Statement of

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"Accelerating Deep Space Travel with Space Nuclear Propulsion"

Chairman Beyer, Ranking Member Babin, and Members of the Committee, thank you for inviting me to join this discussion on behalf of The Aerospace Corporation. It is my honor and pleasure to engage with you on this exciting topic that has received more interest in the past few years than in the last half century.

Since 1960, The Aerospace Corporation has operated a non-profit, federally funded research and development center (FFRDC) dedicated to the nation's space enterprise. We serve as the government's trusted agent and national knowledge repository for space programs, providing objective, unbiased, technical expertise to assure mission success. During my twenty years at Aerospace supporting the Air Force, DARPA, NASA, and other programs, I have served as a subject matter expert in the design, development, and operation of current and future space access systems as well as advanced, emerging propulsion technologies. In my current role, I am the technical coordinator for most Aerospace activities supporting cross-agency projects associated with fission-based space nuclear propulsion and power. I am also an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), the former Chair of the AIAA Nuclear and Future Flight Propulsion Technical Committee, and a former adjunct professor at the Loyola-Marymount University Seaver College of Engineering.

Background

To set the stage for today's discussion, a general overview of traditional chemical propulsion and fission-based space nuclear propulsion and power (SNPP) is useful. Traditional, combustion-based chemical rocket engines mix and burn two propellants to create the extraordinary temperatures needed to produce the thrust forces necessary to move about space. The engine's thermodynamic cycle operates with a certain efficiency, called specific impulse. The specific impulse is directly related to the amount of propulsive energy available to the spacecraft over its life cycle, which is based on the total mass of the spacecraft and how much propellant is on board. To push more massive vehicles, such as a large habitat or spacecraft, more propellant may be needed for the vehicle to attain a target velocity given the specific impulse of the engine.

In contrast, a nuclear thermal propulsion (NTP) engine utilizes the intense heat generated from a solid-core nuclear fission reactor to produce the temperatures needed and imparts that energy to a single propellent, which is then expelled to produce thrust. No combustion takes place inside of these engines. Instead of two propellants, NTP uses only one and does so at double or more the specific impulse of a chemical engine. This means that either the NTP-propelled spacecraft can push the same mass through space using half the amount of propellant as a chemical rocket, or that the NTP spacecraft has twice as much available energy on board to perform missions using the same amount of propellant as a chemical engine. There are also engine concepts that utilize the engine's reactor as an electrical power source for the spacecraft, otherwise known as the bi-modal approach. Regardless of configuration, NTP engines promise to offer significant benefits in mission planning and enhanced spacecraft capability, especially where high thrust or responsiveness is needed.

Another application of nuclear fission for spacecraft is to supply electrical power in lieu of batteries and/or solar panels. In this arrangement, a small reactor on the spacecraft is used as the heat source to produce electrical energy for spacecraft subsystems and sensors. For decades, satellites have used ion thrusters powered by solar panels to provide very high efficiency but low thrust propulsion. A fission reactor can also power electric thrusters for propulsion, which is referred to as nuclear electric propulsion, or NEP. For power production, nuclear fission heats a fluid flowing through the reactor core and then drives a mechanical system to produce electricity. Since work is extracted, the fluid cools, is processed through waste heat radiators, then returns to the reactor in a closed-loop fashion. This process does not rely on batteries, solar visibility, or other duty-cycle limiting aspects that inhibit traditional power sources of spacecraft. NEP can also produce megawatt-class power in space, nearly ten times that of the best solar technology, and is persistent and continuous. Nuclear electric power offers significant mission opportunities for both civil and military applications whether on orbit or as a stationary power source on other celestial bodies, such as the moon or Mars.

There are three main points that I would like to make to the Committee on space applications of fission-based space nuclear propulsion and power (SNPP):

- First, **SNPP could offer enhanced mission capabilities.** SNPP could enable military and civil missions or capabilities not practically achievable using traditional means, and its adoption may therefore bolster US space national security and leadership.
- Second, **SNPP technology maturation would benefit from government-funded, government-led collaboration with industry and academia.** Potential opportunities exist now to rapidly mature and advance space nuclear technology, which would establish the US as the world leader in such systems.
- Third, **regulations and policies for space nuclear systems should be tailored to SNPP.** Fission-based SNPP is fundamentally different from radioisotope thermoelectric generators (RTGs); regulations written for RTGs may be unnecessarily restrictive for SNPP system development, test, launch, and on-orbit operations, slowing SNPP development.

