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ACCELERATING DEEP SPACE TRAVEL WITH SPACE NUCLEAR PROPULSION

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE AND AERONAUTICS

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

OF THE

HOUSE OF REPRESENTATIVES

ONE HUNDRED SEVENTEENTH CONGRESS

FIRST SESSION

OCTOBER 20, 2021

Serial No. 117–35

Printed for the use of the Committee on Science, Space, and Technology



Available via the World Wide Web: http://science.house.gov

U.S. GOVERNMENT PUBLISHING OFFICE

45–865PDF WASHINGTON : 2022

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ACCELERATING DEEP SPACE TRAVEL WITH SPACE NUCLEAR PROPULSION

WEDNESDAY, OCTOBER 20, 2021

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE AND AERONAUTICS,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10:01 a.m., via Zoom, Hon. Don Beyer [Chairman of the Subcommittee] presiding.

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

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[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.

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[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]

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[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.

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[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

Chairman BEYER. So, the time having arrived, let me declare that this—the hearing will come to order, and without objection, the Chair is authorized to declare a recess at any time. And before I deliver my opening remarks, I want to note that the Committee today is meeting virtually, and I hope for not much longer, but today is still virtual. I want to announce a couple of reminders to the Members about the conduct of this hearing. First, Members will please keep their video feed on as long as they're present in the hearing. Members are responsible for their own microphones. Please also keep your microphones muted unless you are speaking. Finally, if Members have documents they wish to submit for the record, please e-mail them to the Committee Clerk, whose e-mail address was circulated prior to the hearing.

So good morning, and welcome to today's hearing on "Accelerating Deep Space Travel with Space Nuclear Propulsion." I want to welcome our panel of impressive expert witnesses today. We're very excited that you accepted our invitation, and thank you for being here. If we're serious about deep space exploration to Mars with humans, which I am serious about, and I know everyone on this Committee is, we need to take bold steps to make it happen and make it sustainable. Today we're talking about one bold effort that could get us much closer to achieving that Mars goal, space nuclear propulsion.

Space nuclear propulsion can produce thrust far more efficiently than conventional chemical systems, allowing for shorter trip times to Mars. Why does this matter? Well, one reason, of course, is that shortening the trip reduces the risk of space radiation exposure to our astronauts. Another is that, depending on the technology used, space nuclear propulsion may enable more frequent trips to Mars than the typical 26-month intervals that rely on favorable Mars/Earth alignments. Reducing that 26-month interval increases mission flexibility to enable both cargo deliveries and human missions to Mars.

However, building an operational space nuclear propulsion system is hard, and the technical challenges are many. Choosing a nuclear fuel type and source, developing a space-qualified fission reactor, developing the requisite materials and infrastructure, and carrying out the testing, all while managing the required safety protocols for nuclear activities, are just a few examples of those challenges. To date, the U.S.'s use of space nuclear technology has been in battery-like radioisotope power sources for probes traveling to distances where sunlight is insufficient to produce power for the spacecraft. But when it comes to propulsion, the United States has yet to fly a fully integrated space nuclear propulsion system in space.

You know, government work on space nuclear propulsion dates back to the 1960's, but it was curtailed in the 1970's, and then follow-on efforts have largely been intermittent since that time. That prior work, however, provides a foundation and a baseline that's still useful today. A recent NASA (National Aeronautics and Space Administration)-commissioned National Academies of Sciences, Engineering, and Medicine study on space nuclear propulsion found that a system could be ready to support a human mission to Mars in 2039—Mr. Perlmutter would prefer 2033—but only if we act ag-

gressively now. According to the study, the required space nuclear propulsion systems would need to be available in 2033 for advanced cargo emplacement and risk reduction prior to a human mission. That's slightly more than 11 years from now. So if the U.S. is serious about leading in a human mission to Mars, we have no time to lose.

