IAC-24-C3.3.4

Current Status of NASA's Fission Surface Power Project

Lindsay K. Kaldon[a], Andrew L. Presby[a], Lee S. Mason[a], Bryan K. Smith[a], Aaron S. Weaver[a]

[a] *National Aeronautics and Space Administration, Glenn Research Center, 21000 Brookpark Rd, Cleveland, Ohio 44135,* lindsay.k.kaldon@nasa.gov, andrew.l.presby@nasa.gov, lee.s.mason@nasa.gov, bryan.k.smith@nasa.gov, aaron.s.weaver@nasa.gov

Abstract

Small nuclear fission systems are powerful and could enable robust space operations for planetary habitation and exploration. On Earth, unless disrupted by storms or grid problems, electrical power for most people is no further than an outlet away. However, the solar system does not provide such easy access to electricity as we know it. Astronauts could take advantage of a reliable power supply to explore both the Moon and Mars. The system will need to be lightweight and capable of running regardless of its location, the weather, or available sunlight and other natural resources. NASA's Fission Surface Power (FSP) project expands on the efforts of the agency's Kilopower project, which ended in 2018. Currently, NASA is working with the US Department of Energy and industry to design a fission power system that would provide at least 40 kilowatts of power – enough to continuously run 30 households for ten years. A future lunar demonstration will pave the way for sustainable operations and even base camps on the Moon and Mars. This manuscript will showcase the current state of the FSP project, technical goals and accomplishments, future plans, and how this technology paves the way for exciting future applications.

Keywords: nuclear, fission, surface, power, technology

Nomenclature

kW_e kilowatt electric
MW_e megawatt electric

Acronyms/Abbreviations

CTE Critical Technology Element
DAC Design Analysis Cycle
DOE Department of Energy
DUFF Demonstration Using Flattop Fission
ESDMD Exploration Systems Development Mission Directorate
FSP Fission Surface Power
GRC Glenn Research Center
HALEU High Assay Low Enriched Uranium
INL Idaho National Lab
KRUSTY Kilopower Reactor Using Stirling Technology
LANL Los Alamos National Lab
NEP Nuclear Electric Propulsion
ORNL Oak Ridge National Lab
RFP Request for Proposal
STMD Science Technology Mission Directorate
TMP Technology Maturation Plan

1. Introduction

Fission surface power is both an essential and sustainable segment of the lunar and Mars power architectures, leverages innovation in commercial microreactor technologies that support national net-zero carbon goals, and reduces technology risks for future Nuclear Electric Propulsion (NEP) systems.

NASA's FSP project is part of NASA's Science Technology Mission Directorate and is managed out of Glenn Research Center (GRC) in Cleveland, Ohio. The current design elements include a high assay low enriched uranium (HALEU)-fueled reactor with an output power of 40kWe, designed for a 10-year life without the need for maintenance. The mass goal is under 6,000 kg (6 metric tons) and a volume of 4m x 6m in a stowed configuration.

1.1 Goals and Objectives

The goals of the Fission Surface Power (FSP) project align with Space Policy Directive Six [1], the NASA 2022 Strategic Plan [2], and priorities in subsequent annual budget submissions. The project immediately supports NASA Strategic Goal 2: "Extend Human Presence to the Moon and on towards Mars for Sustainable Long-term Exploration, Development, and Utilization" and Strategic Goal 3: "Catalyze Economic Growth and Drive Innovation to Address National Challenges."

The project is specifically cited as the closure plan for STMD's 2022 Strategic Framework Thrust 3 Gap A: "Live: Power and Energy Storage: Fission Surface Power" [3]. FSP directly addresses the two top technology shortfalls listed in the 2024 Civil Space Shortfall Ranking document and indirectly addresses over fifteen additional gaps [4]. Furthermore, FSP addresses the NASA 2023 Climate Strategy [5] which identifies "small-scale nuclear" as a clean energy creation investment within the Agency's STMD portfolio.

1.1.1 Surface Power on the Moon and Mars

This initial generation FSP unit represents the first increment in a lunar power architecture as described in the Agency's September 2023 Moon to Mars Objectives [6] LI-1[L] to "develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels." The lunar demonstration also supports Moon to Mars Objective MI-1[M] to "develop Mars surface power sufficient for an initial human Mars exploration campaign."

