SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

HEARING CHARTER

Accelerating Deep Space Travel with Space Nuclear Propulsion

October, 20, 2021
10:00 a.m. EDT
Online Via Zoom

PURPOSE

The purpose of the hearing is to understand the opportunities and challenges of space nuclear propulsion for enabling deep space exploration, examine the status of NASA's R&D activities and plans for space nuclear propulsion, and to consider government and industry contributions to and collaboration on advancing space nuclear propulsion, among other issues.

WITNESSES

- **Dr. Roger M. Myers,** Co-Chair, Committee on Space Nuclear Propulsion Technologies, National Academies of Sciences, Engineering, and Medicine
- **Dr. Bhavya Lal,** Senior Advisor for Budget and Finance; NASA
- **Mr. Greg Meholic,** Senior Project Leader, The Aerospace Corporation
- **Mr. Michael French,** Vice President, Space Systems; Aerospace Industries Association
- **Dr. Franklin Chang Diaz**, Founder and CEO, Ad Astra Rocket Company

OVERARCHING QUESTIONS

- *What are the opportunities for space nuclear propulsion to enable deep space exploration, especially human missions to Mars?*
- *What are the major challenges, including technical hurdles, for developing, testing, demonstrating, and using space nuclear propulsion systems, and what needs to be done to overcome them?*
- *What are the respective capabilities and expertise within the federal government and commercial sectors that could contribute to maturing space nuclear propulsion technologies, and are there any gaps?*
- *How are industry and government collaborating on advancing space nuclear propulsion?*

BACKGROUND

NASA has sent many orbiting spacecraft and robotic landers and rovers to Mars since the 1960s, but a crewed mission to the red planet would be significantly more challenging, requiring far more mass, power, and capabilities than even the most complex robotic missions to date.

Numerous NASA studies and external reports,[1,2] such as the 2014 "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration" report of the National Academies of Sciences, Engineering, and Medicine, have identified advanced in-space propulsion as one of the most critical enabling capabilities and a high-priority area for technology development for future human exploration. With today's chemical propulsion systems, the one-way transit time between Earth and Mars could be six to nine months, and the total round-trip travel time would be approximately three years. The round-trip time is defined by the limitation on possible Earth and Mars departure dates to only when the planets are closest together, and the energy required to leave Earth's orbit and enter Mars' and return is low enough for current propulsion systems to generate. The windows open every twenty-six months, approximately, for a few weeks at a time. A crewed mission would need to stay at Mars for 500 days or more, until the window opens again.

More capable space propulsion systems could reduce some of the risk associated with a human mission to Mars by reducing transit time and the total minimum mission length. Faster travel between the two planets could reduce exposure to in-space radiation and the microgravity environment, which could then reduce the risk of adverse human health effects and hardware degradation. With more powerful propulsion systems, a mission could also leave Mars outside of the limited windows described above, allowing for shorter stays, in what are known as "opposition-class" missions.[3] Shorter stays could reduce the mission complexity and supply needs and reduce the exposure time to the radiation environment and reduced gravity on the Martian surface.

NASA has studied space nuclear propulsion concepts as a means of offering higher performance that could enable shorter transit times and opposition-class Mars missions. While NASA's interest in space nuclear propulsion has, largely, focused on crewed Mars missions, the technology could also enable cargo delivery to Mars, more efficient Solar System robotic missions, and even potential far-future interstellar space missions. In addition, other federal government agencies have interest in space nuclear propulsion for their own mission needs.

To date, NASA's use of nuclear technology in space has been limited to radioisotope power systems, which have generated electrical power on board several deep space robotic missions where the distance from the Sun limits the practicality of solar energy.[4] Early U.S. efforts to develop a nuclear propulsion system for spaceflight date to the 1950s. Advances during that time and over the ensuing years led to ground-based reactor tests, engine tests, and technology

---

[1] National Research Council. *Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration.* Washington, DC: The National Academies Press. Available at: https://doi.org/10.17226/18801
[2] Linck, E.; et al., "Evaluation of a Human Mission to Mars by 2033," IDA Document D-10510, Science & Technology Policy Institute, February 2019. Available at: https://www.ida.org/-/media/feature/publications/e/ev/evaluation-of-a-human-mission-to-mars-by-2033/d-10510.ashx
[3] "Opposition-class" missions are those that allow the Mars-Earth transit to occur at any time, including when Mars is furthest away, on the opposite side of the Sun from Earth, which is also when the energy required to travel between them is highest. By contrast, a "conjunction-class" mission cannot depart Mars for Earth, or Earth for Mars, until the two planets are the same side of the Sun and the energy required to travel between them are minimized.
[4] Radioisotope power systems (RPS) use the heat generated by the natural radioactive decay of plutonium-238 to produce electrical power and sometimes regulate hardware temperature. NASA has flown more than 25 missions using RPS, including Voyagers 1 and 2, Cassini, and the Curiosity and Perseverance Mars rovers. NASA develops RPS in partnership with the Department of Energy, which provides the power systems and nuclear fuel.

development; however, space nuclear propulsion systems have neither undergone full scale ground testing nor flown in space as fully integrated systems.

