A Deployable 40 kWe Lunar Fission Surface Power Concept

Steven Oleson[1], Thomas Packard[2], Elizabeth Turnbull[1], Marc Gibson[1], Dasari Rao[3], Christopher Barth[1], Scott Wilson[1], Paul Schmitz[4], Anthony Colozza[2], Brandon Klefman[1], Lucia Tian[1], and Lee Mason[1]

[1]NASA Glenn Research Center, Cleveland, OH, 44135
[2]HX5, LLC, Brook Park, OH, 44142
[3]Los Alamos National Laboratory, Los Alamos, NM, 87545
[4]Power Computing Solutions Inc., Avon Lake, OH, 44012

Primary Author Contact Information: (216)977-7426, steven.r.oleson@nasa.gov

[Placeholder for Digital Object Identifier (DOI) to be added by ANS]

Continuous power at the kilowatt level will be imperative for future lunar users including crew infrastructure, future science, and in-situ resource utilization (ISRU). The Compass Team explored both 10 kWe and 40 kWe concepts, assuming planned lander and rover capabilities. Both concepts found that a crew pressurized rover chassis, repurposed for deploying reactor power components, could place a fission surface power system (FSPS) at least one km from users. While the 10 kWe fission power system (FPS) could be deployed as a single unit, the 40 kWe system was too large and had to be deployed in multiple trips with the same rover. Key technologies and design approaches included a high-assay low-enriched uranium (HALEU), yttrium hydride (YH) moderated heat pipe reactor, Stirling convertors, deployable radiators based on International Space Station (ISS) designs, and power conversion/transmission at ±2800 VDC for a one km remote distance.

I. INTRODUCTION

While propulsion is the key element in getting to places in space, power is certainly the limiting factor once one gets there. This is especially true for the moon, for while solar power is available without atmospheric attenuation, the sun is only available roughly two weeks out of every month – necessitating either a large energy storage system (plus the additional solar arrays to gather this energy) or a nuclear reactor. A reactor can provide continuous power for long-duration users. Such a nuclear power system is a compelling cornerstone to any sort of lunar base or ISRU systems. Past studies have shown that required power levels for such users, on the moon or mars, are on the order of 10-40 kWe (at least in the near term)[1, 2]. As little as a decade ago, a 40 kWe reactor design was explored and key technologies developed[3, 4].

The past studies showed that a major challenge was how to deliver both the reactor power system as well as the power to the users. While providing ample amounts of power, a reactor system must also be shielded from the crew. One option explored in a previous design looked at burying the reactor close to the base. This eliminated long cable systems, with their associated deployment systems and voltage convertors, but required preparing a sufficient hole for the reactor, transporting it there, placing it in the hole, and covering it.

An alternative approach, explored here, utilizes a transportation system to deploy the reactor to a remote location where the distance can minimize the required shielding. Such an approach eliminates the need for specialized construction equipment but does require a power delivery system with its own challenges. A separation distance on the order of kilometers is required and a one km distance was chosen as representative for this study. As such, a power transmission system will require a high voltage to minimize the conductor mass (similar to terrestrial systems).

The conceptual point design described herein was commissioned to explore both what a 40 kWe fission surface power system (FSPS) might look like as well as how one might deploy it on the south pole of the moon using large crew-class cargo landers. The requirements for this design come loosely from the FSPS request for proposal (RFP)[5].

I.A. Requirements, Assumptions, and Trades

The top-level requirements for the deployable FSPS are shown in Figure 1.

DR-#	Title	Requirement Details
DR-1	Power	The FSP shall be designed to operate at a minimum end-of-life 40 kW_E continuous power output for at least 10 years in the lunar environment as detailed in Attachment A. Higher power ratings are desirable provided remaining DRs are satisfied.
DR-2	Launch and Landing Loads	The FSP shall be designed to withstand structural loads as detailed in Attachment B.
DR-3	Radiation Protection	The FSP shall be designed to limit radiation exposure at a user interface location 1 km away to a baseline value of 5 rem per year above lunar background.

Fig. 1. Deployable FSPS Top-Level Requirements[5]

For the conceptual design, design goals (DG), as seen in Figure 2, were sought, but the mass goal of 6,000 kg was significantly exceeded. However, the final mass still fits on a planned cargo lander that has similar volume dimensions to those in DG-1 (Ref. 6).

DG-#	Title	Goal Details
DG-1	Volume	The FSP should fit within a 4 m diameter cylinder, 6 m in length in the stowed launch configuration.
DG-2	Mass	The total mass of the FSP should not exceed 6,000 kg which includes mass growth allowance and margin.
DG-3	Power Cycles	As a safety feature, the FSP should be capable of multiple commanded and autonomous on/off power cycling.
DG-4	User Load	The FSP should be capable of supporting user loads from zero to 100% power at the user interface
DG-5	Fault Detection & Tolerance	The FSP should minimize single-point failure modes, should be capable of detecting and responding to system faults, and have the capability to continue providing no less than 5 kW_E under faulted conditions.
DG-6	System Transportability	The FSP should be capable of operating from the deck of a lunar lander or be removed from the lander and placed on a separately provided mobile system and transported to another lunar site for operation.

