to consider FSP as a preferred option for flight development.

The FSP project was initiated in 2006 as the NASA Prometheus Program and the Jupiter Icy Moons Orbiter (JIMO) mission were phased out. As a first step, NASA Headquarters commissioned the Affordable Fission Surface Power System Study (AFSPSS) to evaluate the potential for an affordable FSP development approach. With a cost-effective FSP strategy identified, the FSP team evaluated design options and selected a preliminary reference concept to guide technology development. Since then, the FSP preliminary reference concept has served as a point-of-departure for several NASA mission architecture studies examining the use of nuclear power and has provided the foundation for a series of “Pathfinder” hardware tests. The long-term technology goal is a Technology Demonstration Unit (TDU) integrated system test using full-scale components and a non-nuclear reactor simulator.

The FSP team consists of Glenn Research Center (GRC), Marshall Space Flight Center (MSFC), and the DOE National Laboratories at Los Alamos (LANL), Idaho (INL), Oak Ridge (ORNL), and Sandia (SNL). The project is organized into two main elements: Concept Definition and Risk Reduction. Under Concept Definition, the team performs trade studies, develops analytical tools, and formulates system concepts. Under Risk Reduction the team develops hardware prototypes and conducts laboratory-based testing.

Project Context

One of the major challenges to the implementation of space fission power systems is development cost. In April 2006, NASA and DOE initiated the AFSPSS to determine the design features and expected costs of a representative FSP system. A government study team with members from several NASA field centers and DOE laboratories evaluated technology options and design variables and selected a reference concept based on affordability and risk. A low-risk approach was selected over other options that could offer higher system performance and/or lower mass. The team also defined a credible development schedule and generated a detailed Work Breakdown Structure (WBS)-based cost estimate. The results indicated that the initial FSP system could be developed, flight-qualified, and delivered to the lunar surface by 2020 for approximately \$1.4B (2007 dollars) with follow-on systems costing about \$215M each (Ref. 1).

The “affordable” design approach was considered representative of a number of potential system concepts. In order to determine a FSP reference concept, the team generated a comprehensive list of system design options and conducted screening studies that led to six plausible concepts for further study. All of the plausible concepts presumed the use of a low-temperature (<900 K) reactor heat source with conventional materials as a path toward achieving an affordable solution. The plausible concepts included a liquid-metal-cooled reactor with Stirling, Brayton, thermoelectric, or organic-Rankine power conversion, a gas-cooled reactor with Brayton power conversion, and a heat pipe cooled reactor with Stirling power conversion. The concepts were evaluated for performance and relative cost against a common set of mission requirements and development constraints derived from the earlier affordable study. In 2008, a management review panel led by NASA Headquarters selected the liquid-metal reactor with Stirling power conversion as the FSP preliminary reference concept and recommended Brayton as a backup conversion option if unforeseen difficulties arise with the Stirling technology development efforts (Ref. 2).

The resulting preliminary reference concept includes a liquid-metal-cooled, fast-spectrum reactor with Stirling power conversion and water-based heat rejection (Ref. 3). The reactor uses uranium oxide (UO₂) fuel pins in a hexagonal core with an external radial reflector and control drums. Heat is transferred to the Stirling power converters by a pumped sodium-potassium (NaK) reactor coolant loop. The core structure and coolant piping are constructed of stainless steel to reduce cost and development risk. The radial reflector is beryllium in a stainless-steel shell. The control drums are beryllium and boron carbide (B₄C), also enclosed in stainless steel. The reactor is located at the bottom of an approximate 2-m-deep excavation. The lunar regolith limits radiation from the reactor to less than 5 rem/year at a 100 m radius. The Stirling converters generate single-phase alternating current (AC) electric power that is converted to direct current (DC) for user loads. Stirling waste heat is removed by a pumped water coolant loop coupled to a series of two-sided, vertical radiator panels. The radiator panels are composed of titanium-water heat pipes in a composite facesheet sandwich. The FSP concept is designed to produce a net power of 40 kWe with a full-power service life of at least 8 yr. This same technology could be used for missions at essentially any location (equator to poles) on the lunar or Mars surface.

Derived Requirements

Table 1 presents a summary of the top-level requirements developed for the FSP system. The requirements are termed “derived” because they were predominantly defined by the FSP team in response to suggestions by NASA Headquarters and the various NASA architecture study teams. The FSP safety-related requirements were generated by the FSP team based on previous space fission system development projects, such as SP-100 and JIMO. These requirements will undoubtedly be reviewed (and perhaps expanded) by independent design experts once FSP reaches flight development status. For now, they provide a reasonable starting point to guide FSP concept definition and technology development.