Congress has prioritized development of nuclear space propulsion over the past several years, directing about $100 million annually for NASA to advance nuclear thermal propulsion (NTP) capabilities with the goal of conducting a future in-space flight test. I hope that at today's hearing we can examine what progress NASA has made with these dedicated investments, and what further investment is needed in order to achieve the human to Mars goal in the 2030's, and how can NASA leverage other contributions, whether from different parts of the U.S. Government or from commercial industry, to reach that goal? Because NASA is not alone in seeing the potential for space nuclear propulsion. The Defense Advanced Research Projects Agency, DARPA, has its own nuclear thermal propulsion project, albeit for national security interests. And the Department of Energy (DOE), with its nuclear expertise and infrastructure, is also involved. We need to see how the various agencies are collaborating, including on a government-wide strategy and vision for space nuclear propulsion.

So the time to act for America—time for America to act and take bold, well-considered, steps toward the goal of sending humans to Mars, a goal that will both inspire and lead to significant technological advances that will benefit all of us here on Earth. Development of space nuclear propulsion is one such necessary step, and this Subcommittee has an essential role in setting the policy to get us there. I really look forward to our witnesses' testimonies.

[The prepared statement of Chairman Beyer follows:]

Good morning, and welcome to today's hearing on "Accelerating Deep Space Travel with Space Nuclear Propulsion."

I want to welcome our panel of impressive expert witnesses, and I thank you for being here today.

If we're serious about deep space exploration to Mars with humans, which I and others on this Subcommittee are, we need to take bold steps to make it happen and make it sustainable.

Today, we're talking about one bold effort that could get us much closer to achieving the Mars goal-space nuclear propulsion.

Space nuclear propulsion can produce thrust far more efficiently than conventional chemical systems, allowing for shorter trip times to Mars.

Why does this matter? One reason is that shortening the trip reduces the risk of space radiation exposure to our astronauts.

Another is that, depending on the technology used, space nuclear propulsion may enable more frequent trips to Mars than the typical 26-month intervals that rely on favorable Earth and Mars alignment. Reducing that 26-month interval increases mission flexibility to enable both cargo deliveries and human missions to Mars.

However, building an operational space nuclear propulsion system is hard and the technical challenges are many.

Choosing a nuclear fuel type and source, developing a space-qualified fission reactor, developing the requisite materials and infrastructure, and carrying out testing, all while managing the required safety protocols for nuclear activities, are just a few examples of those challenges.

To date, the U.S.'s use of space nuclear technology has been in battery-like radioisotope power sources for probes traveling to distances where sunlight is insufficient to produce power for the spacecraft.

When it comes to propulsion, the United States has yet to fly a fully integrated space nuclear propulsion system in space. Government work on space nuclear pro-

pulsion dates back to the 1960s, was curtailed in the early 1970s, but follow-on efforts have largely been intermittent since that time.

That prior work, however, provided a foundation and a baseline that is still useful today.

A recent NASA-commissioned National Academies of Sciences, Engineering, and Medicine study on space nuclear propulsion found that a system could be ready to support a human mission to Mars in 2039, but only if we act aggressively now.

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I hope that at today's hearing we can examine what progress NASA has made with these dedicated investments, and what further investment is needed in order to achieve the human to Mars goal in the 2030s. And how can NASA leverage other contributions, whether from different parts of the U.S. government or from commercial industry, to reach that goal?

Because NASA is not alone in seeing the potential for space nuclear propulsion. The Defense Advanced Research Projects Agency-DARPA-has its own nuclear thermal propulsion project, albeit for national security interests. And the Department of Energy, with its nuclear expertise and infrastructure, is also involved.

We need to see how the various agencies are collaborating, including on a government-wide strategy and vision for space nuclear propulsion.

The time is ripe for America to act and take bold, well-considered, steps towards the goal of sending humans to Mars, a goal that will both inspire and lead to significant technological advances that will benefit all of us here on Earth. Development of space nuclear propulsion is one such necessary step, and this Subcommittee has an essential role in setting the policy to get us there.

I look forward to our witnesses' testimony.

Chairman BEYER. And I now recognize my friend, the Ranking Member of the Subcommittee, Dr. Babin, for an opening statement.