Fig. 2. FSPS Design Goals[5]

A few more drivers included the use of low enriched uranium (LEU), the placement of the reactor near the lunar south pole, and a self-contained power system that requires no crew or robotic support for startup, operation, and maintenance. The design scalability of this approach to higher powers was considered outside of this effort.

I.B. Transportability Approach

The 40 kWe FSPS is designed to have the ability to be deployed on the lunar surface to a desired location away from the lander that delivers it to the surface. A 6-wheel, pre-deployed rover chassis, designed by NASA Johnson Space Center (JSC) to provide mobility to a pressurized crewed cabin (pressurized rover), is used for transporting the FSPS[7]. In addition to the rover chassis, a modified version of a NASA JSC sled concept is used to deploy the FSPS payloads to the lunar surface from the chassis[8].

The concept of deploying the sled from the chassis is to deploy the two sled legs on one end of the chassis down to the surface using a screw-drive mechanism, then slowly drive the rover out from underneath the sled until the second pair of legs on the other end can be deployed down to the surface, allowing the rover chassis to drive completely out from under the sled. The four legs on the sled can also be used for leveling the sled as needed while on the surface.

II. CONCEPT OF OPERATIONS

Launch and delivery of the 40 kWe FSPS is assumed to be achieved by a human class cargo lunar lander[6]. No final lander design(s) have been chosen, and only a delivery mass (~12 t) and volume are defined. Cargo placement can be on top, inside, or underneath the lander. Given the long times that may be needed to refuel the cargo lander, it is assumed that the FSPS may spend five months getting to the lunar surface, but that the cargo lander will provide up to 2 kWe of power to the FSPS during this time and for up to two days after landing. An off-loading system for the cargo lander is required but undefined. A top-level Concept of Operations (ConOps) of the mission is shown in Figure 3.

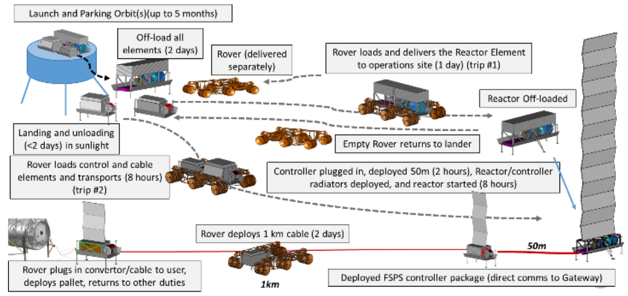

Fig. 3. FSPS Mission ConOps

Given the 40 kWe power requirement, the FSPS system was divided into three separate main elements: the reactor system, the control system, and the one km cable and spool system, which also includes a power conversion system to convert the reactor power to the parameters required by the end user. This split is necessary not only due to the dimensions of the components and deployable radiators contained on each element, but because the mass of all three elements combined exceeds the rover chassis capability. The components contained on each of the three elements were divided up logically by their functionality and required location on the lunar surface. For this reason, each element is integrated with its own sled to allow it to be individually deployed to the surface once transported to its desired location.

While the same pre-deployed rover chassis will deliver all three elements to their respective locations, this is done in two separate trips. First, the rover will deliver the reactor system element from the landing site to a location one km away from the end user location. Next, the rover will return to the landing site to retrieve and transport both the control system element and the cable and spool system element to the reactor element to allow the proper cable connections to be made with the reactor. The rover will then transport both systems 50 meters away from the reactor system, deploy the control systems element, then finally transport and deploy the cable and spool systems element at the end user site one km away. The 50 m distance from the reactor system eliminates the need for radiation shielding on the control system electronics, while the one km distance ensures that radiation exposure to the crew is below allowable limits.

All three elements fit within the payload volume and mass capability for a single lunar cargo lander. Inclusion of the rover chassis on the lander would not allow the entire payload to fit within the payload envelope and would exceed the mass capability for a single lander; thus, as stated earlier, the rover chassis must be pre-deployed on a separate lander. Figure 4 shows the three FSPS elements contained within the payload envelope for the lander.

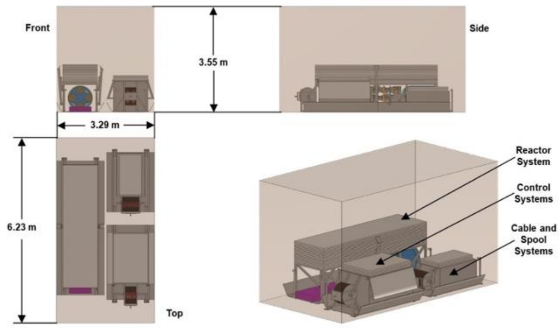

Fig. 4. FSPS elements within the lander payload envelope.

Figure 5 shows the reactor system element in its stowed configuration mated to the rover chassis and both the control system and cable and spool system elements in their stowed configurations mated to the same rover chassis. All three elements will remain in the stowed configuration until deployed onto the lunar surface.