TABLE 1.—FSP-DERIVED REQUIREMENTS

Requirement	Rationale
1. The FSPS shall be designed to produce no less than 40 kWe net power output (after accounting for all power losses and auxiliary loads).	Provides sufficient power for extended-stay crew habitation, ISRU production facilities, rover recharging, and science equipment, including margin.
2. The FSPS shall be designed for use at any location on the lunar surface. Radiator sizing shall be based on worst-case surface temperatures and Sun angles.	Provides maximum flexibility in locating the lunar outpost. (The preferred lunar outpost location has not been determined.)
3. The FSPS shall be designed to operate for no less than 8 yr at full power.	Provides maximum service life without introducing excessive risk in FSP development and qualification.
4. The FSPS shall be flight ready for an initial launch and deployment no later than 2022.	Assures FSPS availability for initial outpost deployment based on current lunar emplacement schedules.
5. The FSPS shall be designed to produce no less than 50% power output after the first credible component failure.	Assures FSPS power availability to meet essential crew power requirements following a component failure.
6. The FSPS shall be recoverable from all credible operational upsets and transients without adverse safety consequences to the crew or outpost.	Assures FSPS power availability following an off-nominal event and a return to safe FSP operation.
7. The radiation from the FSPS shall be less than 5 rem/yr to an unshielded crew member located at the outpost.	Provides a guideline for FSPS shield design that corresponds to 10% of the astronaut annual dose limit. (The allowable crew dose from the FSPS has not been determined.)
8. The reactor shall remain subcritical during all planned and credible unplanned mission events prior to FSPS startup.	Assures that the FSPS does not present a radiological safety hazard before initial startup is commanded.
9. At its end-of-life, the reactor shall be decommissioned in a safe shutdown condition.	Assures that the FSP does not present a human safety hazard after final shutdown is commanded.
10. The FSPS mass shall be minimized and no greater than the current cargo lander down-mass capability of 14 000 kg.	Permits the FSPS to be delivered as a fully integrated package with available cargo mass to accommodate other payloads.
11. The FSPS design shall be extensible to the Mars surface. All materials and design strategies shall be compatible with the Martian environment.	Provides maximum return on FSPS technology investment by designating its applicability for both the Moon and Mars.
12. The FSPS shall be designed for robotic deployment using teleoperation.	Permits the FSPS to be installed at the lunar outpost without local human assistance, but does not preclude it.

The key requirements that drive FSP system design are power level and service life. The 40 kWe power output is consistent with numerous studies that have estimated power requirements for the initial phase of a human lunar outpost dating back to the 1990's Space Exploration Initiative and before. That power level is also well suited for an initial space reactor because it is large enough to demonstrate the mass effectiveness of nuclear fission, but not too large to over-complicate the design and development process. In actuality, the fission technology developed for the 40-kWe design is readily scalable between 10 and 100 kWe. Below 10 kWe, the mass and cost advantages are not as compelling. Above 100 kWe, the reactor and power conversion technologies selected for FSP may need to be reevaluated.

The 8-yr service life also represents a reasonable balance of performance and risk. It is long enough to accommodate most estimates for lunar and Mars surface mission duration. For longer missions, it would be prudent to utilize multiple FSP units and stagger their delivery to provide overlap. The 8-yr design life is also well within current technology projections for low-temperature liquid-metal reactors and dynamic power conversion. In addition, notional FSP development schedules indicate that sufficient qualification testing can be performed to demonstrate 8-yr life while still meeting the proposed launch date.

System mass is another requirement that could influence FSP design. The current derived requirement is that the FSP system mass be less than the payload capacity of the lander. The current cargo lander concept is projected to deliver approximately 14 000 kg to the lunar surface. The 40-kWe FSP system can easily be accommodated within this mass constraint, and most estimates show the system to be less than one-half of the lander cargo capacity. The generous lander payload allocation eliminates system mass as a major FSP design driver and allows the system to utilize low-risk technology to minimize development cost and increase system reliability. Nevertheless, the FSP system design incorporates various mass saving features in order to maximize the mass available for other payloads. This also assures that the concept is relevant for future applications that may be more mass constrained.

Design Summary

The preliminary reference concept layout is shown in Figure 1. The reactor core is located at the bottom of an approximate 2-m-deep excavation with an upper plug shield to protect the equipment above from direct radiation. The NaK pumps, Stirling converters, and water pumps are mounted on a 5-m-tall truss structure that attaches to the top face of the shield. Two symmetric radiator wings are deployed via a scissor mechanism from the truss. Each radiator wing is approximately 4 m tall by 16 m long and is suspended 1 m above the lunar surface. In its stowed configuration, the FSP system is approximately 3 by 3 by 7 m tall.

The buried configuration was selected for the preliminary reference concept because it minimizes the mass of radiation shielding that must be delivered from Earth. It also simplifies the Power Management and Distribution (PMAD) because the buried reactor can be located relatively close to the outpost to shorten transmission cable length. There are numerous other FSP installation options that could be developed depending on mission needs. The basic technology building blocks of the liquid-metal-cooled reactor, Stirling power conversion, and water-based heat rejection would be essentially the same. The decision on FSP configuration can easily be deferred until the flight program since most of the design challenges related to the configuration are engineering based rather than technology based.

The preliminary reference concept schematic is shown in Figure 2. The use of redundant components and parallel fluid loops allows the system to produce partial power in the event of unexpected failures. The schematic shows the system energy balance and the anticipated temperatures, pressures, and flow rates at some of the key interfaces. The reactor (Rx) produces 186 kWt with a peak fuel pin clad temperature of 860 K. It delivers heated NaK at 850 K to a pair of intermediate heat exchangers (IHX) using two fully redundant electromagnetic primary pumps (PP). The IHX is a NaK-to-NaK heat exchanger that provides a buffer between the primary NaK and the Stirling converters, and a means to adjust the NaK flow rate and resulting temperature drop across the Stirling converters separately from the reactor flow and temperature drop. Each intermediate NaK loop services two Stirling converters at a supply temperature of 824 K. The effective Stirling hot-end cycle temperature is 778 K. The secondary NaK loops include an intermediate electromagnetic pump (IP) of similar design to the primary NaK pump.