Mr. BABIN. Thank you very much, Mr. Chairman. This is going to be very interesting, and I'm looking forward to this hearing. Space nuclear power and propulsion holds great promise. It could lead to faster travel times, less radiation exposure for astronauts, greater mission flexibility, and more power for operations and instruments. Other nuclear applications, like surface reactors, could also support a robust space exploration architecture. Nuclear power and propulsion for space exploration is not a novel concept. The Air Force, the Atomic Energy Commission, and NASA partnered in the 1950's and 1960's on Project Rover and the NERVA (Nuclear Engine for Rocket Vehicle Applications) Program to develop nuclear rockets. The SNAP (Systems for Nuclear Auxiliary Power) Program resulted in the launch of a nuclear-powered satellite in 1965. The Russians flew Topaz reactors in the 1980's and 1990's, and NASA has incorporated radio-isotope power systems into missions since the dawn of the Space Age.

Support for new space nuclear projects have come and gone over the years as well. The space reactor prototype was canceled in the 1990's. Nuclear projects associated with the Strategic Defense Initiative and Space Exploration Initiative faded with the overarching programs, and Project Prometheus was canceled due to budget constraints 15 years ago. If future programs are not crafted carefully, with strategic forethought, they may fall victim to the very same fate. And as the National Academies have pointed out—excuse me, pointed out in their report from earlier this year, recent apples to

apples trade studies comparing NEP (nuclear electric propulsion) and NTP systems for a crewed mission to Mars in general, and baseline mission in particular, do not exist.

The Academy also call on NASA to conduct an objective comparison of the two systems. Other decisions, such as whether HEU (highly enriched uranium) or HALEU (high-assay low-enriched uranium) should be used as the fuel, and whether Hall, MPD (magnetoplasmadynamic), or VASIMR (Variable Specific Impulse Magnetoplasma Rocket) should be used for NEP thrusters should also be studied further. Extensibility, or the ability of a system to be used for future missions, and not be a dead-end technology, will also be very important for the future viability of nuclear space propulsion.

Architectures developed for crewed missions, uncrewed mission, surface power, low Earth orbit operations, and missions to the Moon, Mars, and beyond should all build upon each other, and leverage previous investments. These space architecture trades should not only meet near-term goals, but also account for future exploration challenges. What might seem ideal in the near term may not be the very best solution in the long term. And when budgets get tight, and funding gets prioritized, high risk, high reward technologies, like space nuclear power and propulsion, have often been left on the chopping block. Because of this reality, NASA should evaluate extensibility and future strategic decisions regarding space nuclear power and propulsion architectures.

Coordination with other agencies and the private sector will also determine the success of space nuclear power and propulsion research and development (R&D). The Department of Energy has an Advanced Reactor Demonstration Program and a Nuclear Reactor Innovation Center. DARPA initiated the DRACO (Demonstration Rocket for Agile Cislunar Operations) Program. The Strategic Capabilities Office started the Pele Project, and DIU (Defense Innovation Unit) issued a solicitation for small nuclear-powered space engines. Furthermore, companies like BWXT, X-Energy, USNC, and General Atomics have proposed technologies that may meet NASA's space exploration needs.

For NASA's space nuclear power and propulsion efforts to be successful, they will have to coordinate with these other efforts. Space Policy Directive—excuse me, Space Policy Directive 6, the Executive order promoting small modular reactors for national defense and space exploration, and the Presidential memorandum on launch of spacecraft containing space nuclear systems were issued by the last administration to enable this coordination. But oversight will be necessary to ensure that the agencies follow through. Adhering to the national strategy with consistent, steady, and predictable investments, coordinated partnerships with other agencies and the private sector, and a strategic perspective for exploration will all influence whether space nuclear power and propulsion will live up to its promise.

I look very much forward to hearing from our distinguished witnesses today, and I yield back the balance of my time, as I see I'm at the end. So I yield back. Thank you.

[The prepared statement of Mr. Babin follows:]

Space nuclear power and propulsion holds great promise. It could lead to faster travel times, less radiation exposure for astronauts, greater mission flexibility, and more power for operations and instruments. Other nuclear applications like surface reactors could also support a robust space exploration architecture.