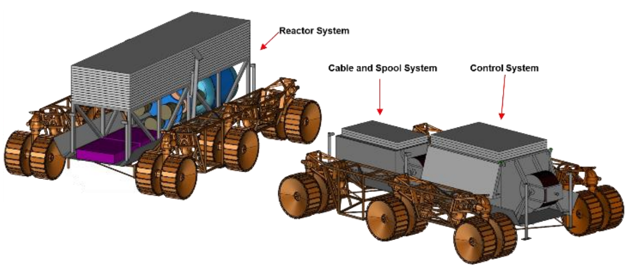

Fig. 5. Reactor system, Control system, and Cable and Spool system elements mated to the rover chassis.

III. SYSTEM DESIGN

MEL Summary: Deployable 40kWe FSPS CD-2021-187 Main Subsystems	Fission Surface Power System Mass (kg)	Control Systems Mass (kg)	Cable and Spool Mass (kg)	Total carried by Lander Mass (kg)
Fission Power System	3969	0	0	3969
Electrical Power Subsystem	0	733	357	1090
Command and Data Handling	0	46	0	46
Communications	0	26	0	26
Thermal Control	1101	184	68	1353
Structures and Mechanisms	520	269	172	962
Element Total (Basic Mass)	5590	1258	597	7446
Element Total (Basic Mass)	5590	1258	597	7446
Element Mass Growth Allowance (MGA)	905	401	177	1483
MGA Percentage	16%	32%	30%	20%
Predicted Mass (Basic+MGA)	6496	1659	774	8929
System Level Mass Margin	839	189	90	1117
System Level Margin Percentage	15%	15%	15%	15%
Element Mass (Basic+ MGA+Margin)	7334	1848	864	10046
	Mobility System Trip 1	*Mobility System Trip 2*		

Fig. 6. Master Equipment List (MEL) summary information for the three FSPS elements.

The 40kWe deployable FSPS was designed following AIAA[9] recommendations for mass growth allowance (MGA) and system-level margin. MGA is estimated by the subsystem leads at the component level based on the design methodology used for each component and 15% system-level growth is added to achieve a "green" rating across the board for the mass risk assessment at authority to proceed (ATP). The mass list in Figure 6 shows the basic subsystem masses for each element, along with the MGA and margin totals. It also notes which elements are carried in which mobility system trip for clarity. Figure 7 shows the mass assumptions for the mobility system (rover chassis).

MEL Summary: Deployable 40kWe FSPS CD-2021-187 Main Subsystems	Mobility System Mass (kg)
Element Total (Basic Mass)	1600
Element Mass Growth Allowance (MGA)	240
MGA Percentage	15%
Predicted Mass (Basic+MGA)	1840
System Level Mass Margin	240
System Level Margin Percentage	15%
Element Mass (Basic+ MGA+Margin)	2080

Fig. 7. Mobility system (rover chassis) mass assumptions.

III.A. Reactor Element Design

III.A.1. Reactor Design

A previous NASA analysis developed a highly enriched uranium (HEU) fueled fast-spectrum reactor (175 kWth) to meet these same functional needs[10]. Recently, Los Alamos National Laboratory (LANL) undertook a preliminary assessment of alternatives to develop a high-assay low-enriched uranium (HALEU) fueled reactor design. Results indicate that yttrium hydride (YH)-moderated HALEU fueled reactors could be used to achieve the required functionality. This HALEU FSPS reactor will need to provide ~250 kWth to supply the required 40 kWe for 10-year operation. The basic HALEU design would use ~20% enriched uranium nitride (UN) pellets with sodium (Na) – molybdenum (Mo) (steel-wick) heat pipes and a YH moderator.

Reactor shielding is a major portion of the reactor mass but can be reduced by situating the power conversion, control electronics, and indeed the crew, at appropriate distances. Table I shows the assumptions used in this analysis.

TABLE I. Distance/ Radiation Tolerance Assumptions.

Item	Distance	Radiation Tolerance
Stirling Components	1 m	n: 5×10^{14} n/cm^2 (>100 keV) Gamma: 25 MRad (Rad Si)
Electronics	10 m	n: 5×10^{11} n/cm^2 Gamma: 25 kRad
Humans (Crew)	1 km	Total 5 rem/yr (gamma + neutron); 100% occupancy; 1 km wide

Assuming the one km distance and the requirement for less than 5 rem/yr for permanently present crew, a shadow shield approach was taken. This eliminates a heavy, four-pi-shield, but would require the crew to remain in a one km wide area, one km from the reactor. A mass breakdown of the fission power subsystem for the 40kWe design can be seen in Table II. Note that these are basic masses and do not include MGA or margin.

TABLE II. Fission Power Subsystem Mass Breakdown.