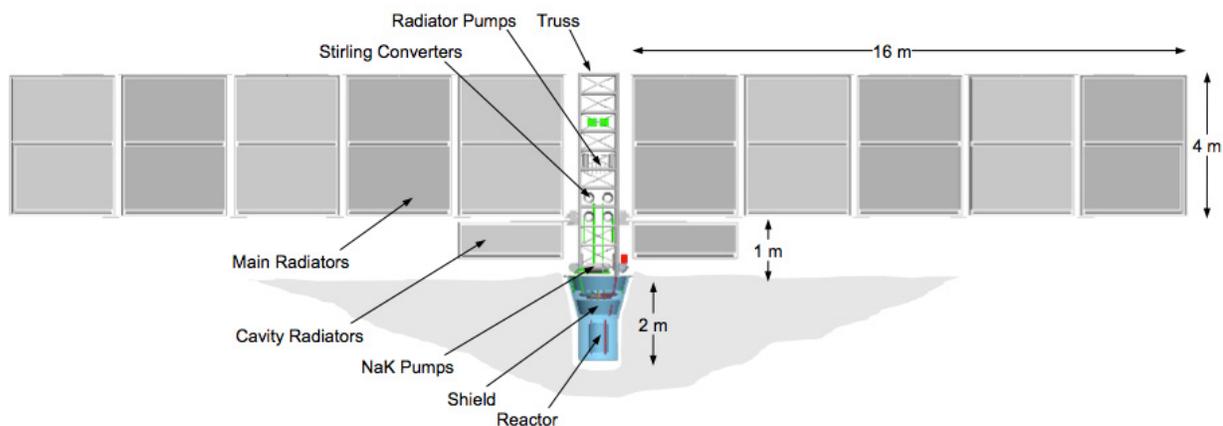


Figure 1.—FSP concept layout.

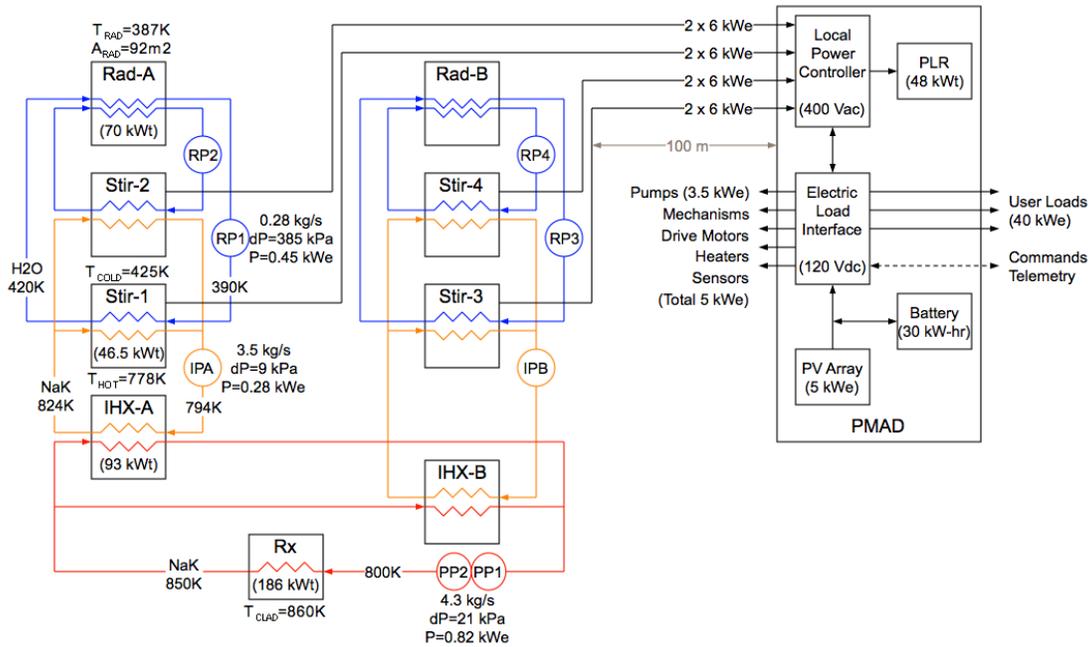


Figure 2.—FSP concept schematic.

TABLE 2.—FSP MASS SUMMARY

1.0	Fission surface power system (kg)	5820
1.1	Reactor module (kg)	1440
1.2	Power conversion module (kg)	411
1.3	Heat rejection module (kg)	767
1.4	Power management and distribution module (kg)	1071
1.5	Radiation shield module (kg)	2080
1.6	Integration structure (kg)	51

Each Stirling converter (Stir) is composed of two axially opposed Stirling heat engines and two linear alternators. Power conversion thermal-to-electric efficiency is estimated at 26 percent. The alternators deliver 6 kWe each at 400 Vac rms and 60 Hz to the PMAD. A Local Power Controller (LPC), located approximately 100 m from the reactor, converts the 400 Vac to 120 Vdc for distribution to the Electrical Load Interface (ELI). The 48 kWe gross Stirling output power provides sufficient capacity to account for electrical losses (~3 kWe) and system parasitic loads (~5 kWe) and still delivers 40 kWe net for user loads. A Parasitic Load Radiator (PLR) dissipates electric power that is not required by the user loads and allows the system to be operated at constant power thus eliminating the complexity of thermal system load following. The ELI serves as the primary power bus and system interface for commands and telemetry. A 5-kWe photovoltaic (PV) array and a 30-kW-hr battery are included with the FSP PMAD for startup and backup power.

