Overview of Nuclear Power Capabilities and Considerations for Applications on the Lunar Surface

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ABSTRACT

Lunar Fission Surface Power (FSP) systems are an enabling technology for the development of human activities on the lunar surface and beyond. FSP systems are game changing technology because its ability to provide kW and MW scales of power in compact form factors. Importantly, FSP systems can provide a solution for power and heat during the lunar night and in permanently shadowed regions.

Key to the successful implementation of lunar FSP systems is understanding the FSP design drivers, the different system architectures available, and the changing regulatory and policy environment surrounding their implementation. This poster presents an overview of these topics to better inform the community at large on the applicability of space nuclear power systems to the lunar surface.

DESIGN DRIVERS FOR LUNAR FSP SYSTEMS

The architecture of nuclear power for the lunar surface is principally driven by three drivers: ability to deliver the system (mass and volume), mission performance requirements (power and life-time), and long-term scalability (commercialization potential and meeting future demand). The first two are traditionally the primary drivers for historical and current NASA studies placing a focus on meeting stringent mass and volume requirements while providing power for deep-space science missions. With the shift to the moon and a long-term vision of enabling commercial activities on the lunar surface, the driver for long-term scalability has been added and is becoming increasingly important in determining the architecture if the reactor system. This last is gaining importance as decisions made to meet today's near-term mission will have a profound impact on scalability and the ability to meet future commercial needs.

Design Drivers for the Lunar Surface

Deliverability	Performance	Scalability
CLPS Lunar Lander	Artemis Base	Lunar Community
Mass / Volume	Power / Life-time	Commercial / Future Demand

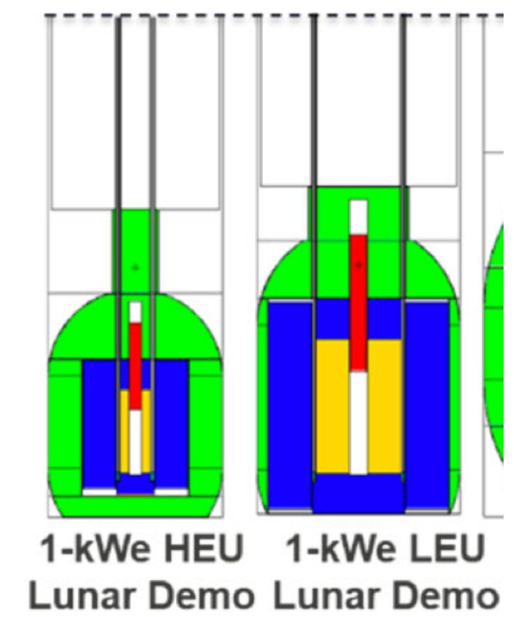
MEETING THE DESIGN DRIVERS OF FSP SYSTEMS

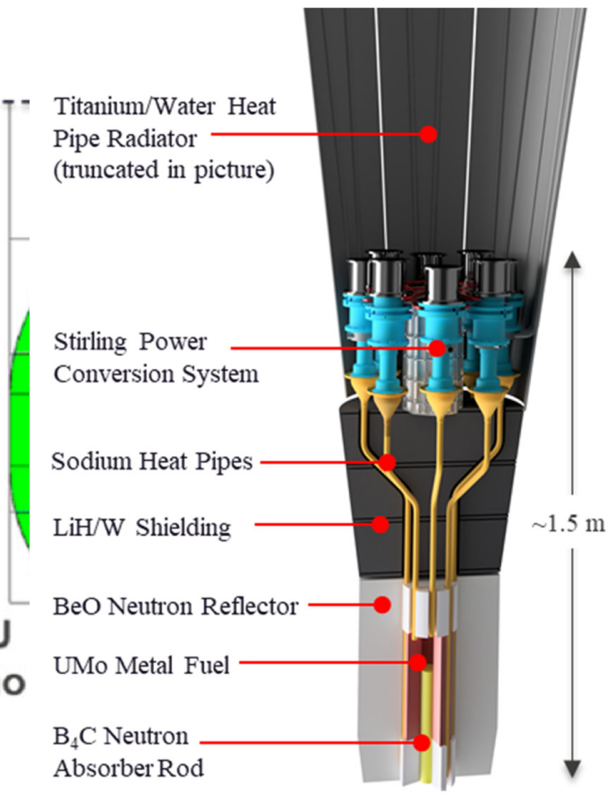
To meet the design drivers for lunar FSP systems, a number of systems architectures have been proposed. These can be divided into four broad architectures named after primary examples of their implementation: Fast metal fueled reactors, Fast ceramic fueled reactors, UZrH fueled reactors, and Moderated coated particle fueled reactor. While other architectures do exist, the bulk of proposed designs exist as sub-variants of these four. They are summarized in table below and then presented with further detail in the neighboring panel.