Name	QTY	Unit Mass (kg)	Basic Mass (kg)
Primary Heat Exchanger	1	497	497
Shielding- LiH & W	1	1250	1250
Reactor Control and Instrumentation	1	6	6
Reactor Control Mechanism	1	18	18
Stirling Convertors – gas bearing	8	110	878
Stirling Convertor to Reactor Structure	8	12	93
Balance of Core Assembly	1	1000	1000
Assembly Structure and Cold Plate	1	228	228

III.A.2. Power Conversion Design

Based upon development efforts during the KiloPower program, thermal losses from the reactor were estimated to be 18%. Additionally, thermal losses from the reactor to the Stirling convertor hot end interface were 2% based upon recent work at Glenn Research Center (GRC). Significant research and development have gone into the development of 6 kWe-class Stirling convertors, both in and outside of NASA. Because of this, a configuration of eight, 6.2 kWe convertors operating as dual opposed pairs were selected after the downstream power management and distribution system losses were estimated. No spare convertors are included for this architecture, and if Stirling convertors fail (forced to fail in pairs), power output from the system would degrade by approximately ¼ for each lost pair.

A hot end temperature of 700°C (973 K) was set by material limits of the superalloy used for Stirling convertors designed for long-duration operation. Normally, a spectrum of cold end temperatures is traded with the final cold end temperature selected based on which provides the best specific mass (W/kg). Because reactors scale [specific power (W_{th}/kg)] very efficiently with increasing power, the overall system tends to have lower temperature ratios than radioisotope power systems. Therefore, an optimal temperature ratio of about 2.0 was found to maximize specific power. Due to limitations in alternator organics development, the cold end temperature was limited to 150°C (420K) rather than the best specific system power cold end temperature of 460 K.

Overall end-to-end thermal to electric efficiency is 18.1%. Convertor efficiency is 26.1%, while downstream power management and distribution (PMAD) efficiency is 87%. Radiator inlet/outlet temperatures via a pumped fluid are 420 K/370 K respectively.

III.A.3. Thermal Design

There are three main components to the reactor power system. Each has a separate thermal control system needed for their operation on the lunar surface. Also included is a shunt radiator for rejecting waste power from the reactor. Table III identifies the assumptions and requirements for the thermal system designs.

TABLE III. Thermal System Design Specifications.

Specifications	Value/Description
Waste heat: Fission Reactor Electronics/Shunt Power Distribution	 126,400 W 5,100 W 2,000 W
Operating Temperature	Average reactor operating temperature 395 K (420K inlet, 50 K Temperature drop across the radiator with exit temperature at 370 K), Electronics ~271 K to 310 K (-3 °C to 37°C), Shunt Radiator 800 K
Multi-layer insulation (MLI)	25 layers of MLI are used to cover all external surfaces for the electronics enclosure and back side of the shunt radiators.
Environment	Lunar polar operation 50 K to 220 K surface temperature range
Radiators	Reactor: Accordion Deployable, Double Sided Electronics: Fixed, Single Sided Shunt: Fixed Single Sided
Cooling	Reactor: Pump Loop Cooling System Electronics: Heat Pipe Cooling System Shunt: Electrical Heaters
Heating	Electric heaters are used to provide heating to the internal components as needed.

The radiator is deployed vertically on the top deck of the transport sled with both the front and back sides acting as radiating surfaces. This provides a good view to deep space and the surrounding lunar surface. The reactor main radiator is based on International Space Station (ISS) radiators. The system provides the ability to utilize space qualified hardware and flight heritage in the radiator and coolant system design. The design specifications are shown in Table IV.

The pump loop cooling system utilized with the reactor represents a generalized approach to the coolant system components for the reactor radiator pump loop coolant system. The layout is like that utilized by the ISS, providing development benefits since that system has space heritage.

A worst-case sun angle (solar flux normal to one side of the radiator) onto the radiator was assumed. However, due to the dual-sided operation of the radiator, the opposite side only had a view to deep space and the surface. This situation was approximated by a 45° sun angle to the total radiator area. The radiator sizing was based on an energy balance analysis of the area needed to reject the identified heat load to space. From the area, a series of scaling equations were used to determine the mass of the radiator.

TABLE IV. Reactor Radiator Design Specifications.

Variable	Value
Radiator Solar Absorptivity	0.14
Radiator Emissivity	0.84
Max Radiator Sun Angle	45°
View factor to lunar surface	0.5
View factor to deep space	0.5
Radiator Operating Temperature	In sunlight: 395 K nominal (420 K inlet, 370 K exit) In shadow: 375 K nominal
Power Dissipation & Radiator Area (operation at the pole)	126,400 W 133.4 m^2 (Accordion Deployable)
Power Dissipation & Radiator Area (operation at the equator)	126,400 W 216.2 m^2 (Accordion Deployable)

The radiator was sized to remove the waste heat from the reactor during worst case hot operational conditions, which occur while sunlit on the lunar surface under full power operation. A pump loop cooling system was baselined as the means of moving heat from the Stirling engines to the radiator. If operation was moved from the pole to the lunar equator, a 62% increase in radiator surface area would be required.

TABLE V. Electronics and Shunt Thermal Control System Specifications.