The heat rejection subsystem is composed of four water heat transport loops and two radiator (Rad) wings (two loops per wing). The radiator wings receive heated water at 420 K from the Stirling converters and return the water at 390 K using a mechanical radiator pump (RP), while rejecting approximately 35 kWt per loop. The resulting Stirling cold-end cycle temperature is 425 K. The total heat load is approximately 140 kWt and the total two-sided FSP system radiator area is 185 m² assuming a 250 K effective sink temperature and 10 percent area margin. Each radiator wing includes 10 subpanels, each measuring approximately 2.7 m wide by 1.7 m tall. The preliminary reference concept mass summary for the buried reactor configuration is shown in Table 2. The total system mass without margin is 5820 kg.

Lunar and Mars Architecture Studies

Beginning with the Exploration Systems Architecture Study (ESAS) in 2005, NASA has conducted various mission architecture studies to evaluate implementation options for the U.S. Space Policy (formerly the Vision for Space Exploration). Several of the studies examined the use of fission power systems for human missions to the lunar and Martian surface. The FSP team contributed by supplying FSP design characteristics, developing mission-compatible configuration options, and defining a concept-of-operations consistent with the mission objectives.

Lunar Architecture Team

In 2007, the second phase of the Lunar Architecture Team (LAT2) developed an FSP-based architecture known as Option 6 for a polar lunar outpost at the Shackleton Crater site. The nuclear-based architecture was proposed to accelerate outpost buildup, achieve earlier 180-day crewed surface missions, and maximize the total number of crew days on the surface over a 10 year lunar campaign. Option 6 uses the buried reactor concept delivered on a cargo lander and installed by a combination of robots and crew, as shown in Figure 3. An earlier lander delivers a small solar array and battery to supply initial power, the FSP PMAD equipment, and a bladed-rover that prepares the site for the reactor. Once installed, the FSP system provides a robust power capability of 40 kWe resulting in substantial power margin for early outpost buildup and operations. It also provides capacity for power increases associated with the initial surface elements and the potential for expanded science and resource utilization. System trades comparing Option 6 to similar LAT2 architectures with solar PV arrays and regenerative fuel cells (RFCs) showed the FSP-based architecture to offer significantly more power with less power system mass and comparable cost despite the favorable conditions for solar power at Shackleton.

A key question raised about the FSP installation was the feasibility of excavating the reactor hole. Independent studies were conducted by the in situ resource utilization (ISRU) team during LAT2 to evaluate methods for excavating a 2 m-deep hole. The ISRU study evaluated various digging methods and developed analytical models to predict the mass and power requirements for the machinery. It was determined that the process could use the same semi-automated regolith-moving equipment planned for the ISRU oxygen production plant. The recommended approach was to prepare an oversized hole with a ramp that could accommodate ingress/egress of a bladed rover. Preliminary estimates indicated the need to move about 24 m³ of regolith, including the final backfilling of the ramp, over a time period of 41 to 50 days.

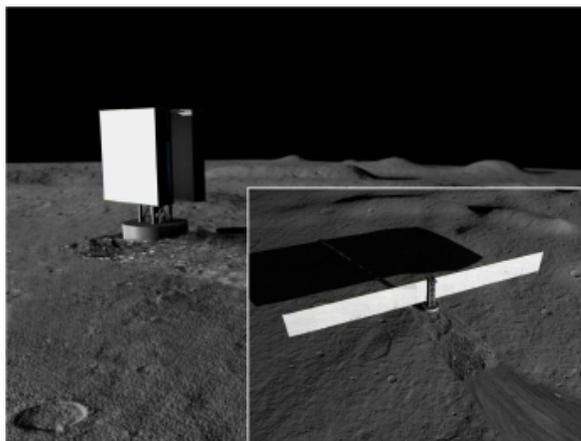


Figure 3.—FSP system for LAT2 Option 6.

Mars Architecture Team

During the same time period, the Mars Architecture Team (MAT) was reviewing power system options for a crewed mission to Mars. The basic architecture was derived from previous Mars mission concepts in which an initial cargo lander delivers a power system and ISRU plant to locally produce the return propellant before the crew ever leaves Earth. A nuclear system allows the propellant production to be completed faster and more efficiently through continuous day/night operations. The power requirements for the nuclear power option were about 30 kWe during the pre-crew deployment phase and about 20 kWe after the crew arrives. The 30-kWe power level was similar enough to the reference 40 kWe lunar concept that no power system design changes were required. The MAT-based FSP concept assumed the reactor on a mobile cart with integral shielding that is robotically deployed from the lander, as shown in Figure 4. The above-grade reactor configuration was chosen for this application because the MAT wanted to avoid digging operations. FSP was selected as the baseline power system for MAT based on advantages in system mass, operational flexibility, and environmental robustness as compared to solar power systems with energy storage (Ref. 4).