Nuclear power and propulsion for space exploration is not a novel concept. The Air Force, the Atomic Energy Commission, and NASA partnered in the 1950s and 60s on Project Rover and the Nuclear Engine for Rocket Vehicle Applications (NERVA) program to develop nuclear rockets. The Systems for Nuclear Auxiliary Power (SNAP) program resulted in the launch of a nuclear-powered satellite in 1965, the Russians flew TOPAZ reactors in the 80s and 90s, and NASA has incorporated Radioisotope Power Systems into missions since the dawn of the space age. Support for new space nuclear projects have come and gone over the years as well. The Space Reactor Prototype was cancelled in the 90s, nuclear projects associated with the Strategic Defense Initiative and the Space Exploration Initiative faded with the overarching programs, and Project Prometheus was cancelled due to budget constraints 15 years ago.

If future programs are not crafted carefully with strategic forethought, they may fall victim to the same fate. As the National Academies pointed out in their report from earlier this year, "[r]ecent, apples-to-apples trade studies comparing [nuclear electric propulsion] NEP and [nuclear thermal propulsion] NTP systems for a crewed mission to Mars in general and the baseline mission in particular do not exist." The Academy also called on NASA to conduct an objective comparison of the two systems. Other decisions such as whether Highly Enriched Uranium (HEU) or High Assay Low Enriched Uranium (HALEU) should be used as the fuel and whether Hall, MPD, or VASMIR should be used for NEP thrusters should also be studied further.

Extensibility, or the ability of a system to be used for future missions and not be a "dead-end" technology, will also be important for the future viability of nuclear space propulsion. Architectures developed for crewed missions, uncrewed mission, surface power, low-Earth orbit operations, and missions to the Moon, Mars, and beyond should all build upon each other and leverage previous investments. These space architecture trades should not only meet near-term goals, but also account for future exploration challenges. What might seem ideal in the near-term may not be the best solution in the long-term. When budgets get tight, and funding gets prioritized, high-risk, high-reward technologies like space nuclear power and propulsion have often been left on the chopping block. Because of this reality, NASA should evaluate extensibility in future strategic decisions regarding space nuclear power and propulsion architectures.

Coordination with other agencies and the private sector will also determine the success of space nuclear power and propulsion research and development. The Department of Energy has an Advanced Reactor Demonstration Program and a Nuclear Reactor Innovation Center, DARPA initiated the Demonstration Rocket for Agile Cislunar Operations (DRACO) program, the Strategic Capabilities Office started the Pele project, the Defense Innovation Unit issued a solicitation for small nuclear-powered space engines. Furthermore, companies like BWXT, X-energy, USNC, and General Atomics have proposed technologies that may meet NASA's space exploration needs. For NASA's space nuclear power and propulsion efforts to be successful, they will have to coordinate with these other efforts. The National Strategy for Space Nuclear Power and Propulsion (Space Policy Directive 6), the Executive Order Promoting Small Modular Reactors for National Defense and Space Exploration, and the Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems were issued by the last Administration to enable this coordination, but oversight will be necessary to ensure the agencies follow through.

Adhering to the National Strategy with consistent, steady, and predictable investments; coordinated partnerships with other agencies and the private sector; and a strategic perspective for exploration will all influence whether space nuclear power and propulsion will live up to its promise. I look forward to hearing from our witnesses today and yield back the balance of my time.

Chairman BEYER. Thank you, Dr. Babin, very much. So if there are Members who wish to submit additional opening statements, your statements will be added to the record at this point. At this time I'd like to introduce our witnesses.

Dr. Roger Myers is a senior aerospace consultant with more than 30 years of experience in space technology development, flight programs, in-space mission architecture planning. He previously

worked at Aerojet Rocketdyne, and held positions at NASA's Glenn Research Center. Dr. Myers also served as Co-Chair of the National Academies of Sciences, Engineering, Medicine's Committee on Space Nuclear Propulsion Technologies. He holds a Ph.D. in Mechanical and Aerospace Engineering from Princeton University.