I will discuss each of these three points in more detail below.

SNPP Could Offer Enhanced Mission Capabilities

Following the nuclear fission technology development efforts from the 1950's, aerospace applications flourished in many forms including nuclear-powered, air-breathing systems and the large rocket engine prototypes that were successfully ground tested under the Rover/NERVA program (1960-1972). The NERVA program was able to demonstrate that NTP engines could not only operate and be safely controlled, but that they delivered the substantial efficiency and performance gains as promised. The program was also instrumental in establishing the engineering capabilities and industrial base associated with uranium fuel processing, reactor design, control systems and test facilities. Given that NERVA was primarily a ground test program, the reliability of these NTP engines remained an open question. After the NERVA program was terminated during the Nixon administration, interest in space nuclear propulsion systems waned in favor of other programs.

Several kilowatt-class, nuclear power reactors were launched in the 1960's (the Soviets sent over 30), but space nuclear power never matured beyond those experiments due to the rapid advancements in solar arrays and battery storage systems that were easier to implement aboard space assets. Radioisotope thermoelectric generators (RTG), which operate on the natural decay of plutonium or other radioactive material, had also been developed for long-term power. Complicating matters for fission systems were the additional subsystems, active assemblies and integration complexities needed to reliably produce the power and cool the reactor, so their overall mass was a detriment to spacecraft performance. Since those early days, though, spacecraft buses and on-board assets have demanded more power for longer durations that stretch the limit of what solar or battery technology can provide. This is where the continuous high power from fission-based nuclear electric systems offers attractive opportunities that must be weighed with the impacts to spacecraft mass and reliability.

Modern advances in material science, manufacturing methods, physics modeling, design practices and risk reduction activities coming out of industries like terrestrial nuclear power and aerospace propulsion have contributed to a resurgence of SNPP interests by government agencies seeking more capable alternatives to traditional systems. Government interest includes both NTP and nuclear electric propulsion. Since SNPP offers significantly improved energy efficiency, it is considered an attractive option for missions like crewed planetary exploration (NASA) or space domain awareness (DoD), to name a few.

SNPP Technology Maturation Would Benefit from Government-Funded, Government-Led Collaboration with Industry and Academia

If fission-based SNPP configurations and technology trade well against other candidate options for propulsion or power depending on mission requirements, a series of well-funded, government-led collaboration programs with industry and academia would likely result in viable paths towards mitigating the technical challenges and development risks.

A significant realization from the current SNPP efforts, projects, and studies indicate that there may not be a "one size fits all" uranium fuel form and reactor core design that could satisfy the performance demands of both an NTP engine and a nuclear electric power system. This mainly stems from the difference in reactor temperatures for which these applications are best optimized and the duration of the reactor's operation. For NTP, the higher the temperature, the better the propulsive efficiency, but those environments introduce significant challenges with the uranium fuel form design, coatings, materials and compatibility, reliability, system mass, manufacturing and a host of other areas. For nuclear electric power, reactor temperatures are somewhat cooler, but operation times are considerably longer which leads to different uranium fuel form and reactor materials issues. In either case, the full system heavily relies upon the parallel development, maturation and demonstrated integration of many stand-alone subsystems systems such as power (electricity) conversion/production mechanisms, waste heat rejection, thermal management, pump systems, power transfer and storage, and if NEP is considered, high power electric thruster development.

Whether for propulsion or power, current projects have put heavy attention on the development and domestic production of the modern uranium fuel forms as well as the acquisition and manufacturing of the other core materials needed to enable reliable, flight-weight reactor designs. Accompanying this are efforts to validate computer-based modeling codes to potentially streamline the design cycle and reduce development time. Maturation of the systems surrounding the reactor (for NTP or nuclear electric power) is also recognized as a significant engineering challenge with high confidence that multiple solutions can be produced.

