**NUCLEAR POWER SYSTEM CONCEPTS FOR ELECTRIC PROPULSION MISSIONS TO NEAR EARTH OBJECTS AND MARS.**

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**Introduction:** Nuclear power provides an enabling capability for human exploration missions which might otherwise be constrained by power availability, mission duration, or operational robustness. NASA and the Department of Energy (DOE) are developing fission power system technology to serve a wide range of future space uses. Extensive studies have been performed on lunar and Mars surface power systems using fission technology [1]. Advantages include lower mass, longer life, and greater mission flexibility than competing options. This paper examines the fission power concepts developed to support recent studies for nuclear electric propulsion (NEP) missions to near earth objects (NEOs) and Mars [2,3].

**Fission Technology Development Project:** The fission technology development project is a collaboration between NASA Glenn, NASA Marshall, and the DOE National Laboratories at Idaho, Los Alamos, Oak Ridge, and Sandia. The project currently resides under the Office of Chief Technologist, Game Changing Development Program. The team has been in place since the end of the Prometheus Program performing analysis and hardware testing to establish technology readiness. The current focus centers on a non-nuclear Technology Demonstration Unit (TDU) that will be tested in thermal-vacuum to demonstrate integrated system performance. The TDU test assembly, shown in Figure 1, serves as an essential hardware foundation for any future space fission power system.

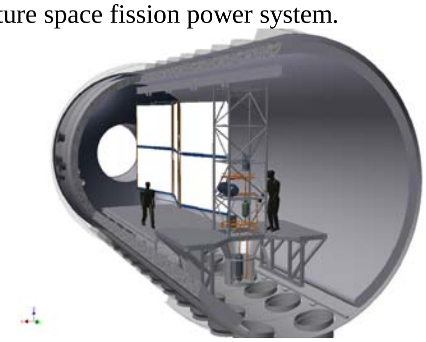

Figure 1. Fission Technology Demonstration Unit

**Fission System Design Evolution:** Fission power technology can be classified into three main categories that represent evolutionary advances relative to the state-of-the-art.

*Fission Surface Power (FSP).* FSP systems for the moon and Mars are expected to produce between 10 and 100 kWe. Emphasis is on low risk, operational robustness, and affordability. The reactor design leverages terrestrial technology with fast-spectrum $UO_2$ pin-type fuel, stainless steel construction, and NaK coolant. The reactor design allows for operating temperatures up to 900 K, well suited for Stirling power conversion. The power system would utilize multiple redundant Stirling convertors with 400 VAC power distribution and a 120 VDC power bus. Heat rejection is provided by pumped water coolant coupled to composite radiator panels with titanium-water heat pipes operating at around 400 K. The primary technical challenge is incorporating established reactor technology into a practical space power system and demonstrating end-to-end performance.

*Moderate Power NEP.* Initial NEP power systems are expected to produce between 100 kWe and 1 MWe. Low system specific mass (kg/kWe) is crucial to mission performance, and higher reactor operating temperature is the key to low specific mass. Extensibility from the FSP-class is maintained through the use of the liquid metal cooled, fast-spectrum reactor technology and pin-type fuel. Substituting UN fuel, refractory alloy construction, and Li coolant permits reactor operating temperatures of at least 1200 K. The higher power levels are better accommodated by closed Brayton cycle power conversion and the reactor temperature is well-matched to heritage Brayton designs using superalloy construction. The high-voltage AC power distribution and water heat pipe radiators from the FSP-class can be retained. However, an increase in the radiator temperature to 500 K may require a change to pumped NaK coolant. The primary technical challenge is the reactor materials development.

*High Power NEP.* Farther term NEP power systems could produce several MWe or more, and low specific mass is essential. A further increase in reactor temperature to 1500 K would require an improved UN fuel or other advanced fuel form and improved refractory alloy materials. The high power levels and high reactor temperatures necessitate the use of advanced refractory alloy Brayton or potassium Rankine power conversion. Specific mass can be further improved with kilovolt AC power distribution and 800 K composite radiators with embedded liquid metal heat pipes. Since the reactor is an evolutionary step from the moderate power NEP-class, the primary technical challenge resides in developing the high power, high temperature power conversion technology.

**Near Earth Object Mission:** Near-term human missions to NEOs are among the leading strategies for expanding human presence beyond Low Earth Orbit (LEO). One approach is to use Solar Electric Propulsion (SEP). Such a mission could utilize a 300 kWe SEP stage to deliver the crew transfer vehicle to an Earth-Moon libration point where the crew, launched on a separate chemical stage, would rendezvous and board the SEP vehicle. The SEP vehicle would transport the crew to the NEO for a 30 day mission and return them to Earth with a total round-trip mission duration of approximately 400 days. The SEP stage and crew transfer vehicle could be accommodated in a single 100 MT-class launch. The high solar flux available in Earth orbit and the lightweight solar power system (~9 kg/kWe) makes SEP an attractive option.