Space Nuclear Propulsion Systems

Nuclear propulsion systems are a class of propulsion systems that can produce thrust more efficiently than traditional chemical or electrical propulsion systems. Spacecraft propulsion, regardless of technique, relies on the generation of thrust: an engine heats and accelerates matter, sending it as exhaust in one direction, and the spacecraft or rocket moves in the opposite direction. Space propulsion today is generally conducted using either chemical propulsion systems—which combust liquid or solid rocket fuel with an oxidizer to produce hot, fast-moving chemical exhaust—or electrical propulsion systems—which use electricity, often generated by solar power, to ionize and accelerate fuel to produce a plasma exhaust plume.

Nuclear thermal propulsion (NTP) systems operate similarly to chemical propulsion systems, except, instead of a combustion chamber, the propellant, such as liquid hydrogen, is directly heated by a nuclear reactor to generate thrust. Nuclear electric propulsion (NEP) systems operate similarly to nuclear power plants on Earth by converting heat from nuclear fission to electrical power. NEP systems then use the electrical power and, in some cases, a magnetic field, to accelerate an ionized propellant and produce thrust.

The current concepts for reactors in both NTP and NEP systems are based on fission reactors using uranium-235 (U-235) as the nuclear fuel. Uranium that is enriched 20% or more by U-235 is classified as highly enriched uranium (HEU) and subject to certain domestic and international policies and regulations related to security and proliferation. Uranium enriched by less than 20% U-235 is classified as low enriched uranium (LEU); high-assay LEU (HALEU) is enriched by U-235 between 5% and 20%. HALEU is currently produced primarily by "downblending," essentially diluting, HEU; however, the federal government and the commercial terrestrial nuclear industry are maturing capabilities to instead enrich LEU to produce HALEU.[5]

National Academies Report: Space Nuclear Propulsion for Human Mars Exploration

In 2020, NASA's Space Technology Mission Directorate (STMD) requested that the National Academies of Sciences, Engineering, and Medicine (NASEM) convene an ad hoc committee to identify the primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion technologies of interest to future exploration missions.[6] The technologies of interest were a nuclear thermal propulsion (NTP) system that heats hydrogen to 2700 K (4400°F) and produces a specific impulse[7] of at least 900 seconds and a nuclear electric propulsion (NEP) system with at least 1 megawatt of electric power and a mass-to-power ratio that is substantially lower than the current state of the art.

---

[5] Department of Energy, "What is High-Assay Low-Enriched Uranium (HALEU)?" April 7, 2020. Available at: https://www.energy.gov/ne/articles/what-high-assay-low-enriched-uranium-haleu

[6] National Academies of Sciences, Engineering, and Medicine. 2021. *Space Nuclear Propulsion for Human Mars Exploration*. Washington, DC: The National Academies Press. Available at: https://doi.org/10.17226/25977.

[7] Specific impulse (I_{sp}) is the thrust of a rocket (or electric thruster) divided by the weight flow rate of the propellant. The unit for I_{sp} is seconds. I_{sp} is a primary performance parameter for NTP systems.

The committee was tasked with determining the key milestones, a top-level development and demonstration roadmap, and other missions that could be enabled by successful development of nuclear propulsion systems. NASA also requested that the committee's assessment be conducted in reference to a specific baseline mission: the launch of a crewed, opposition-class mission to Mars in 2039, which would be preceded by cargo missions beginning in 2033. The consensus findings and recommendations of the committee were released in the February 2021 NASEM study, "Space Nuclear Propulsion for Human Mars Exploration."

For NTP systems, the committee identified that the development challenges are driven by the "fundamental challenge" to meeting the requirement is heating the propellant, quickly, to very high temperatures and maintaining the high temperatures for the full duration of each burn. The fundamental challenge for NEP, according to the committee, is scaling individual NEP subsystems up to megawatt-class operation—orders of magnitude larger than current capabilities—and then developing an integrated NEP system.

