Accelerating Fission Surface Power Development and Deployment for Off-Planet Missions through a Digital-Twin Lifecycle Approach

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A fission surface power system is a compact, lightweight nuclear reactor specifically engineered to provide continuous and reliable electrical power in space or extraterrestrial environments through the process of nuclear fission. In these systems, typically atoms of uranium-235 undergo fission reactions, where their nuclei are split to release a substantial amount of energy in the form of heat. The generated thermal energy is then converted into electricity using either a Stirling cycle or a closed Brayton cycle power conversion system, typically involving a gas turbine driven by heated working fluid in a sealed loop, maximizing efficiency and minimizing moving parts.

One of the key advantages of fission surface power systems over solar power is their ability to function effectively in shadowed regions, such as permanently shaded lunar craters, or during extended periods of darkness, like the two-week-long lunar nights. This makes them an ideal solution for sustaining long-duration missions on the Moon, Mars, or other celestial bodies where sunlight may be intermittent or unreliable.

These nuclear systems are envisioned as a cornerstone of future space exploration infrastructure. They will provide dependable power to support human habitats, environmental control and life support systems, communication arrays, scientific instrumentation, in-situ resource utilization technologies, and other mission-critical equipment. By ensuring a consistent and scalable energy source, fission surface power systems will play a crucial role in enabling sustained human presence and scientific activity beyond Earth.

NASA is currently seeking industry input in developing a fission surface power system to support future lunar and Martian missions, aiming to deploy a nuclear reactor on the Moon by 2030.[1] **This future fission power reactor will provide at least 100 kilowatts of electrical power, independent of sunlight, to support long-term and permanent human non-terrestrial exploration activities. Additionally, the reactor will likely require iterative development for various off-planet applications and environments, where the exploration mission and life safety are dependent on effective power generation. Given these facts, the fission power reactor lifecycle, produced and validated at the necessary scale for human space exploration, will be challenging to accomplish using traditional engineering and operational practices.**

The development and lifecycle testing of such a fission reactor is inherently challenging, high-risk, and costly. Approval of development, test, and the launch of fission reactors by NASA stakeholders is likely to face challenges that will increase exponentially when met by popular and political opposition commonly observed to recent proposed fission power projects. A uranium-based fission reactor, unlike a radioisotope generator, is effectively inert before it undergoes fission for the first time at startup. Once a fission reactor has been activated, residual radiation and component ionization will occur, persisting even after the

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reactor is deactivated.[2] **Thus, a key advantage exists in the construction, transportation, and launch of a reactor before it has undergone that initial startup sequence. An inert reactor presents many benefits to the space mission: including improving flight safety, simplifying spacecraft design, reducing protective measures and hazards during loading and transportation, and reduced residual hazards in the case of catastrophic failure of the launch vehicle.**

Under current flight hardware frameworks, a physical fission reactor test would likely be necessary for a system of this level of importance Thus, the ability to digitally validate a reactor prior to flight would be beneficial for the reduction of mission cost and risk through the reduction of shielding and crew protection requirements, hazards associated with loading and launching ionized reactor components, and other direct implications related to the test, transportation, and deployment of a previously activated reactor.

The development of a system that encapsulates the design, validation, operation, sustainment, and disposal of fission power systems is crucial for the permanent human habitation of the Moon and Mars. Modern work in Digital Engineering (DE) and similar modernization approaches in use in the Defense, Automotive, and Aerospace industries provide digital tools and processes to streamline the development of technology. Intrinsic to these nascent digital capabilities is the ability to apply Modeling and Simulation to an extent where aerospace and defense systems will transition a significant portion of qualification, verification, validation, and acceptance testing within validated simulation frameworks. These advances in DE technologies will prove vital to the reduction in certification and test cost through combinations of digital and Hardware in the Loop simulations. DE will also reduce risk to pilots, bystanders, and the environment by permitting testing of Aerospace and Defense systems throughout the entire performance envelope, including failure modes. It is unquestionable that for the foreseeable future, there will still be demonstrations required to validate the test outcomes and underlying framework. However, such demonstrations will likely result in a greatly reduced portion of the development budget and schedule. Our approach will be to leverage available DE technologies to not only develop and test the candidate fission surface power reactor, but to also explore the concept of operationalizing the Digital Twin to provide a near real-time, closed-loop feedback system where the simulation is running in parallel with the operational system.

The Operational Digital Twin (ODT) is envisioned as a leap forward in the operation, control, and sustainment of a complex system, a valid and feasible application for the lifecycle of a fission surface power system. The ODT will begin its life during manufacture as modular components are allocated into a baseline configuration. The digital models of the constituent components will be incorporated into the ODT, and their respective characteristics will be refined with test data obtained during the assembly process. A simulation framework will stimulate the ODT through data produced by the operational system and the ODT will be used to inform the crew of operational parameters, potential incipient faults, and provide assistance in diagnosing and resolving anomalous conditions using specialized Artificial Intelligence and analytical tools. Additionally, data and operational feedback will inform evolution of the ODT for both local optimization and improved Truth data backhauled for use on Earth. Backhauled Truth data will subsequently inform further development of components and systems for future iterations of similar systems.

Our intent for this research effort is to explore the processes and architecture necessary for the Digital Twin Lifecycle development of a candidate fission surface power reactor of the type currently sought by NASA. Our effort will involve evaluating the technological state of the art in Digital Twin technologies for the purpose of conducting a gap analysis to determine new technologies and digital tools that are necessary to accomplish the lifecycle goals of complex systems developed through a rapid, iterative, and digital framework. We will then concentrate on the development of a prototypical Digital Twin Lifecycle Framework in parallel with the candidate reactor. This approach will incorporate existing digital tools (both vendor provided and team developed) and manual and digital methods for reactor design while also laying the groundwork for extension of the candidate reactor and underlying Framework to the Operational Digital Twin for operational control. Next, an iterative design process will be used to stimulate the Framework by performing initial design, optimization,

and trade studies for the prototype fission surface power reactor. Designing the reactor through the prototypical Framework will inform us on the effectiveness of the Framework and identify processes and workflows that must see further refinement. Additionally, this effort will examine the implications of applying a Modular and Open Systems Approach (MOSA) to design efforts anchored in this Framework, as multiple digital tool vendors and varying degrees of proprietary information are likely to require integration for complex end-products and systems. This effort is intended to demonstrate how the proposed Framework will provide for a fully integrated model of not only the reactor system including its surroundings and operations over the course of its mission lifetime. This novel approach will provide for cost and schedule improvements for Technological Maturation and Risk Reduction activities, and to enable digital system validation and test for space hardware. Finally, we will address one of the key benefits of Framework: the vital concept of digital flight qualification of the candidate reactor system as to avoid the deleterious effects of preflight reactor activation.

I. References

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