Variable	Power Production Electronics	Shunt Radiator	Power Distribution Electronics
Radiator Solar Absorptivity	0.14	0.14	0.14
Radiator Emissivity	0.84	0.84	0.84
Max Radiator Sun Angle	45°	45°	45°
View Factor to Lunar Surface	0.5	0.3	0.5
View Factor to Deep Space	0.5	0.7	0.5
Radiator Operating Temperature	Electronics: 288 K-300 K	795 K-800 K	Electronics: 288 K-300 K
Power Dissipation & Radiator Area:	5,100 W, 15.3 m^2, (Double Sided, Deployable)	40,000 W, 2.1 m^2 (Single Sided, Fixed)	2,000 W, 6.0 m^2 (Double Sided, Deployable)
Heat Transfer Method	Cold plates with variable conductance heat pipes	Electrical Power	Cold plates with variable conductance heat pipes

The other main segments of the reactor system that require thermal control are the power distribution system; shunt radiator, used to radiate excess power from the reactor to space; and the power electronics. Both systems utilize deployable accordion radiators like the main reactor radiator. The heat transfer system for both utilizes heat pipes to move the heat from the electronics to the radiator. The shunt radiator is a fixed flat plate radiator with integral electrical resistors for rejecting the excess electrical power. The details of these three heat rejection systems are summarized in Table V.

III.A.4. Reactor Element Configuration

The reactor system is located inside the box truss structure with the reactor side at one end of the truss and is mated directly to the base of the sled in a horizontal position. In addition to the actual reactor, the system includes radiation shielding, two cold heat exchangers, a hot heat exchanger, four opposing pairs of Stirling converters, and the heat pipes used to transfer the heat from the reactor to the heat exchangers. Also mounted directly to the sled structure at the opposite end from the reactor are the two boxes that make up the coolant pump system for the reactor radiator. The system stows to a length of 461 cm, width of 160 cm, and height 160 cm.

Once the system is deployed from the rover chassis, the two outriggers and the double-sided reactor radiator must be deployed. Located near the middle and on the long sides of the sled base are the outriggers, which will pivot downwards to the surface. The deployment concept for the reactor system element is shown in Figure 8.

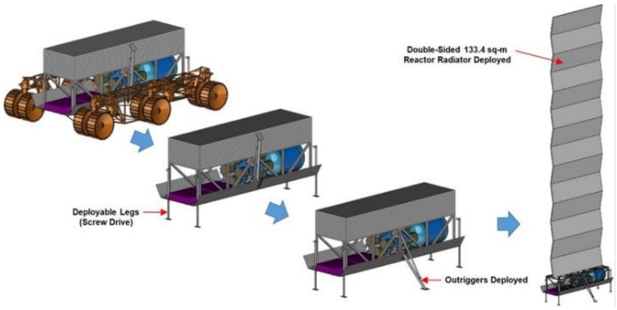

Fig. 8. Deployment of the reactor system element.

The fully deployed outriggers triple the base width provided by the sled legs alone (to 320 cm), creating a significant increase in stability in the event the fully deployed radiators experience any tip over to one side or the other at the top. The radiator deployed height is ~16 m to achieve the required 134 m^2 radiator area. The sled legs are 60 cm, leading to an overall system height of 17.6 m.

In addition to the reactor radiator, outriggers, box truss structure, and sled structures and mechanisms, those components located on the reactor system element include the reactor system and the coolant pump system for the radiators. All these components are shown in Figure 9.

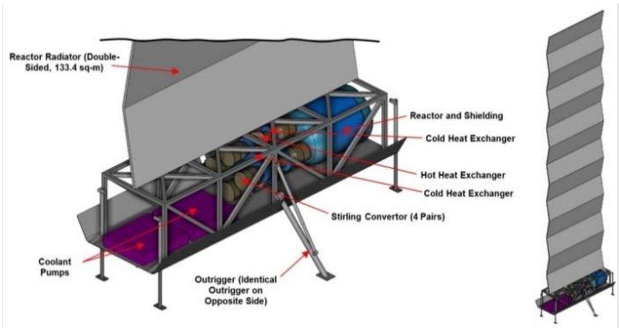

Fig. 9. Components on the reactor system element.

III.B. Control System Element Design

III.B.1. Controller Design

Stirling convertors are used to convert heat energy from the reactor into reciprocating motion in the linear alternator and then into electrical energy. The flow of heat energy from the reactor into the engine is constant on the time scale of the engine reciprocating frequency and therefore constant electrical energy must be drawn from the alternator to prevent an energy imbalance in the Stirling convertor, which would manifest as the acceleration and overstroke of the piston. The electrical energy drawn from the engine must be equal to the thermal energy into the engine minus losses averaged over the full piston stroke. It is impossible for the user load to perfectly match the constant heat input, and therefore a controller is required to continuously regulate engine operation independent of both the user load and the precise thermal input.

At their core, the controllers specified for this design are power factor correcting boost rectifiers that modulate the load they impose on the engine to limit the piston stroke of the engine to the designed amplitude. This convertor load holds constant independent of the variable user load. Excess energy from Stirling convertors not sent to the user is dissipated in a resistive load bank to maintain the energy balance in the system. Because the Stirling convertors are short-stroke reciprocating alternators, they produce a single-phase alternating current (AC) with a corresponding power waveform that ripples at twice the electrical frequency. A large capacitive bank is required to buffer the rippling AC power into DC, and this bank represents a significant portion of the controller volume. A wide variety of strategies have been proposed and demonstrated to accomplish Stirling control, but all utilize similar power conversion hardware, which was the focus of the sizing efforts in this study. Full controller redundancy is included the design.