Dr. Bhavya Lal is senior advisor to the NASA Administrator for Budget and Finance. Previously Dr. Lal led the space technology and policy portfolio at the Institute for Defense Analysis, Science and Technology Policy Institute, where she led analyses for the White House Office of Science and Technology Policy, the National Space Council, and Federal Government agencies. She has served on National Academies committees, including on the Committee on Space Nuclear Propulsion Technologies. She holds a bachelor's and a master's degree in nuclear engineering, a master's degree in technology policy from MIT (Massachusetts Institute of Technology), and a doctorate in public policy and public administration from George Washington University.

Mr. Greg Meholic is a senior project leader for Civil Systems Technology at The Aerospace Corporation, a federally funded research and development center dedicated to the Nation's space enterprise. Mr. Meholic is the technical coordinator for cross-agency projects associated with fission-based space nuclear propulsion and power (SNPP). His portfolio includes launch vehicle concept development and advanced propulsion technology planning for future access to space. Mr. Meholic holds bachelor's and master's degrees in aerospace engineering from Embry-Riddle Aeronautical University.

Mr. Michael French is Vice President for Space Systems at the Aerospace Industries Association. He previously served as the Senior Vice President for Commercial Space at Bryce Space and Technology and has held Federal Government positions, including as NASA's Chief of Staff. Prior to serving in government, he practiced law in the defense and aerospace sector. Mr. French holds a Bachelor of Science in business administration from the University of California Berkeley, and a J.D. from Harvard Law School.

Dr. Franklin Chang-Diaz is Chairman and CEO of Ad Astra, or Ad Astra, Rocket Company. A former astronaut, Dr. Chang-Diaz flew on seven space missions and completed three space walks. Dr. Chang-Diaz initiated the VASIMR plasma rocket engine project in 1980 at the Johnson Space Center. In 2005 he retired from NASA and founded Ad Astra to continue to mature the technology through the private sector. Dr. Chang-Diaz has received a Ph.D. in applied plasma physics from MIT, and a bachelor's degree in mechanical engineering from the University of Connecticut.

As our witnesses should know, you'll each have 5 minutes for your spoken testimony. There's a cool little clock on the Zoom screen. And your written testimony will be included in the record for the hearing. And when you've all completed your spoken testimony, we will begin with the difficult questions, and each Member will have 5 minutes to question the panel. So let's begin with Dr. Myers. Dr. Myers, the floor is yours.

TESTIMONY OF DR. ROGER M. MYERS, CO-CHAIR, COMMITTEE ON SPACE NUCLEAR PROPULSION TECHNOLOGIES, NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE

Dr. MYERS. Good morning, Chairman Beyer, Congressman Babin, and Members of the Committee. My name is Roger Myers. I'm the owner of R. Myers Consulting, the President of the Washington State Academy of Sciences, and the Chair of the Washington State Joint Center for Aerospace Technology Innovation. I served as the Co-Chair, along with Dr. Robert Braun, of the Committee on Space Nuclear Propulsion for Human Mars Exploration of the National Academies of Sciences, Engineering, and Medicine.

NASA's Space Technology Mission Directorate commissioned this study to assess the primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion systems for human missions to Mars, including both nuclear thermal and nuclear electric technology options. Specifically, we were asked to assess these factors for a nuclear thermal propulsion system providing 900 second specific impulse, and a nuclear electric propulsion system providing at least one megawatt of electric power, and a power to mass ration that is substantially better than the state-of-the-art. Additionally, the propulsion systems were to be ready for a human mission in 2039, with a round trip time, including Mars surface stay, of less than 750 days.

Based on the input that we gathered, and our committee deliberations, we arrived at several consensus findings and recommendations. I will discuss only the most important of these in my oral testimony because of time limitations. They are all addressed in my written testimony. I will first address those for nuclear thermal propulsion, and then I will review those for nuclear electric propulsion.

Concerning nuclear thermal propulsion, our key findings were, first, we found that there are currently no nuclear reactor fuels that can provide the reactor temperatures to meet—the required temperatures to meet the required performance or engine lifetime. The Committee recommends that the characterization of reactor core materials, including fuels and moderators, begin immediately, as it is a fundamental risk to nuclear thermal propulsion technology. Second, we found that technology to store liquid hydrogen in space for the required mission durations does not exist. Our committee recommends that NASA develop high-capacity liquid hydrogen storage technology to meet the 3 to 4 year in-space storage requirement.