Once on the moon, the FSP system will initially be demonstrated for up to one year, then would become available to the Exploration Systems Development Mission Directorate (ESDMD) to serve an additional nine years in an extended operational mission. The unit will be available to provide power to lunar surface architecture elements during the extended mission.

1.1.2 NEP Benefits

In addition to the enabling power source FSP provides for the surface of a celestial body, the technologies being invested in by the FSP project are applicable to future NEP systems. As shown in Figure 1, there are currently five critical technology elements (CTEs) identified in the technology maturation plan (TMP) for NEP systems [7], of which all but the Electric Propulsion Subsystem are currently being worked under the FSP project portfolio.

NEP Critical Technology Element (CTE)	FSP
Reactor and Coolant Subsystem (RXS)	✓
Power Conversion System (PCS)	✓
Power Management and Distribution (PMAD)	✓
Electric Propulsion Subsystem (EPS)	✓
Primary Heat Rejection Subsystem (PHRS)	✓

Fig. 1. NEP Critical Technology Elements (CTE)

1.2 Mission Architectures

This 40kWe reactor is the first generation FSP system, however a future FSP generation system may be in the MWe-scale to support in-situ resource utilization and the future lunar economy.

The scope of mission architectures and system concepts will encompass an array of lunar lander vehicles; surface deployment methods; system sizes and architectures; and mission durations and scope. The goal is to satisfy as many stakeholder expectations and project goals and objectives as possible while remaining cost effective. An analysis of alternative missions will inform the project's stakeholders of the cost, schedule, programmatic, and technical risk of meeting their expectations. This will enable risk-informed decision-making on the mission scope and architecture.

2. Background

In 2018, the Kilopower Project (aka Kilopower Reactor Utilizing Stirling Technology (KRUSTY) was successfully demonstrated in Nevada. The Kilopower Project stepped through a build-and-test sequence of phases that completed the demonstration of a flight like system operated at prototypic conditions in a relevant environment (Technology Readiness Level 5) for space science and human exploration power needs. This nuclear steady state and transient test of a space reactor was the first such experiment performed in the United States since the 1960s. This accomplishment established the readiness of nuclear-tested FSP technology for affordable, lightweight application to human and robotic exploration wherever it is needed [8].

The Kilopower Project was just one of several space fission systems NASA has pursued over the past several decades. In the early 2000s, the Prometheus Project intended to use a 200kWe NEP system to study Jupiter's icy moons for 20 years. Prometheus concluded in 2005 due to cost and complexity. The high temperature of the reactor was 1300K and the power conversion system utilized closed cycle Brayton technology [9].

Between 2010-2015, the Agency wanted a more "affordable FSP" for the moon and Mars, which resulted in the FSP Technology Demonstration Unit (TDU). This unit aimed to produce 40 kW for an 8-year surface mission using a low-temperature 900K reactor and Stirling power conversion. The agency built the TDU using full-scale components in a representative lunar configuration. The full system was installed in one of GRC's large vacuum chambers and operated at full power under representative lunar conditions [10].

NASA/DOE team desired an easier first mission – a smaller reactor that could compliment Radio Isotope Power systems, which rely on a tenuous supply of Pu238. The Demonstration Using Flattop Fission (DUFF) test was conducted in 2012 using an existing nuclear reactor located in a remote Nevada Test Site. It demonstrated proof-of-concept for a kilowatt-class space reactor with heat pipes and Stirling power conversion. The DUFF test took 6 months and cost

$1M. It was the first ever use of heat pipes with a reactor and the first ever reactor-heated Stirling. It produced 24 watts [11].

All the work done by NASA and DOE since Prometheus gives the current FSP project a deep repository of lessons learned and invested research into not only the reactor technology, but also balance of plant subsystems such as power conversion and heat transfer/rejection methods.

3. Project Execution

The FSP project is executed over two distinct phases. For a NASA project, FSP is considered in the Pre-Formulation phase (Phase 1), where gathering concept designs is the primary focus to support a mission concept review, acquisition strategy, system requirements review, and ultimately the release of a Request for Proposal (RFP) for Phase 2. Phase 2 covers the Formulation and Implementation phases for the remainder of the FSP lifecycle [12].