The committee recommended, for both NTP and NEP development for the baseline mission, that that NASA make "extensive investments" in modeling and simulation capabilities, conduct full-scale testing on the ground, and use cargo missions ahead of the first crewed mission as flight demonstration and qualification opportunities. The committee also found that common challenges and areas of synergy for NTP and NEP system development include the need for low-mass, radiation-hardened, and high-temperature-tolerant materials; ground-based testing facilities that do not current exist; cryogenic fluid management, such as the long-term, in-space storage of liquid hydrogen; and nuclear fuel development.

In comparing NEP and NTP systems, the committee found that there are no recent "apples-to-apples" trade studies for a crewed Mars mission.[8] As the current spaceflight readiness, development program activity levels, and engineering designs of NTP and NEP have key differences, the study recommends that NASA develop consistent figures of merit and technical expertise to compare NTP and NEP systems for the baseline mission. The committee additionally recommends a near-term comprehensive assessment of HEU and HALEU fuels for NTP and NEP systems for the baseline mission. The study also notes the shared technology areas between NTP and NEP systems, as well as work in modeling and simulation, system safety, and regulatory approvals, that can be matured before selection of either system for the baseline mission. The committee further recommended that NASA leverage synergies with other governmental programs and seek collaboration opportunities with the Department of Energy and Department of Defense development programs, and the Defense Advanced Research Projects Agency (DARPA) Demonstration Rocket for Agile Cislunar Operations (DRACO) program.

In addition to technology development and requirements, the committee discussed science, technology, engineering, and mathematics (STEM) education and workforce factors affecting the future of space nuclear propulsion. In particular, the report identified three principal challenges of the STEM educational pipeline that the space nuclear industrial base should work to overcome: a lack of gender and ethnic diversity; competition from non-aerospace technology companies with the aerospace sector for talent; and limitations on non-U.S. citizens participating

---

[8] National Academies of Sciences, Engineering, and Medicine. 2021. *Space Nuclear Propulsion for Human Mars Exploration*. Washington, DC: The National Academies Press. Available at: https://doi.org/10.17226/25977.

in the pipeline due to export control regulations and classification status of some relevant research and development.[9]

NASA Activities in Space Nuclear Propulsion

NASA manages the Space Nuclear Technologies (SNT) portfolio within the Technology Demonstration element of the Space Technology Mission Directorate (STMD). SNT projects include both power and propulsion activities. In recent years, Congress has consistently directed funding, through annual appropriations, for NASA to develop and demonstrate an NTP system and the FY 2021 enacted appropriation for NTP was $110 million. The House Appropriations Committee report for Commerce, Justice, Science, and Related Agencies for FY 2022 also includes $110 million for NASA work on an NTP system. It also recognizes the potential for space NEP and provides $10 million for NASA "to begin a systematic approach to nuclear electric propulsion."[10]

In response to the Congressional appropriations, NASA's current efforts in space nuclear propulsion development have focused on conducting design and trade studies to define operational requirements for an NTP system[11] leading to an in-space demonstration. In July 2021, NASA announced three new contract awards, each valued at approximately $5 million for a 12-month award period, for conceptual reactor designs for a nuclear thermal propulsion system that uses HALEU fuel.[12] The three awardees and their partners are BWX Technologies, Inc., with Lockheed Martin; General Atomics Electromagnetic Systems of San Diego, with X-Energy, LLC and Aerojet Rocketdyne; and Ultra Safe Nuclear Technologies, with Ultra Safe Nuclear Corporation, Blue Origin, General Electric Hitachi Nuclear Energy, General Electric Research, Framatome, and Materion. The contracts are awarded and managed through the Department of Energy's Idaho National Laboratory (INL) using NASA funds. INL will conduct design reviews at the end of the twelve-month contract period and provide findings to NASA.

NASA's Space Technology Mission Directorate also supports work on related system elements needed to support space nuclear propulsion, including development and demonstration of technologies for in-space cryogenic fluid management. Cryogenic fluid management involves the ability to contain and maintain rocket propellants, such as oxygen or hydrogen, in liquid form at extremely cold temperatures in space environments and is important for many in-space propulsion capabilities, including nuclear thermal and electric propulsion.[13]

---

[9] *Ibid.*

[10] Report 117-87, Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2022, July 19, 2021. Available at: https://www.congress.gov/117/crpt/hrpt97/CRPT-117hrpt97.pdf

[11] Klein, Andrew, et al., "Operational Considerations for Fission Reactors Utilized on Nuclear Thermal Propulsion Missions to Mars," Contractor Report 20210000387, January 2021. Available at: https://ntrs.nasa.gov/citations/20210000387