III.B.2. Power Conversion/Cabling Design

The power design for the control system is shown in Figure 10. Eight pairs of 10-AWG copper wiring transfer single-phase, 240 VAC, 50 Hz power from the Stirling generators to the Stirling controllers over 50m. Stirling controllers, sized here as AC-DC rectifiers, convert the 240 VAC into a nominal 400 VDC. Each of the eight parallel rectifiers is connected to a Stirling generator and outputs up to 5.9 kW. A DC-DC converter unit (DDCU) boosts the 400 VDC up to ±2800 VDC for the power transfer cable in the cable/spool system downstream. Estimated component efficiencies are labeled in the figure as percentages. The final end-to-end efficiency between the Stirling terminals and the end user load (see Section III.C) is ~78%.

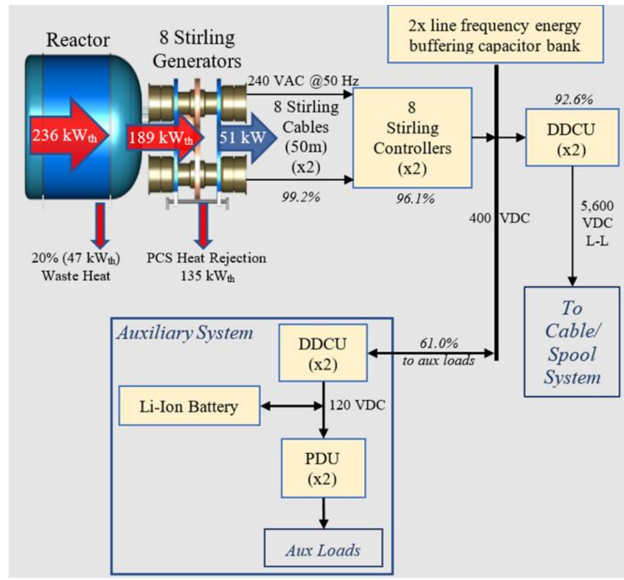

Fig. 10. EPS design of the control systems element.

The auxiliary system provides for power needs during reactor startup. The auxiliary DDCU allows for bi-directional power flow and conversion between the 400 VDC main bus and the 120 VDC auxiliary system, as reactor startup power must flow from the battery back up through the auxiliary DDCU. After startup, the reactor supplies power to the cable/spool system as well as to the auxiliary DDCU for battery charging and power distribution. The auxiliary power distribution unit (PDU) provides ~374 W to the 120 VDC auxiliary loads.

The rectifiers and DDCU were sized using the Metcalf Model[11], which is based on ISS power components, and the PDU was sized from NASA GRC's Advanced Exploration Systems (AES) Modular Power System (AMPS) components[12]. For single-fault tolerance, each non-battery component in the system has one fully redundant unit – e.g., there are 16 total Stirling cables, 16 total rectifiers in parallel, 2 auxiliary DDCUs, etc. – as indicated by "x2" in the figure. To provide sufficient startup power, the rechargeable lithium-ion battery was sized to 4000 W for 1 h (4 kWh) with a maximum depth of discharge (DoD) of 80%. The battery design has a specific energy of ~173 Wh/kg and uses commercial off-the-shelf (COTS) LG 18650 MJ1 battery cells in a 34S-13P cell configuration, which includes one spare string of cells for single-fault tolerance.

III.B.3. Control Systems Element Configuration

The stowed control system element is 160 cm wide, 278 cm long, and 123 cm tall. The deployment concept for the control systems element is shown in Figure 11. Once deployed, the system is 623 cm tall. In addition to the electronics radiator, those components located on the outside of the box truss structure include: two fixed, single-sided shunt radiators; the spool containing 50 meters of cabling; and two low-gain Ka band antennas. All the external components can be seen in Figure 12.

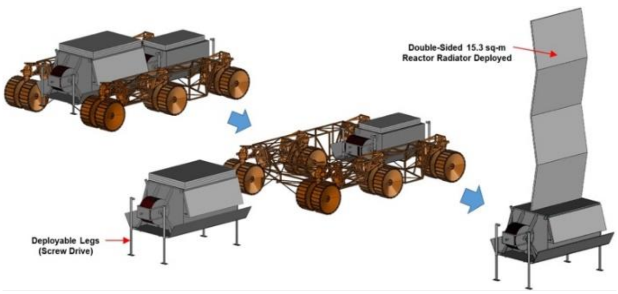

Fig. 11. Deployment of the control system element.

The spool is sized to carry the 50 meters of cable that runs between the reactor system and control system elements. Located at the top two corners on the spool end of the box truss structure are the two low-gain Ka band antennas. Each antenna provides a hemispherical coverage area, thus due to their location, two antennas were used to eliminate the obstruction from the deployed electronics radiator. Coverage can be passed from one antenna to the other as the target becomes obstructed by the electronics radiator ensuring continual coverage while the target is in view. Those components located inside the closed-out box truss structure include: all the electronics of the EPS; all the electronics for the Communications System; and the enclosure for the cards that comprise the Command and Data Handling (C&DH) system.