Lunar Surface Systems/Constellation Architecture Team

In 2008, Lunar Surface Systems (LSS) and the Constellation Architecture Team developed an FSP-based architecture known as Scenario 5. Two basic FSP options were investigated including the typical off-loaded and buried system and a new concept where the FSP system remained on the lander, as shown in Figure 5. In either case, the FSP system was to be delivered on the first cargo lander to provide a power-rich environment for early outpost buildup. Both systems also assumed a central power distribution node at the outpost. This provided an easy-access power bus for outpost loads such as habitats, ISRU equipment, rover recharging, and science experiments. It also placed the FSP system's power and control electronics at a location that was readily accessible should maintenance be required. A small solar array (5 kWe) and battery (30 kW-hr) was included with the FSP PMAD for startup and emergency backup. A follow-on architecture evaluated by LSS, referred to as Scenario 12, included an FSP system that was delivered later in the lunar campaign using a similar design approach.

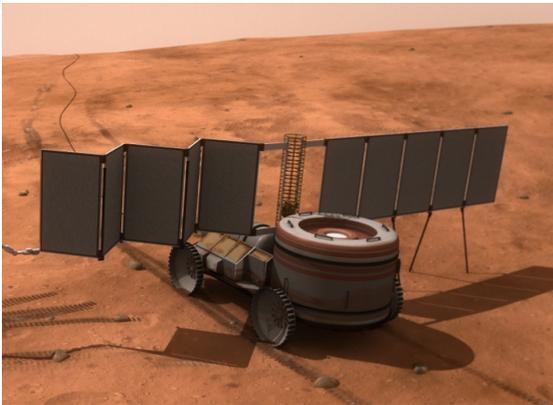


Figure 4.—Mars FSP concept.



Figure 5.—Lander-integrated FSP system for LSS Scenario 5.

The FSP team did an extensive evaluation of radiation shielding options to support the Scenario 5 architecture definition (Ref. 5). Figure 6 shows graphical representations of the Monte Carlo N-Particle (MCNP) transport code models developed for the four shielding approaches that were examined including A) FSP system off-loaded and reactor buried, B) FSP system off-loaded and placed on surface with surrounding regolith berm, C) FSP stays on the lander as delivered from Earth, and D) FSP system stays on the lander with regolith shielding augmentation.

All options assumed a 3 mrem/hr (26.3 rem/yr) reactor dose rate to an unshielded astronaut at a specified separation distance. This is higher than the 5 rem/yr dose mentioned previously to account for more realistic crew routines and schedules. Crew length-of-stay is expected to be no greater than 180 days with the majority of time spent in shielded habitats and rovers away from the hypothetical reactor boundary. Given reasonable assumptions for crew operations, the total radiation to a crew member from the reactor based on the 3 mrem/hr dose rate at the specified distance is expected to total much less than 5 rem per year of duty. The actual allowable astronaut radiation dose is not defined yet and will depend on many factors including natural radiation levels, proximity to nuclear sources (such as FSP), crew shielding, length of mission, and Extra-Vehicular Activity (EVA) duty cycle. The FSP-related dose is expected to be a small percentage of the total received by crew members during their lunar stay. The FSP shielding must also protect its own components located on the truss above the shield. The assumed dose limits for truss-mounted equipment above the shield were 5 Mrad (gamma) and 2.5×10^{14} neutrons/cm². Recent testing of Stirling convertor components and materials at SNL, ORNL, and Texas A&M University suggest that these dose limits could be increased. In most cases, the FSP equipment was the limiting factor in determining the required FSP shield mass.

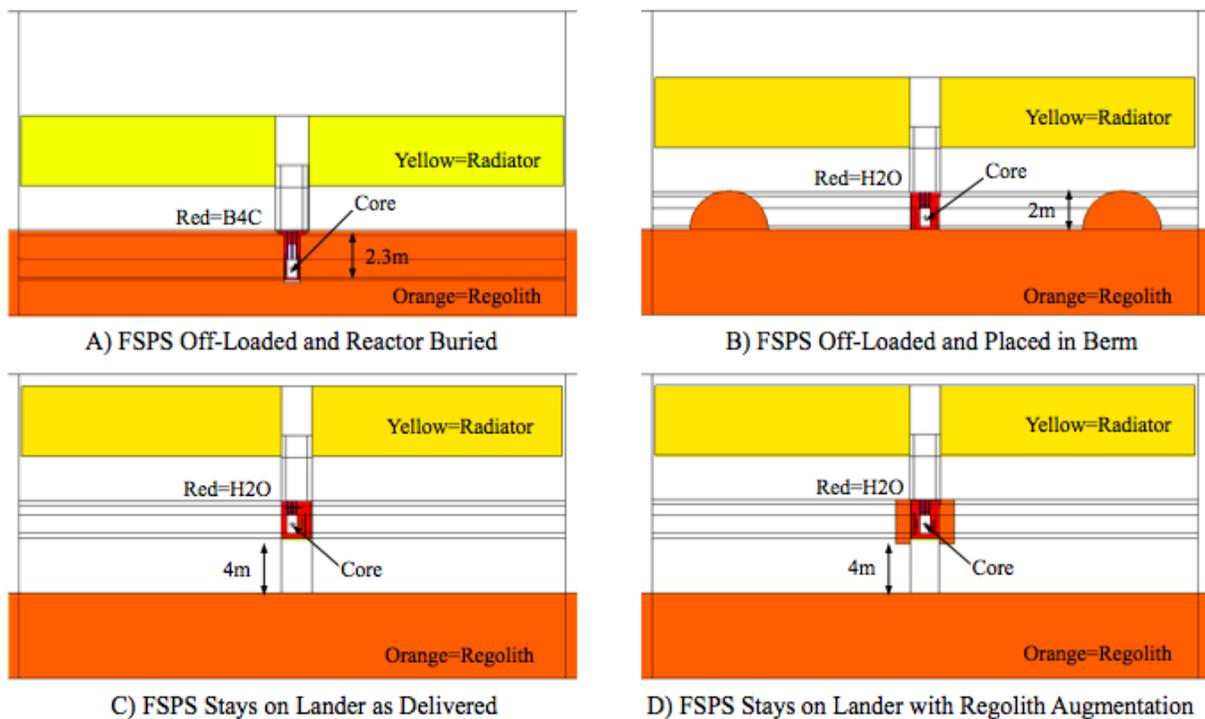


Figure 6.—Scenario 5 shielding options.