For any of the above considerations, a series of multi-year, government-funded, government-led efforts built upon SNPP technical maturation plans dedicated to addressing these challenges would greatly benefit technology development and risk reduction to allow for timely implementation. These efforts would rely on the recognition by DoD and/or civil customers that flight demonstrations of SNPP, or perhaps even operational systems, could be realized in the near-term with their dedicated support, continued interest and SNPP-specific mission development. These projects would help to validate the viability of SNPP and reduce the technical and cost uncertainties being brought to light in other programs such as from NASA's architectural considerations for Mars. Broad government programs would marry the unique or urgent mission needs of the government customers with the exemplary technology research and development that has been taking place under current tasks within key industries, government labs and academia. This engagement may also help to stimulate and grow the SNPP workforce, secure government-industry collaborative agreements and encourage technology invention through internal research and development. Whatever the case, government-backed efforts would show that the US could maintain its status as the world leader in SNPP.

Regulations and Policies for Space Nuclear Systems Should be Tailored to SNPP

Current regulations and policies associated with nuclear materials in space are centered around the launch and in-space uses of RTGs. As described earlier, RTGs are nuclear devices that passively generate electricity through the natural radioactive decay of plutonium-238 or other radioactive material. RTGs are relatively small and can produce sub-kilowatt levels of electrical power for decades making them popular with deep-space spacecraft where solar light is too dim for direct power. Despite their operational advantages, the primary concern with RTGs is that they are "always on" and always radiating, from the moment they are manufactured. This introduces the need for stringent personnel safety and handling issues, dedicated transport and spacecraft processing facilities, radiation contingencies in the event of a launch accident, and the establishment of regulatory safeguards and policies to ensure these measures are in effect to reduce risk and harm to the public and environment.

In contrast, fission-based SNPP systems are manufactured and launched in the “off” state. Even though SNPP reactors could contain many kilograms of fissile uranium-235, they must be actively brought to a “critical” condition that enables the fission process to begin and for heat to be generated. Prior to being taken critical, the reactor emits negligible harmful radiation which allows for relaxation of personnel safety protocols, eases manufacturing and assembly processes, and would permit reactor transport, processing and integration within existing, approved facilities. During launch, the reactor would remain in the off state until commanded to activate after successfully reaching orbit. This also means that should the reactor be subject to a launch accident and never achieve orbit, the uranium nuclear fuel in the core would very likely remain in the off, non-emissive condition even after impact, thereby dramatically reducing any threats to the environment or life. Even so, considerations for redundant safeguards to assure the reactor remains non-critical are part of current SNPP projects aimed at flight experiments.

This comparison between fission-based systems and RTGs is important to illustrate that the federal regulations and policies currently in place that could affect SNPP development are mainly associated with RTGs. As SNPP programs become more active, however, careful review of the policies authored by several government agencies (DoE, DoT, EPA, NRC, etc.) must be performed to determine their applicability to fission SNPP systems, especially if they might impose restrictive measures that would hinder development, test, certification (for crewed or uncrewed missions), launch acquisition and on-orbit operation. While preliminary examination indicates that certain current regulations are satisfactory to encompass fission SNPP, there may also be gaps in the policy structures where new language to address SNPP systems may be required.

One example of how regulation and policy may affect fission-based SNPP development is in the area of NTP engine ground test. While the NERVA program routinely accomplished multi-run, open-air ground tests campaigns of various engines at dedicated, customized facilities, those engines occasionally exhausted radioactive particulate directly to the atmosphere. This was due in part to the design and materials technologies used in the reactor core at the time, and release levels were not considered environmentally unsafe based on the regulations of the day. Current regulations are of course far more restrictive on allowable levels. The expectation exists that current regulations would dictate that exhaust gases from NTP ground tests would need to be captured and processed to eliminate radiologic sources before release to the atmosphere even if the engine produces negligible levels of contaminants. This adds significant complexity and cost to the ground test facility design, operation and certification.