Third, we found that subscale in-space testing of nuclear thermal propulsion systems cannot adequately address the baseline mission risks, and therefore full-scale integrated ground testing of the nuclear thermal system is required. Combining this full-scale ground testing with extensive modeling and simulation enables the use of the precursor cargo missions to Mars to meet the flight qualification requirements for the human mission, and eliminates the need for the precursor demonstration flights. Our committee recommends directly addressing these needs, and adopting this flight qualification approach. Finally, our committee found that an aggressive program could develop a nuclear thermal propulsion sys-

tem capable of executing the baseline mission in 2039, but that major challenges require near-term resolution.

For nuclear electric propulsion, first, our committee found that developing a megawatt class nuclear electric propulsion system for the baseline mission will require increasing several subsystems' power by orders of magnitude over available technology. Second, similar to nuclear thermal propulsion, our committee found that subscale in-space flight testing of nuclear electric propulsion systems cannot address the risks associated with the baseline mission system, but with sufficient modeling, and simulation, and ground testing, flight qualification requirements can be met by the cargo precursor missions. Additionally, nuclear electric propulsion may not require fully integrated ground testing. Modular subsystem tests at full power may be adequate. Our committee recommends directly addressing these needs and adopting this flight qualification approach.

Finally, our committee found that due to low and intermittent investment over the past several decades, it is unclear if even an aggressive program would be able to develop a nuclear electric propulsion system capable of executing the baseline mission. To clarify, we're not saying that we—that it cannot, but rather that we do not have the data now on which to base a good assessment.

In summary, our committee found that either nuclear thermal propulsion or nuclear electric propulsion systems would provide substantial benefits to human Mars exploration missions, but that both systems have significant technical risk today. There is a need for significant investment in both systems before a data-driven selection can be made between the two. Thank you for the opportunity to testify. I'm happy to answer any questions the Subcommittee may have.

[The prepared statement of Dr. Myers follows:]

Statement of

Roger M. Myers, Ph.D.
Owner, R Myers Consulting, LLC
and
President, Washington State Academy of Sciences
Chair, Washington State Joint Center for Aerospace Technology Innovation

and

Co-Chair, Committee on Space Nuclear Propulsion for Human Mars Exploration

before the

Subcommittee on Space and Aeronautics
Committee on Science, Space and Technology
House of Representatives

October 20th, 2021

Good morning, Chairman Beyer, Ranking Member Babin, and members of the subcommittee. My name is Roger Myers. I am the owner of R Myers Consulting, the President of the Washington State Academy of Sciences, and Chair of the Washington State Joint Center for Aerospace Technology Innovation. I served as the Co-Chair, along with Dr. Robert Braun, of the committee that wrote the National Academies of Sciences, Engineering, and Medicine report, *Space Nuclear Propulsion for Human Mars Exploration*. The National Academy of Sciences was chartered by Congress in 1863 to advise the government on matters of science and technology and later expanded to include the National Academies of Engineering and Medicine. This study was commissioned in early 2020 by NASA's Space Technology Mission Directorate to assess the primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion systems for human exploration missions to Mars, including both nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) technology options. Specifically, we were asked to assess these factors for an NTP system providing 900s specific impulse, and an NEP system providing at least 1 MW of electric power with a power-to-mass ratio that is substantially better than the current state-of-the-art. Additionally, the propulsion systems were to be ready for a human mission in 2039, with a round trip time, including the Mars surface stay, of less than 750 days. I refer to this as the baseline mission.

Our ad hoc Committee performing this work included highly experienced representatives from industry, the Department of Energy, the Department of Defense, and academia, and we received outstanding support from the National Academies' study director Alan Angleman. Our Committee received input and presentations from NASA, the Department of Energy, several companies, and universities. We held over twenty meetings over the course of the year, completing our work in February of 2021.