The buried reactor case (A) resulted in a 2080 kg delivered shield, predominantly B₄C, with the reactor core buried to a 2.3 m depth. This approach offered the shortest separation distance among the options at 100 m. It also offers the lowest delivered shield mass, and the potential for shield mass reduction by using water rather than B₄C. The berm shield case (B) assumed a 2-m-tall regolith berm surrounding the reactor. It resulted in a 2660-kg delivered shield using water and depleted uranium (DU) and a 200 m separation distance. The landed shield cases assumed that the reactor remained in the central lander cavity between the propellant tanks at a height of approximately 4 m above the lunar surface. The “as-delivered” lander case (C) required a shaped shield of water and DU that was thicker in the direction of the outpost. It was still the heaviest delivered shield at 2980 kg and required a separation distance of 1000 m. The regolith-augmented lander case (D) resulted in a 2250 kg delivered shield of water and DU supplemented with 0.8-m-thick regolith-filled annulus surrounding the water vessel and a 400 m separation distance.

The separation distances for the various shield options were determined in conjunction with power transmission cable mass estimates. Generally, there is an optimum distance that balances shield mass and cable mass. Table 3 provides a summary of the power transmission assumptions and resulting cable masses for the four cases. Larger distances require more complex power transmission approaches. In all cases, the power distribution node was assumed to be located at the specified separation distance and a 25 percent margin was added for cable length. The cable bundle was assumed to include a main power cable, auxiliary power cable (for FSP parasitic loads), and a data transmission cable (for FSP instrumentation signals). The main power cable includes parallel channels for each of the eight Stirling alternators. The auxiliary power cable is assumed to carry a total of 5 kWe via 10 parallel channels.

TABLE 3.—SCENARIO 5 POWER TRANSMISSION ANALYSIS

Shield option	A	B	C	D
Separation distance, m	100	200	1000	400
Cable length, m	125	250	1250	500
Transmission, Vac	400	400	2000	400
Auxiliary bus, Vdc	120	120	120	270
Auxiliary bus location	Outpost	Outpost	FSP	Outpost
Main power cable, kg	48	128	688	400
Auxiliary power cable, kg	120	450	120	300
Data cable, kg	12	32	12	100
High-voltage transformers, kg	-----	-----	144	-----
Total transmission mass, kg	180	610	964	800

Cases A and B assumed direct 400-Vac-power cabling from the Stirling alternators to the power distribution node where the 400 Vac was converted to 120 Vdc for the user load bus. The same 120 Vdc bus was used to power FSP parasitic loads, such as pumps and motors, via a power cable from the distribution node back to the FSP system. The larger separation distance for Case C required the addition of high-voltage transformers near the FSP system to boost the transmission voltage to 2000 Vac. The 2000 Vac provides a reasonable compromise on cable mass, development risk, and operational complexity. The 120-Vdc auxiliary power bus and FSP data bus was assumed to be co-located with the transformers at a 100 m distance from the FSP system. Case D assumed direct 400-Vac transmission, a 120-Vdc user load bus, and a 270-Vdc auxiliary power bus and return cable.

The LSS and Constellation Architecture Team settled on two FSP configurations for Scenario 5. The two systems used the same reactor, power conversion, heat rejection, and PMAD electronics. The off-loaded configuration assumed the use of the “ATHLETE” utility rover for excavating a hole, removing the FSP system from the lander, transporting it to the site, and positioning it in the hole. The total FSP system mass was about 5800 kg including shielding and cabling. The landed configuration assumed the regolith-augmented shield with the lander cavity filled using a crane that scoops regolith collected near the lander by a bladed rover. The total FSP system mass was about 6600 kg with shielding and cabling.

International Architecture Working Group—Power Function Team

Beginning in April 2009, a Power Function Team was formed to support the International Architecture Working Group (IAWG) and develop power system concepts for a Global-Point-of-Departure human lunar mission. The team consisted of members from NASA, the European Space Agency (ESA), and the Japanese Space Agency (JAXA). The proposed IAWG mission architecture assumed an initial human mission to the lunar south pole (Shackleton crater) followed by robotic relocation of the initial surface assets to accommodate subsequent human missions to nonpolar sites such as Malapert Mountain and Schrodinger Basin. Once these initial areas were explored, a single site could be selected for a follow-on long-duration mission phase. Solar-based power systems with RFCs were baselined to include adequate energy storage capacity for 5-day eclipse durations at Shackleton. However, nighttime power requirements may exceed available energy storage capacity for missions beyond Shackleton. Two nuclear-based options were analyzed including a 2-kWe Large-Scale Stirling Radioisotope Generator (LSRG) and a 10-kWe Mobile Fission Power System (MFPS). The LSRG-based architecture enabled 11-day eclipse missions at Malapert, while the MFPS-based architecture provided sufficient capacity to enable both the 11-day eclipse missions at Malapert and 15-day eclipse missions at Schrodinger.