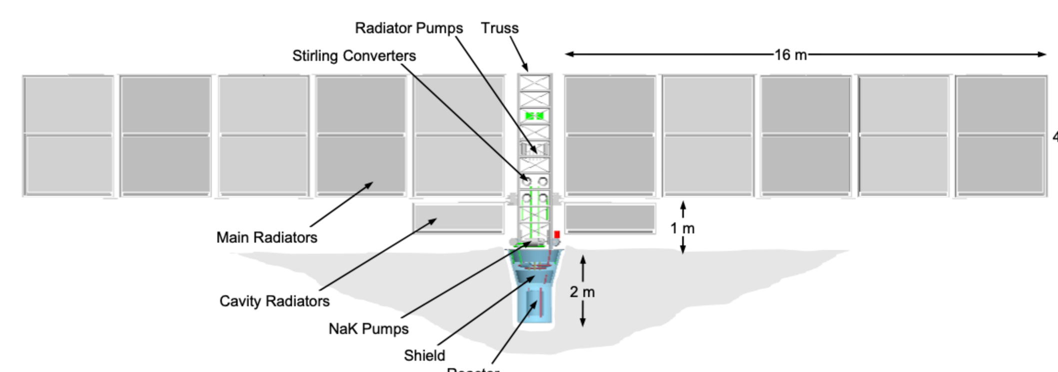
Category	Kilopower	FSPS	SNAP	Pylon
Relevant Program	Kilopower	FSPS (2000s), SP-100, SNAP-50	SNAP-10a	Pylon, JIMO-variant, USNC MMR, TCR
Fuel	Metal Fuel	UO2/UN in Metal Clad	Hydride Fuel	FCM™ (coated particle fuel)
Coolant	Heat-pipe	Metal coolant	Metal Coolant	Gas
Power Conversion	Sterling engine	Sterling	Thermoelectric	Brayton
HALEU Compatible	Good	Poor	Good	Good
Scalability Philosophy	Scalable to 50 kWe per unit	Scalable to MW per unit	Scalable to 50 kWe units	Scalable to MW per unit
NTP Technology Overlap	Poor	Poor	Poor	Good
NEP Technology Overlap	Poor	Good	Poor	Good

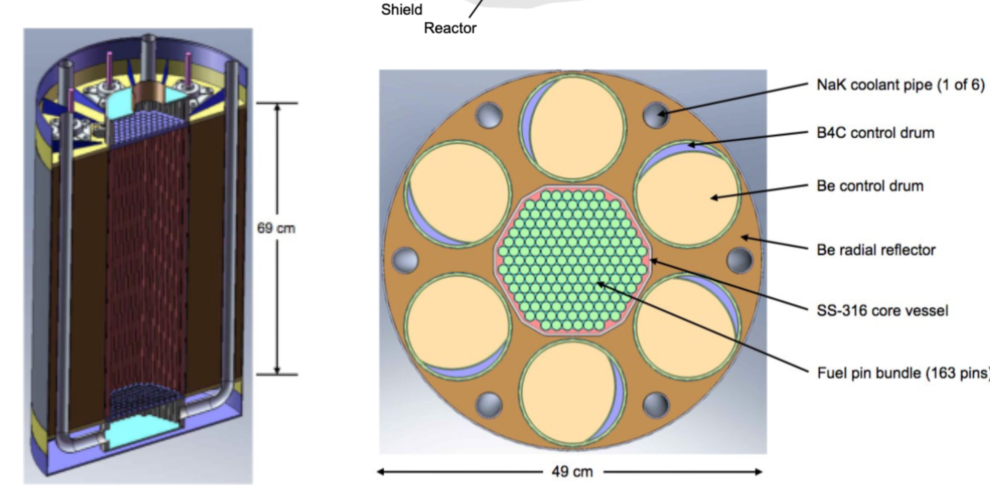
KILOPOWER [1][2]