[12] NASA, "NASA Announces Nuclear Thermal Propulsion Reactor Concept Awards," Release 21-091, July 13, 2021. Available at: https://www.nasa.gov/press-release/nasa-announces-nuclear-thermal-propulsion-reactor-concept-awards

[13] Hansen, Hans C.; Johnson, Wesley L.; et al., "Cryogenic Fluid Management Technologies Enabling for the Artemis Program and Beyond," AIAA 2020-4000, November 2, 2020. Available at: https://ntrs.nasa.gov/api/citations/20205008297/downloads/ASCEND%20-%20CFM%20Technologies%20for%20Artemis%20Paper%202020-10-06%20Final.pdf

Industry Activities in Space Nuclear Propulsion

Historically, as has been the case for many space development programs, space nuclear technology development has largely been led by the federal government, with the private sector supporting as contractors or through other partnerships. However, commercial interest and activities in space nuclear technology development are growing, consistent with the broader trends in space commercialization. Commercial organizations with activities in space nuclear propulsion range from startups to legacy corporations. Some are established, terrestrial nuclear power companies looking to leverage technologies, safety processes, and infrastructure for space applications. Others are established aerospace and space sector companies looking to leverage the synergies between the technologies used for space, including chemical propulsion systems, with those needed for space nuclear propulsion and other space nuclear applications. Many commercial organizations pursuing near- to mid-term space nuclear capabilities focus on fission NTP, but there are also some early-stage, venture-capital-funded development companies pursuing fusion propulsion.[14]

A 2019 conference proceeding based on research by the Science and Technology Policy Institute (STPI) describes commercial activities and interests within each of four main elements of the space nuclear enterprise: development and supply, fuel and fueling, launch, and operation of nuclear systems.[15] In the paper, STPI found "growing interest" among commercial actors in the *development and supply* of fission power systems for space applications across multiple companies. Some companies are executing development plans specifically for in-space reactor designs, while others were adapting their own terrestrial reactor designs for space applications. As of 2019, the earliest estimates of a full-scale, in-space system demonstration from the companies STPI examined was for the mid-2020s. Regarding nuclear *fuel and fueling*, STPI found that commercial interests are nearly exclusive to LEU fuel sources, including and especially HALEU, due to the relatively low safety, regulatory, and cost burdens, as compared to HEU.[16] As of 2019, only one company had conducted *launches* with radioisotope power—not propulsion—systems on board NASA science missions to distant Solar System destinations. STPI found many commercial entities interested in being future *operators* of nuclear systems in space, including NTP and NEP systems; however, regulatory uncertainty[17] and the absence of a near-term commercial market were noted as factors regarding investment decisions.

---

[14] Aerospace Corporation, "State of Play: Emerging, In-Space Propulsion Technologies," June 8, 2021. Available at: https://aerospace.org/sites/default/files/2021-07/SOP_InSpace_Propulsion_0621.pdf

[15] Locke, Jericho and Lal, Bhavya, "Emergence of a Commercial Space Nuclear Enterprise," *Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting,* February 25-28, 2019. Available at: https://www.ida.org/-/media/feature/publications/e/em/emergence-of-a-commercial-space-nuclear-enterprise/nets2019_locke_final.ashx?la=en&hash=B4C61697938DF5CDA788C1B72B4A423C

[16] Only one private company is licensed to handle and manufacture HEU: the contractor currently supplying and servicing the U.S. Navy's submarine nuclear reactors.

[17] The Federal Aviation Administration (FAA) regulates the launch and reentry of commercial space vehicles, but no fission reactors have ever been launched to space by any actors, government or private, and no formal regulations or laws specific to launching space nuclear propulsion systems currently exist, though previous Administrations have issued some guidance on the process for launch process approval and safety considerations.

The 2021 NASEM study on space nuclear propulsion similarly found that "a growing number of private-sector companies are developing system concepts for space nuclear systems."[18] Further, the NASEM study reports that while, currently, "very few private-sector entities have the capability to develop nuclear reactor fuels, cores, shields, and control systems," it is also true that "several are investing in these capabilities and can be expected to contribute directly to the design, manufacturing, and assembly of space nuclear propulsion systems."

In addition to commercial participation in the NASA NTP award described in the previous section, industry is also partnering with the Department of Defense's DARPA DRACO project for NTP.

[18] National Academies of Sciences, Engineering, and Medicine. 2021. *Space Nuclear Propulsion for Human Mars Exploration*. Washington, DC: The National Academies Press. Available at: https://doi.org/10.17226/25977