Because there have been remarkable advancements in the production of accident-tolerant nuclear fuels and core materials technology that offer to dramatically reduce the likelihood and severity of radioactive effluent from NTP reactors, many stakeholders are concerned that existing policies have become hurdles for some projects that aim to perform NTP ground tests and eventual flight certification campaigns to meet program schedule and cost goals. A review of these policies, supported by detailed technical analyses, may reveal that even slight adjustments could preserve the objective of the language yet ease the burdens on NTP ground testing and/or accelerate NTP technology development.[1]

Space nuclear power systems include a fission-based reactor and will be subject to governing regulation and policy reviews even though the end application and purpose are different than NTP. Operations surrounding spacecraft transport, processing, and launch will need to include nuclear power systems. The launch acquisition and regulatory approval process for any type of fission-based mission will need to be deeply examined to identify long-lead tasks that could adversely influence mission timelines. Streamlining this approach while wholly preserving the security and safety of the overall process would be a giant step forward for both military and civil customers.

Concluding Remarks:

A key highlight of this testimony is that fission-based space nuclear propulsion and power has remarkably advanced over the past fifty years and may be the next leap forward in space domain technology. Several government stakeholders including NASA, the Department of Energy, DARPA, the US Space Force, US Space Command, the Air Force Research Labs (AFRL) and others have not only developed a close interest in SNPP, but some have well-established, industry-sourced, cross-agency programs of record to demonstrate specific SNPP applications or rapidly mature critical technologies. The dedication and conviction of those involved with SNPP have advanced its viability and credibility well beyond concepts and analytical studies to the point of planned test programs, ground and/or flight demonstrations, and long-term technology maturation efforts.

While those projects and programs aimed at developing and refining the key aspects of fission-based SNPP are making progress, the uncertainty of future interest, funding, and public acceptance remains an impediment to US leadership in this emerging technology. Encouraging support and development of fission-based SNPP may spur industry investment opportunities that could cross over to better serve government needs.

My sincerest thanks to the Committee for holding this hearing and for your generous attention.

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[1] NTP ground test is an area where direct government involvement and support could profoundly influence the advancement of SNPP technology. Some stakeholders suggest that regulatory adjustments aimed at safely promoting interests in SNPP ground testing could potentially lead to the development of a unique national capability (facility) that would perhaps enable timely implementation of NTP systems.

Biography
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Greg Meholic is a Senior Project Leader for Civil Systems Technology at the Aerospace Corporation, the only Federally Funded Research and Development Center (FFRDC) dedicated to the nation's space enterprise. He joined Aerospace in 2001.

In his current role, Greg is the technical coordinator for Aerospace activities supporting cross-agency (e.g. DARPA, NASA, AFRL) projects associated with fission-based space nuclear propulsion and power. Since 2008 his portfolio has included launch vehicle concept development and advanced propulsion technology planning for future access to space, with a focus on next-generation, far-term propulsion concepts and vehicle systems. He has served as the Aerospace technical manager for projects associated with reusable launch systems, rocket engine performance and stability software development, suborbital flight experiment campaigns, space nuclear propulsion and power initiatives, and several technology assessment activities. From 2001 to 2008 he supported over 48 space launch missions as the upper stage propulsion lead. While in this role, Greg performed detailed technical analyses and gained system-level knowledge and experience to become an expert in heritage, current, and future space access systems; the design, performance and testing of large rocket engines; and the technical assessment of alternative, advanced or emerging technologies.

Greg is a 25-year member and Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is an active member and former has Chair of AIAA's Nuclear and Future Flight Propulsion Technical Committee, and an active member of two other AIAA propulsion-related technical committees. As a Distinguished Speaker for AIAA he is regularly invited to give talks to student and regional chapters around the country on advanced space propulsion systems, and has been a guest on several science and technology-oriented internet and radio broadcasts.

Prior to joining Aerospace, Greg spent six years with General Electric Aircraft Engines, where his main focus was preliminary and advanced gas turbine design and alternative air-breathing propulsion systems. He has four patents related to his work on those systems. From 2005 to 2020, Greg was an adjunct educator at Loyola-Marymount University (Los Angeles) where he taught a senior/graduate-level course in propulsion systems for both aircraft and spacecraft.

Greg holds both a Bachelors degree and a Masters degree in Aerospace Engineering from Embry-Riddle Aeronautical University. He is an avid private pilot with 23 years of experience, and is also a Certified Flight Instructor.