The Kilopower reactor architecture is defined by the metal-fuel core at its center. Exemplified by the Kilopower reactor, it is comprised by a U-Mo metal cores surrounded by a BeO reflector and has in-core heat-pipes to transport heat to the sterling generators. The Kilopower architecture has been tested as part of the KRUSTY criticality experiment. Variations of Kilopower have been designed to go up to 10kWe using the same fuel and power conversion technology. While the architecture was originally designed around the use of HEU, it has since been shown the HALEU can be used and meet near-term mass requirements.







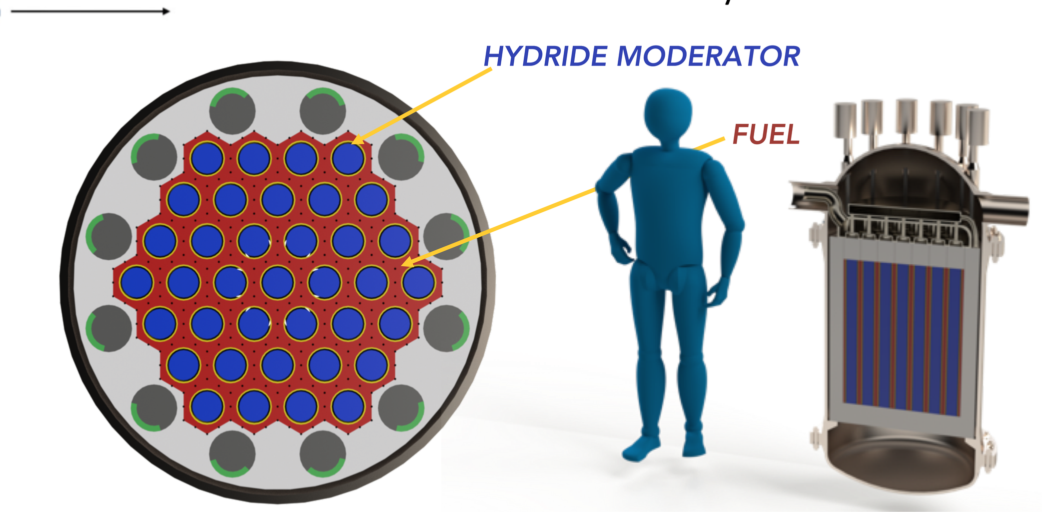


FSPS [3][4]

NASA's late 2000's FSPS is defined by the use of high-TRL components and materials. It is a NaK metal cooled system with UO2 fuel pellets clad in stainless steel. The power conversion uses a sterling engine to produce 40 kWe for 8 years. The reactor is a fast-reactor system and uses HEU. The system underwent considerable development and demonstrations of important sub-systems including full-scale radiator tests, multiple power conversion systems, and metal coolant pumps. The system was sized for deployment to the Lunar surface and extensibility to Mars missions.