Mobile Fission Power System

The objective for the MFPS was to provide a small fission power system that could be easily deployed and moved if necessary. The basic concept was a scaled-version of the buried 40-kWe FSP system that would be off-loaded from the lander, placed on the lunar surface, and shielded with a regolith berm as shown in Figure 7. The system would be designed to produce 10 kWe output, continuously during the lunar daylight and nighttime periods. The reactor would be oversized, based on the larger 40-kWe system, to provide growth capacity and simplify the qualification of possible follow-on systems. The system would utilize a single 12-kWe dual-opposed Stirling convertor, instead of the four units used on the 40-kWe system. Heat rejection would be provided by a simple two-panel deployable radiator, as opposed to the 10 radiator assemblies required on the 40-kWe system. A 200-m transmission cable with remote electrical controls and 120-Vdc load bus would provide the interface to the mission power loads. In addition to the regolith berm, a supplemental water shield would surround the reactor to limit radiation to 3 mrem/hr at the 200 m power hub. The key feature that distinguishes this concept from others is the capability to be shut down and moved to a new location if required.

The MFPS mass summary with Current Best Estimate (CBE) mass values is provided in Table 4. The system could be delivered in as many as three separate packages. The water could be delivered specifically for this use or scavenged from lunar sources. The mass of regolith-moving equipment to create a surrounding berm is not included and assumed to be an available asset, if needed.

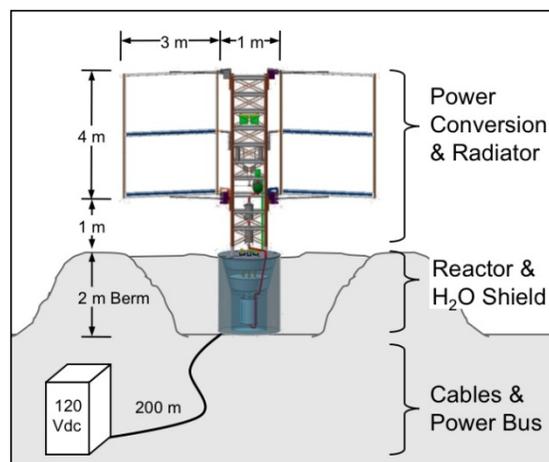


Figure 7.—Mobile fission power system concept.

TABLE 4.—MOBILE FISSION POWER SYSTEM MASS SUMMARY

Mobile FPS subsystem	Mass, kg	Includes
Power plant	1615	Reactor, water shield vessel, power conversion, radiator, and truss/structure.
Power Management and Distribution (PMAD)	415	Cabling, electrical controls, and 120-Vdc load interface bus.
Water (for shield)	1310	Liquid water for filling shield vessel prior to reactor startup.
Total current best estimate	3340	

The MFPS can provide various benefits for the relocation and long-duration mission phases. During the relocation phase, the MFPS provides a continuous 10-kWe day/night power source for stationary applications that can be shut down and relocated as needed. During the long-duration phase, the 10-kWe MFPS could be moved to the long-duration site and reused, or the design could be scaled to 40 kWe and a follow-on system could be delivered to the site. The higher power capacity could provide expanded outpost operations to allow closed loop life support, high-production rate ISRU, and larger crew size if desired. The 8-yr design life assures long-term campaign use for the entire mission phase. The same technology could be used on Mars, making this option very well aligned with “Mars Forward” goals.

MFPS Concept-of-Operations

A preliminary assessment was made to determine the activities associated with launching, installing, and operating a MFPS. The main activities are summarized in the paragraphs below.

Launch and Delivery

The reactor is launched cold and subcritical. The reactor presents essentially no radiological hazard during lander and launch vehicle integration. The power plant will be delivered to the launch site as a fully integrated package. The MFPS system can be delivered as a single payload or in a series of packages depending on the available capacity of the lander. Prior to delivery, the MFPS system would be acceptance tested at a DOE nuclear facility. The reactor contains Special Nuclear Material that requires a specific class of security and safeguards. This is the primary difference between the MFPS payload and other lunar surface payloads. The reactor is designed to preclude inadvertent criticality under potential launch accident scenarios. During launch and delivery, the MFPS system may require periodic electrical power to exercise fluid pumps and monitor instrumentation sensors.

Off-Loading and Setup

A suitable site for the power plant must be determined that is approximately 200 m away from the outpost. If the local terrain offers natural outcroppings, these could provide shielding benefits and possibly eliminate the need for the water shield and regolith berm. The PMAD (415 kg) would be off-loaded from the lander. A single power electronics pallet (1 by 1 by 1 m, 175 kg) would be setup near the outpost with easy access for the electric power users. The pallet provides the interface for power loads and data communications. A transmission cable bundle (<1 m diam., 240 kg) would be connected to the electronics pallet and unfurled via a spool to the power plant site. A robotic rover could deploy the cable. The transmission cable includes the main power cable, data signal cable, and return power cable for power plant auxiliary loads. The power plant (3 by 1.5 by 7 m, 1615 kg) would be off-loaded from the lander and transported via a cargo rover to the installation site. The power plant would be set directly on a flat regolith surface. The center of mass is very low and centered. Support bracing could be added if desired. A bladed rover would be used to move regolith to form a 2-m-high berm around the power plant, in lieu of using natural topography.