3.1 Phase 1

Three $5M concept design study contracts were awarded in 2022 to the following industry partnerships: Intuitive Machines with X-Energy, Lockheed Martin with BWXT, and Westinghouse with Aerojet Rocketdyne (now L3 Harris). The contracts completed in Sept 2023 and deliverables included concept designs, schedules, and cost estimates for a 40kWe FSP system that could operate on the surface of the moon for 10-years without need for maintenance or human intervention. There were only three requirements levied on the partnerships: to produce 40kWe for 10 years, for the reactor to withstand launch and vibration loads, and the radiation dose cannot exceed 5 REM/year above background at 1km away from the reactor (for astronaut safety).

The Phase 1 FSP design concept studies established several viable paths to developing and qualifying a fission power system for the lunar surface. The minimal number of requirements allowed for innovative concepts to come forward, ensuring the return-on-investment NASA was looking for. Challenges and risks were identified, and opportunities became known.

3.1.1 Phase 1A

After the conclusion of the Phase 1 studies, the project initiated follow-on Phase 1A studies. The objective of the Phase 1A scope of work is to continue to draw down technical risk for the final FSP design. The Phase 1A effort attempts to mitigate high risk design concepts identified during the Phase 1 design studies by furthering research and development within those areas. This effort increases the fidelity of the Phase 1 deliverables and reduces risks that are helping inform the government as it develops Phase 2 requirements.

3.2 Phase 2

Phase 2 will start with the release of an RFP to all industry and is planned to be an open and fair competition for the design, build, test and delivery of an engineering demonstration unit and reactor that will be flown to the moon. The timing of the release of the RFP for Phase 2 is pending current FY25 budgets.

3.3 Government Reference Design

As the three industry partnerships listed above were working on Phase 1, NASA in collaboration with DOE's National Labs (Los Alamos National Laboratory (LANL), Idaho National Laboratory (INL), and Oak Ridge National Laboratory (ORNL)), worked on an FSP concept as well using the same requirements industry had in Phase 1. GRC provided expertise, analysis, and design decisions for the power conversion, heat rejection, power management & distribution (PMAD), and mission integration. The DOE laboratories provided expertise, analysis, and design decisions for the reactor and shielding,

The primary objectives of the Government Reference Design (GRD) were: 1) acquire insights to help the government team be better informed during an acquisition, 2) identify risks and opportunities to inform government technology investments, 3) develop concepts that can be provided to NASA architecture study teams, and 4) collect data to guide the Phase 2 Request-for-Proposal (RFP) requirements.

The FSP GRD investigated a transportable 40 kW FSP system that included three separate pallets deployed from the lander (see Fig. 2) [13]. Beginning in Jan 2023, the FSP team completed three Design Analysis Cycles (DACs). These explored different technology variants and alternative mission integration options of the 40kWe system. DAC1 was completed in April 2023, DAC2 in Aug 2023, and DAC3 Nov 2023.

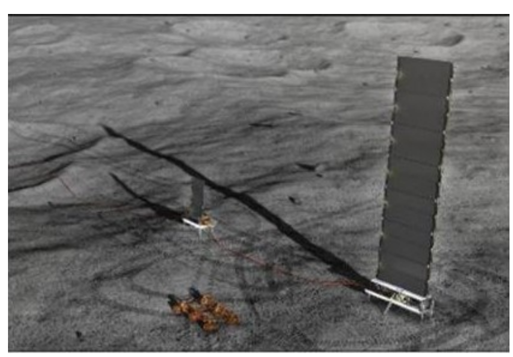

Fig. 2. FSP Government Reference Design

Overall, the aerospace and nuclear industry partners demonstrated how their unique skills and capabilities from commercial efforts directly enable and enhance space fission systems. The NASA/DOE team, in parallel with industry, performed a similar analysis in addition to technology readiness assessments and developed the timeline of technology maturation activities to enable risk-informed decision-making as the project develops its Phase 2 solicitation for a flight system.