PYLON [5]

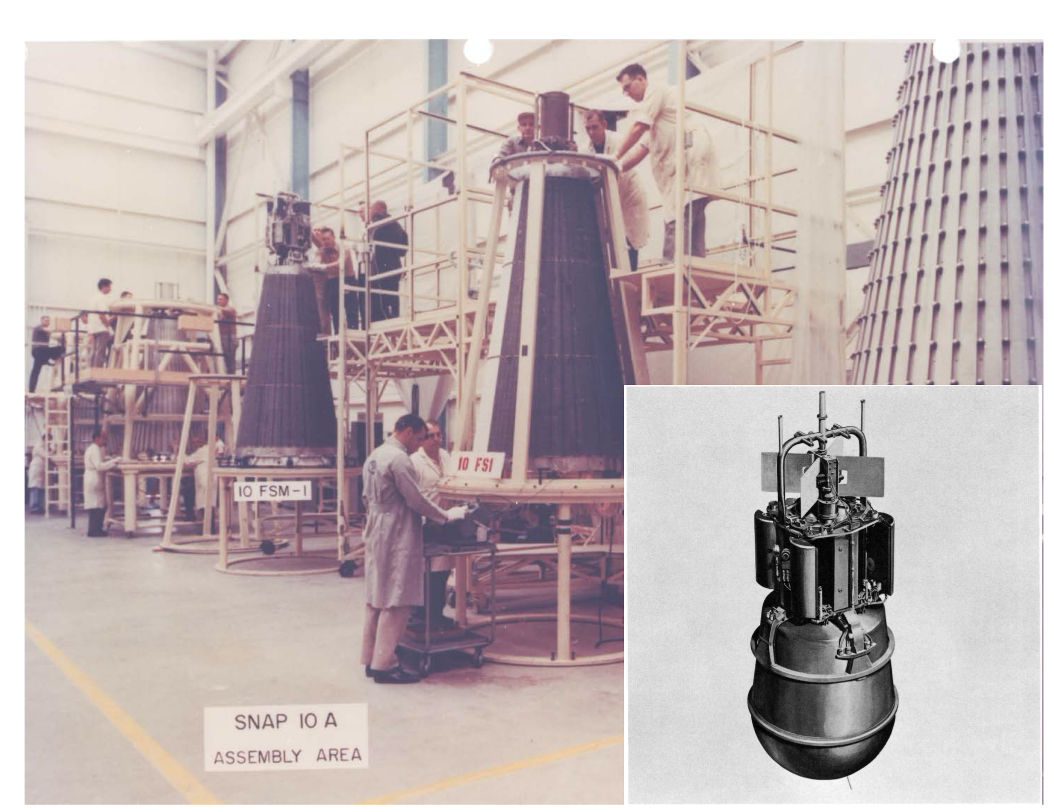
The Pylon is USNC-Tech's HALEU space reactor system. The Pylon architecture is a direct-Brayton gas-cooled reactor that uses a moderated thermal spectrum to enable the use of HALEU fuel. It utilizes FCM™ fuel technology (derived from USNC's MMR™ Reactor) to provide increased fission product retention and operating safety margins. The reactor architecture is scalable from 10 kWe up to the MWe scale without changes in central technology choices and materials. Current designs are sized to fit on CLPS landers such as the Blue Origin's Blue Moon.



Reactor	Reactor Mass (CBE) (kg)	Power Level (kW_{th})	Power per Reactor Mass (W_{th}/kg)
PYLON-10	950	60	60
PYLON-150	1,500	1000	650
PYLON-1000	3,000	6,000	2,000

Parameter	Value
Reactor Outlet	1,150 K (875°C)
Lifetime	10 years
Uranium Enrichment	19.75 % (LEU)
Fuel Type	FCM™

SNAP [6][7]