System Startup

Startup could be performed by local crew members or remotely from Earth. After connection of the transmission cable, initial communications would be established via telemetry signals to the electronics pallet. Computers and instrumentation would be started at 100 W total input power. Trace heating of the one reactor coolant (NaK) loop and two radiator coolant (H₂O) loops would be started with 100 W input power on each loop. The shield vessel would be filled with liquid water (1310 kg). The one reactor NaK pump would be started with 250 W input power. The NaK loop trace heaters would be turned off. The two radiator loops would be charged with H₂O coolant from a heated storage tank. The two radiator H₂O pumps would each be started with 100 W input power. The H₂O loop trace heaters would be turned off. Three of the six reactor control drums would be adjusted to the reactor operating position. The fourth, fifth, and sixth control drums would be adjusted in succession resulting in initial reactor criticality. The control drums would be adjusted to reach 600 K NaK outlet temperature. The Stirling convertor would be started resulting in approximately 1 kWe power output. The two radiator panels would be deployed. The control drums would be adjusted in steps and the Stirling convertor stroke would be gradually increased with hold-points at 2.5, 5, 7.5, and 10 kWe. The regulated 120-Vdc bus would be enabled at 5 kWe. The total startup energy for this process is estimated at 10 kW hr.

Water for Reactor Shield

The combination of the water shield and regolith berm reduces the reactor radiation to 3 mrem/hr at 200 m. The resulting dose to an unshielded astronaut at the 200 m boundary during a typical 30-day mission is about 2.2 rem. The OSHA limit for nuclear power workers is 5 rem/yr and the NASA guideline for astronauts is 50 rem annually. The use of natural topography could reduce or eliminate the need for the water and/or regolith berm. The 1310 kg of liquid water for the water shield could be delivered from Earth, or acquired from lunar sources. The water could also be scavenged from other lunar surface assets, such as fuel cells or propellant tanks.

System Operations

Once the MFPS system reaches full power it can operate with minimal human intervention requiring only periodic health monitoring from a data console at the outpost or Earth. The MFPS system is designed to automatically respond to lunar day/night transients, electric load changes, and recoverable power plant faults without human intervention. The MFPS system would produce electric power continuously and shunt excess power not required by loads via a parasitic load radiator. A periodic control drum adjustment (perhaps twice per Earth month) may be performed to maintain reactor coolant temperature within a nominal band. The electronics pallet includes a power switch panel that allows users to connect electric loads as needed. This would be the power interface for habitats, landers, ISRU plants, rover recharging, science experiments, etc. The electronics pallet is located near the crew for maintenance, if required. The power plant is designed for an 8-yr service life without maintenance. The design life would be demonstrated as part of the ground verification testing. Performance degradation over the design life should be negligible. Radiator area margin is included to account for environmental degradation such as ultraviolet radiation and dust. The redundancy in the reactor control drums provides fault tolerance for reactivity adjustments.

Shutdown and Relocation

At end-of-life, the power plant would be shut down and could remain at the installation site. Within several weeks, the radiation will decrease below natural background levels and the plant should not pose any particular safety concern. The plant shutdown would include an adjustment of the control drums to make the reactor subcritical, and a commanded stop to the Stirling convertor, reactor pump, and radiator pumps. The power plant and PMAD could also be shut down and moved to another location. Robotic access would be permitted within hours; human access may be permitted within days. To prepare for relocation, the radiator panels would be retracted and the transmission cable would be disconnected. The

water shield could be drained, if desired, to reduce the mass for transport. The MFPS system cannot provide power while it is being moved. At the new location, the setup and startup would be repeated as described previously. Subsequent startups should be easier and faster. After setup, the system could be operational within ~12 hr. The MFPS system could be relocated multiple times recognizing that each shutdown, movement, and restart increases the probability of a system malfunction.

Conclusions

Fission Surface Power (FSP) systems are currently being studied by NASA as an option for future human exploration missions to the Moon and Mars. NASA and the Department of Energy (DOE) have partnered to help mature FSP technology so that it may be considered for future flight development. The NASA/DOE team has generated a preliminary FSP reference concept to help guide technology development and provide a possible starting point for future flight systems. A portion of the FSP project is focused on concept definition and integration studies to evaluate the use of FSP technology for various mission architectures. This paper discusses some of the recent architecture studies and potential methods for utilizing FSP systems. The FSP team has supported these architecture studies by supplying FSP design characteristics, developing mission-compatible configuration options, and defining a concept-of-operations consistent with the mission objectives. The technology is adaptable to meet a wide range of mission needs. Configuration options include buried-reactor systems, lander-integrated systems, surface-mounted systems, and systems which are deployed via a wheeled cart. Power levels can range from several kilowatts up to about 100 kWe without a significant change to the basic technology. The primary building blocks of the FSP system: reactor, power conversion, and heat rejection can be common to many design configurations making the technology extremely robust and versatile.

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14. ABSTRACT Beginning with the Exploration Systems Architecture Study in 2005, NASA has conducted various mission architecture studies to evaluate implementation options for the U.S. Space Policy. Several of the studies examined the use of Fission Surface Power (FSP) systems for human missions to the lunar and Martian surface. This paper summarizes the FSP concepts developed under four different NASA-sponsored architecture studies: Lunar Architecture Team, Mars Architecture Team, Lunar Surface Systems/Constellation Architecture Team, and International Architecture Working Group-Power Function Team.					
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