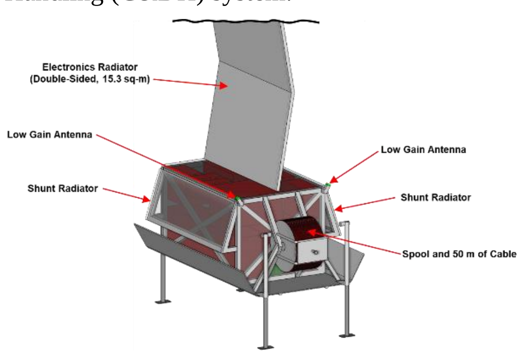

Fig. 12. Control systems element with external components called out

Overall length of the box truss structure is driven by the length of the Stirling controllers as they are the largest of the electronics boxes. Both Stirling controllers are mounted directly to the base of the sled structure. The remaining EPS electronics and battery are mounted directly to the top closeout panel for the box truss. This top panel is a 1-inch-thick honeycomb panel rather than the thin face sheets used for the other four side closeout panels.

Those communications system electronics located inside the box truss structure include two Traveling Wave Tube Amplifiers (TWTA) and Electronic Power Conditioners (EPC), two splitter/combiners, two Ka-band Small Deep Space Transponder (SDST) radios, and two frequency diplexers.

III.C. Cable and Spool System Element Design

III.C.1. Power Transmission Cable System

In implementation, FSP transmission voltage and form (AC vs. DC) will be set by trades considering system mass minimization, reliability, radiation-hardened component availability, and programmatic risk. An AC system will utilize transformers for voltage boost and buck eliminating the need for high voltage, single-event tolerant FETs. In this study, the cable efficiency was held at 95%, and an optimization was performed to trade the mass of aluminum conductors versus the mass of wire insulation over cable operating voltage. This design only allocated mass for a vacuum-rated insulated cable without considering micrometeor shielding or redundancy. The minimum wire gauge was capped at 16 AWG for mechanical strength. Figure 13 shows the mass vs. voltage for a one km cable carrying 43.5 kWe of power at 95% efficiency. This design reaches a mass minimization of ~45 kg at ±2800 VDC. A similar sweep can be performed for an AC design, resulting in an overall cable which is slightly heavier due to the need for increased insulation thickness because of the increased insulation degradation caused by the AC voltage waveform. Note that the mass reduction offered by elevated voltages is accentuated at longer transmission distances. Holding efficiency at 95%, a 3 km cable would weigh 3300 kg at 500 V and 240 kg at 2800 V.

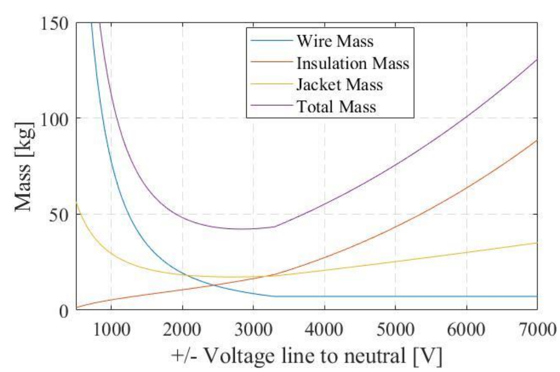

Fig. 13. Wire mass trend for a 1 km, 95% efficient DC insulated, aluminum cable as a function of transmission voltage.

III.C.2. Power Down Convertor

The downstream power system consists of a DDCU and a PDU as shown in Figure 14, with an additional DDCU and PDU included in the design to provide single-fault tolerance. The DDCU bucks the ±2800 VDC from the transmission cable to 120 VDC for the user loads. The PDU provides fault protection and distribution of the 40 kWe as eight 5 kWe user output feeds to the end user. Both component types were sized using the Metcalf Model[11]. Estimated component efficiencies are labeled in the figure as percentages.

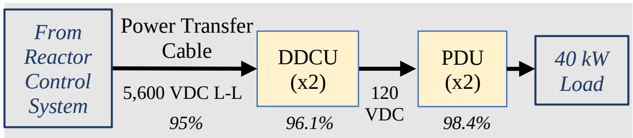

Fig. 14. EPS Design of the cable and spool system.

III.C.3. Cable and Spool System Configuration

The stowed cable and spool system element is 160 cm wide, 224 cm long, and 85 cm tall. As with the control system element design, a box truss is used to provide space for the stacked electronics radiator panels stowed on top, and closeout panels are added to the box truss to assist in mounting the insulation required to provide an acceptable thermal environment for the electronics contained inside the truss.