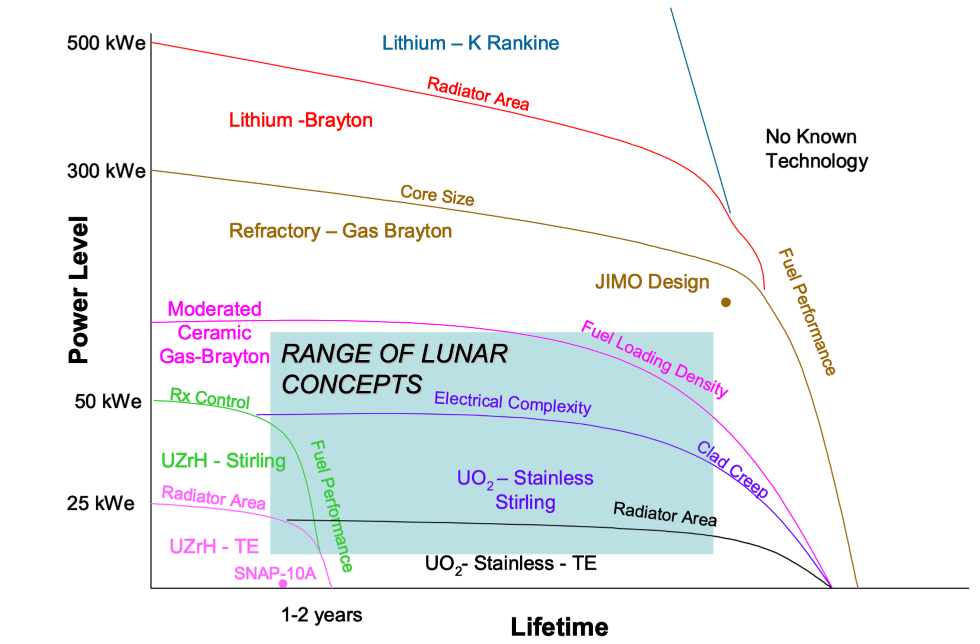


The SNAP reactor architecture is the original US space reactor design. It utilizes UZrH fuel to minimize both the reactor mass and fissile mass for the system. It is limited to lower temperatures (<700 C) and lower power levels due to the upper temperature limits of the hydride fuel. The fuel developed under the original SNAP program has seen continued use and development as part of the commercial TRIGA research reactors built and commercialized by General Atomics. Due to the thermal spectrum, the SNAP reactor architecture can accommodate HALEU fuel despite being originally designed for HEU fuel.

SCALABILITY OF LUNAR FSP ARCHITECTURE

In-situ resource utilization (ISRU), long term human presence, and commercial activity will eventually necessitate megawatt levels of power on the lunar surface. In the near-term, activities such as human presence through the lunar night and demonstrating ISRU processes require power on the scale of 50 kWe. This calls for any chosen reactor architecture to be scalable to meet these power levels beyond initial demonstrations. For scalability, there are two over-arching philosophies: 1.) modular scale-up and 2.) unit scale-up.

Under modular scale-up, additional units are added to meet growing demand. This attractive because each unit can be small and redundancy is built into the system. It has limitations due to the need for additional launches to deliver additional units. This has the unintended consequence of significantly increasing the cost of the entire system. Kilopower and SNAP are examples of architectures that would use this scale-up method.



Performance space for different nuclear system architectures for space applications [8].

With unit scale-up the same architecture and technology is used to design a build low and high-power systems. This is attractive because it is mass-effective and relies on continual improvement of a basic set of technology. It has limitations because the first generation of reactors will likely by lower performing than architectures optimized for performance at lower power levels needed for early demonstration missions. Pylon and FSPS are examples that would use this scale-up method.

The figure in this section presents a summary of how different reactor architectures scale in power as a function of reactor life-time. UZrH correspond to the SNAP architecture and the UO2 Stainless Stirling corresponds to the FSPS architecture. Enhanced FSPS with refractory cladding and Lithium coolants corresponds to Lithium-K Rankine. At the time of its publishing, Kilopower had not been developed but would fit in the same space as the UZrH Stirling. Pylon is an enhancement of the Moderated Ceramic Gas-Brayton with improvements in fuel loading. This allows it to operate in the same space as the Lithium-K Rankine systems.

THE CHANGING POLICY LANDSCAPE

The political and policy landscape surrounding nuclear systems in space has experienced developments in the last three years that will facilitate their deployment. Three key developments include the recent Presidential Memorandum on the launch of nuclear space systems, the political emphasis on the use of HALEU over HEU, and the renewed support for nuclear technology beyond space applications.