5. Technology Maturation Efforts

The FSP project actively invests in technology maturation efforts each year, both in nuclear and non-nuclear activities. Subsystems that benefit from technology investments are [14,15, 16]:

- *Power Conversion:* Closed Cycle Brayton; Stirling
- *Radiation Tolerance*: Organics in PCS and Heat Pipe Fluids; Electronics Protection
- *Materials Research:* Advanced Manufactured Turbines and Heater Heads
- *Heat Rejection:* Radiation Dust Tolerance
- *Primary Heat Transfer*: Heat Pipes (Integrated Heat Pipe Stirling Test); Liquid Metal Pumps
- *Power Management and Distribution*: High Voltage Power Transmission
- *Reactor:* Metallic Hydride Moderators (Yttrium Hydride); Instrumentation and Control, Shielding

The intent of technology maturation activities is to improve the quality, readiness, and overall risk reduction posture of the fully integrated FSP flight unit, both current and future generations (kWe to MWe).

6. Summary

The FSP team is developing a system that meets NASA's goals and objectives for lunar and Mars surface power and provides synergetic technology maturation for NEP applications. In 2022, NASA issued Phase 1 single-year contracts to three industry teams for preliminary designs of integrated lunar fission power systems. NASA also initiated technology maturation efforts for non-nuclear subsystem areas to include power conversion, thermal efforts, and power management and, in collaboration with the Department of Energy (DOE), technology maturation for high-risk nuclear design elements.

These efforts, combined with a government reference design led out of GRC, constitute the Pre-Formulation and Formation efforts in NASA's project lifecycle plan. Phase 2 will be the official beginning of the demonstration flight project with the release of a solicitation to industry for the flight hardware contract. FSP is truly an enabling space technology for future surface and deep space capabilities.

Acknowledgements

Thank you to the entire NASA FSP team, to include the DOE, for its steadfast dedication towards placing a reactor on the moon someday!

References

[1] Office of the President, Presidential Policy Directive 6 "National Strategy for Space Nuclear Power and Propulsion", December 2020.
[2] NASA, 2022 Strategic Plan, March 2022.
[3] NASA, 2022 Space Technology Mission Directorate Strategic Framework, May 2022.
[4] NASA, 2024 Civil Space Shortfall Ranking, July 2024. (https://www.nasa.gov/wp-content/uploads/2024/07/civil-space-shortfall-ranking-july-2024.pdf?emrc=66de19a9608f6v)
[5] NASA, Climate Strategy, March 2023.
[6] NASA, Moon to Mars Objectives, March 2023.
[7] Adam K. Martin, Kurt A. Polzin, Francis M. Curran, Roger M. Myers, Mitchell A. Rodriguez (2022) A Technology Maturation Plan for the Development of Nuclear Electric Propulsion.
[8] Patrick R. McClure, David I. Poston, Marc A. Gibson, Lee S. Mason & R. Chris Robinson (2020) Kilopower Project: The KRUSTY Fission Power Experiment and Potential Missions, Nuclear Technology, 206:sup1, S1-S12, DOI: 10.1080/00295450.2020.1722554.
[9] NASA Jet Propulsion Laboratory, Prometheus Project Final Report, Oct 2005.
[10] Lee S. Mason, et al. "System Concepts for Affordable Fission Surface Power," (STAIF-2008).
[11] Marc A. Gibson, et al. "Heat Pipe Powered Stirling Conversion for the Demonstration Using Flattop Fission (DUFF) Test," NETS–2013–6812 (NASA/TM—2013- 216542), 2013.
[12] NPR 7120.5F, NASA Space Flight Program and Project Management Requirements, August 2021.
[13] Steven R. Oleson, et al. "A Deployable 40 kWe Lunar Fission Surface Power Concept," NETS-2022.
[14] Christopher Barth, David Pike, "Lunar power transmission for fission surface power," NETS-2022.
[15] Greeta J. Thaikattil, et. al. "Consolidation of a Sodium Heat Pipe and Stirling Engine for Fission Surface Power," TFAWS-2023.
[16] Advanced Closed Brayton Cycle (ACBC) Statement of Work (SOW), sam.gov (2023).