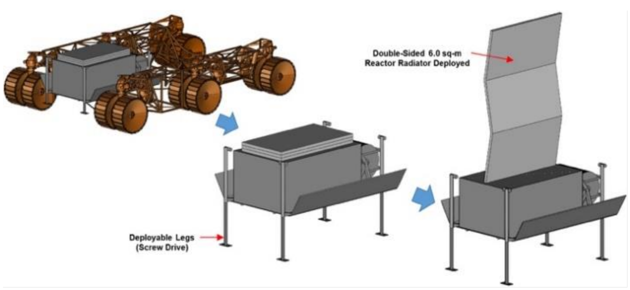

Fig. 15. Deployment of the cable and spool systems element

Those components that require deployment once on the surface include the double-sided electronics radiator and the one km of cabling that will be deployed as the rover transports the cable and spool system element to the end user location one km away from the reactor system element. The deployment concept for the cable and spool system element is shown in Figure 15. Once deployed, the system is 350 cm tall.

In addition to the electronics radiator, the only other component located on the outside of the box truss structure is the spool containing one km of cabling, as seen in Figure 16. Those components on the cable and spool systems element that are located inside the closed-out box truss structure are the two DDCU and the two PDU of the EPS. All four boxes mount directly to the sled base structure.

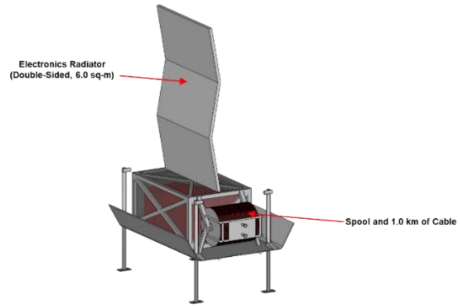

Fig. 16. Cable and spool system element with external components called out.

IV. CONCLUSIONS

The 40 kWe conceptual design shows just one design solution for such a power system, focusing on nearer-term technologies. The ~10 t-design is far above the goal of 6 t and cannot be landed with the chosen mobility system. Using the current rover chassis to deploy the 40 kWe system requires that it be deployed as three separate elements due to volume and mass constraints of the rover. These three separate elements add complexity, mass, and an additional trip to/from the lander. A new, dedicated rover could be developed, but at added cost.

By laying down the reactor and placing the control electronics 50 m away, directional shielding can be optimized to provide the 5 rem/year for the crew and eliminate added shielding for the control electronics. In the current configuration, adding distance between the reactor and the crew or moving the reactor over the horizon will not reduce shield mass.

Two other options were addressed at least cursorily: modifying the design for lunar equatorial use and keeping the reactor on the lander. Modifying the design for equatorial use was estimated to require 62% more radiator area and different radiator configurations for all elements. Keeping the reactor on the lander seems to have a similar design solution to the current point design; assuming the lander can be placed more than one km from the crew, the current reactor pallet could be kept on the lander – only the control system and cable and spool system would need to be unloaded and deployed. Further work is needed to assess radiation and any interactions with the lander.

ACKNOWLEDGMENTS

This design concept study was performed for the NASA Fission Surface Power Project. The authors would also like to thank the following for their assistance with the design: Omar Bekdash, James Fittje, John Gyekenyesi, Nicholas Lantz, Bushara Dosa, and Christine Schmid.

REFERENCES

1. B. DRAKE, editor, “Human Exploration of Mars: Design Reference Architecture 5.0,” *NASA/SP-2009-566* (2009).

2. D. POSTON, L. MASON, and M. HOUTS, "Radiation Shielding Architecture Studies for NASA's Lunar Fission Surface Power System," *NETS*, Atlanta, GA (2009).

3. FISSION SURFACE POWER TEAM, "Fission Surface Power System Initial Concept Definition," *NASA Technical Reports Server*, Cleveland, OH (2010).

4. L. MASON, D. POSTON, and L. QUALLS, "System Concepts for Affordable Fission Surface Power," *NASA Technical Reports Server*, Cleveland, OH (2008).

5. "Fission Surface Power (FSP) Project Statement of Work (SOW) No. 18960 Revision ID: 0," *sam.gov* (2021).

6. NASA, "Human Class Cargo Lunar Lander (HCCLL) System to Cargo Interface Requirements Documents (IRD)- HLS-IRD-010," *NASA*, Houston, TX (2021).

7. NASA, "NASA Facts: Space Exploration Vehicle Concept: FS-2011-08-045-JSC," *nasa.gov*, Houston, TX (2011).

8. M. GERNHARDT et al., unpublished analysis and conceptual design in support of *Human Exploration and Operations Mission Directorate*, Systems Engineering and Integration, National Aeronautics and Space Administration (2020).

9. AIAA, "Standard: Mass Properties Control for Space Systems (ANSI/AIAA S-120A-2015 (2019))," *AIAA*, Reston, VA (2019).

10. L. MASON, D. POSTON, and L. QUALLS, "System Concepts for Affordable Fission Surface Power," *NASA Technical Reports Server*, Cleveland, OH (2008).

11. K. J. METCALF, "Power Management and Distribution (PMAD) Model Development: Final Report," *NASA Technical Reports Server*, Canoga Park, CA (2011).

12. K. BOZAK et al., "Advanced Modular Power System (AMPS) Project 101," *NASA Technical Reports Server*, Cleveland, OH (2020).