Alternatively, a 300 kWe NEP vehicle as shown in Figure 2 could be used to perform the same mission in the same 400 day duration with the same 100 MT-class launch vehicle. The NEP power system consists of a 1.2 MWt, 1200 K Li-cooled reactor and two fully redundant 300 kWe-class Brayton convertors operating at 50% capacity. The reactor and LiH/W shadow shield are located at the end of a telescoping boom to provide crew radiation protection. The 0.8 MWt, 500 K radiator comprises a simple "box" structure and four hinged-wings that deploy to form a cruciform, providing 560 m$^2$ total surface area. The overall NEP stage length is 30 m and the power system specific mass is about 27 kg/kWe.

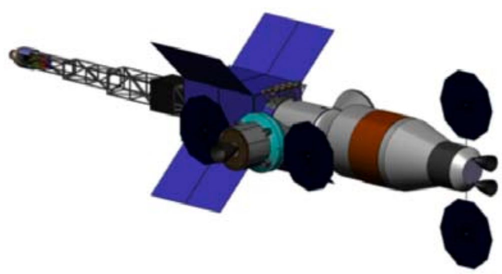

Figure 2. NEP Vehicle for Human NEO Mission

While the SEP power system limits thrusting by available sunlight, the NEP power system produces continuous steady power, and as much as 10% greater power during the deep space transfer due to the lower thermal sink. The near-continuous thruster operation allows lower thrust and an increase in the EP specific impulse from 2000 to 2600 seconds resulting in an 18% reduction in xenon propellant. The higher mass of the reactor power system is offset by the propellant reduction resulting in a similar overall launch mass. An important advantage of the nuclear option is the extensibility for EP missions at higher power and/or greater solar distance. The commonality with a lunar or Mars surface-based fission system is another benefit.

**Mars Cargo Mission:** In order to evaluate the versatility of NEP, a second study examined its use for a Mars cargo delivery to support a human outpost. The mission would deliver 100 MT of cargo to the Martian surface in advance of a crew departure from Earth, similar to that proposed in NASA's Mars Design Reference Architecture 5.0 [4]. The NEP stage and cargo payload element would be launched on separate 100 MT-class vehicles and mated in LEO as shown in Figure 3. The NEP vehicle would deliver the payload to a 1 SOL elliptical Mars orbit, from which it would be deployed to the surface. The total trip time assuming 1 MWe input power and 3400 second EP specific impulse is approximately 3.1 years. Once in Mars orbit, the NEP stage can serve as a reusable tug or high power communications relay.

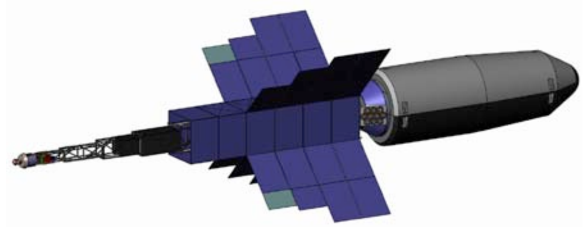

Figure 3. NEP Vehicle for Mars Cargo Mission

The 1 MWe NEP power system consists of a 3.7 MWt, 1200 K Li-cooled reactor and four 300 kWe-class Brayton convertors. Like the 300 kWe system, the configuration includes a telescoping reactor boom and a radiator box with deployable wings. The wings are tapered to remain within the radiation shield cone angle. The 2.5 MWt, 500 K radiator requires a total surface area of 1800 m$^2$ and the overall NEP stage length is 50 m. Relative to the 300 kWe design, the power system specific mass improves by 37% to about 17 kg/kWe due to the favorable economy-of-scale inherent with nuclear power.

**Conclusion:** Nuclear power provides an enabling capability for human surface missions and high-power electric propulsion missions. A step-wise technology evolution strategy can result in a practical and affordable implementation. The TDU provides a crucial first step in establishing this game-changing technology.

**References:** [1] Mason L. S. and Poston D. I. "A Summary of NASA Architecture Studies Utilizing Fission Surface Power Technology" NASA/TM-2011-216819. [2] Mercer C. R. et al. "Benefits of Power and Propulsion Technology for a Piloted Electric Vehicle to an Asteroid" *AIAA Space 2011*. [3] Gilland J. H. et al. "MW-Class Electric Propulsion System Designs for Mars Cargo Transport" *AIAA Space 2011*. [4] "Human Exploration of Mars, Design Reference Architecture 5.0" NASA/SP-2009-566.