A key factor in the current enabling of space nuclear systems is the recent "Presidential Memorandum on the Launch of Spacecraft Containing Space Nuclear Systems"[9]. In this memorandum, the executive branch lays out a new process for securing launch approval for government owned space nuclear systems. The MOU introduces a tiered system for launch approvals where the level of approval needed for launch is dependent on the radio-toxicity or proliferation risk of the payload. In only one of the three tiers is presidential approval required. It also goes one step forward, and while it does not lay down a process for commercial systems, it does indicate that such a process will be developed.

The memorandum also lays out a clear distinction between HEU and HALEU systems, reflecting the political and non-proliferation imperative to restrict the use and potential proliferation of nuclear weapons. This shift away from the use of HEU is also prominent in NASA Nuclear Thermal Propulsion program as well as the DARPA DRACO program. The new guidance seems to be to use HALEU as a baseline and use HEU only in cases where HALEU is unfeasible.

Finally, nuclear power and technology has seen a renewed level of support and interest outside of space applications. This is shown in bipartisan support in congress for nuclear bills (Nuclear Energy Innovation and Modernization Act and the Nuclear Energy Innovation Capabilities Act) and the presence of nuclear energy as an energy solution for the future in both Democratic [10] and Republican party platforms (the Trump administration continues to lead the development of advanced nuclear power). These and other instances lend credence to the existence of continued support for both terrestrial and space nuclear systems into the foreseeable future,.

REFERENCES

[1]Poston, David; Gibson, Marc; McClure, Patrick; "KiloPower Reactors for Potential Future Space Exploration Missions," Nuclear and Emerging Technologies for Space 2019, Richland WA, 2019, http://anstd.ans.org/NETS-2019-Papers/Track-4--Space-Reactors/abstract-96-0.pdf.

[2] Gibson, Marc; Poston, David; Creasy, John; et. Al "Development of NASA"s Small Fission Power System for Science and Human Exploration," NASA Report NASA/TM-2015-218460, 2015, https://fas.org/nuke/space/krusty.pdf.

[3]Palac, Donald, "Fission Surface Power System (FSPS) Project Final Report for the Exploration Technology Development Program (ETDP)," NASA /TM-2011-2011-216975, 2011, https://strives-uploads-prod.s3.us-gov-west-1.amazonaws.com/20110007114/20110007114.pdf?AWSAccessKeyId=AKIASEVSKC45ZTTM42XZ&Expires=1602446785&Signature=aNc5n6Pvgoj%2BLKl%2BiIjsmssQVtk%3D.

[4] Mason, Lee; et. al, "Fission Surface Power Systems Initial Concept Definition," NASA Report NASA/TM-2010-216772, 2010.

[5] Eades, Michael; et. al, "The Pylon: Commercial LEU Nuclear Fission Power for Lunar, Martian, and Deep Space Applications," Nuclear and Emerging Technologies for Space 2019, Richland WA, 2019, http://anstd.ans.org/NETS-2019-Papers/Track-4--Space-Reactors/abstract-129-0.pdf.

[6] Schmidt, Glen, "SNAP Overview", 2011, http://anstd.ans.org/NETS2011/Documents/Presentations/Opening%20Dinner%20SNAP%2010A%20Schmidt.pdf.

[7]Atomics International, "SNAP 10A Reactor Design Summary", NAA Report NAA-SR-MEMO-8679, 1973, https://www.osti.gov/servlets/purl/4476722.

[8]Ashcroft, John; Eshelmann, Cutis; "Summary of NR Program Prometheus Efforts", LM-05k188, 2006, https://www.osti.gov/servlets/purl/881290.

[9] The White House, "Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems", 2019, https://www.whitehouse.gov/presidential-actions/presidential-memorandum-launch-spacecraft-containing-space-nuclear-systems/ .

[10] https://www.forbes.com/sites/robertbryce/2020/08/23/after-48-years-democrats-endorse-nuclear-energy-in-platform/#6e509a4e5829