By way of background, NTP systems are conceptually similar to chemical rockets, where the combustion chamber has been replaced by a compact, very high-power-density nuclear reactor. To achieve the required specific impulse of 900s, the hydrogen propellant is pumped through the high-temperature reactor and is heated to a temperature of at least 2,700 Kelvin. Achieving this hydrogen temperature requires the nuclear reactor fuel to operate at a temperature of approximately 2900 K or more. The reactor must also start very rapidly compared to other reactors: a start time of less than one minute is best in order to reach the required performance levels rapidly. An NTP system thus requires a liquid hydrogen storage and pumping subsystem, a high-performance nuclear reactor with shielding, and a nozzle that converts thermal energy from the reactor into thrust. By contrast, an NEP system requires a lower temperature, slow-start nuclear reactor with shielding, a power conversion subsystem to generate the electrical power, a heat rejection subsystem consisting of large radiators, an electrical power management and distribution subsystem, and an electric propulsion subsystem, all of which work together for successful NEP system operation. NTP and NEP are very different technologies that have very different challenges.

Based on all the input we received, an extensive review of the available literature, and our Committee deliberations, we arrived at several consensus findings and recommendations. All the relevant background and details are provided in our report (see http://www.nap.edu/25977). For this testimony, I will first address the key findings and recommendations for NTP systems,

then I will review those for NEP systems, and finally I will address those that are applicable to both NTP and NEP.

Concerning NTP, our key findings and recommendations are:

First, we found that no currently available nuclear reactor fuels can provide the required temperatures to meet the required performance or engine life. The Committee recommends that NASA should expeditiously select and validate a fuel architecture for the NTP system that can achieve the required 2,700 K hydrogen temperature at the reactor exit without significant deterioration during the mission, including the required rapid engine start transients (1 minute or less). This selection process should consider whether the appropriate fuel feedstock production capabilities will be sufficient.

Second, we found that technology to store liquid hydrogen in space for the required missions does not exist. Our Committee recommends that NASA develop high-capacity tank systems capable of storing liquid hydrogen at 20 K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission.

Third, we found that subscale in-space testing of NTP systems cannot adequately address the baseline mission risks and potential failure mechanisms of NTP systems. Therefore, full-scale and full-thrust integrated ground testing of the NTP system is required. Combining this full-scale ground testing with extensive modeling and simulation enables the use of the precursor cargo missions to Mars to meet the flight qualification requirements for the human mission and eliminates the need for precursor demonstration flights. Our Committee recommends that NASA rely on extensive investments in (1) modeling and simulation, (2) ground testing, including integrated system tests at full scale and thrust; and (3) the use of cargo missions as a means of flight qualification of the NTP system that will be incorporated into the first crewed mission.

Finally, our Committee found that an aggressive program could develop an NTP system capable of executing the baseline mission in 2039. However, to achieve this, our Committee recommends that NASA invigorate technology development associated with the fundamental NTP challenges, which is to develop an NTP fuel system that can heat its hydrogen propellant to approximately 2,700 K at the reactor exit for the duration of each burn. NASA should also invigorate technology development associated with the long-term storage of liquid hydrogen in space with minimal loss, the lack of adequate ground-based test facilities, and the need to rapidly bring an NTP system to full operating temperature (preferably in 1 minute or less).

For NEP, our key findings and recommendations are:

First, our Committee found that developing a MWe-class NEP system for the baseline mission will require increasing the power of several subsystems by orders of magnitude over available technology.

Second, similar to NTP, our Committee found that subscale in-space flight testing of NEP systems cannot adequately address the risks and potential failure modes associated with the

baseline mission NEP system. With sufficient modeling, simulation, and ground testing, including modular subsystem tests at full scale and power, flight qualification requirements can be met by the cargo missions that will precede the first crewed mission to Mars. Additionally, NEP systems may not require fully integrated ground testing - modular subsystem tests at full power may be adequate. In order to develop an NEP system for the baseline mission, our Committee recommends that NASA rely on (1) extensive investments in modeling and simulation, (2) ground testing (including modular subsystem tests at full scale and power), and (3) the use of cargo missions as a means of flight qualification.

Finally, our Committee found that as a result of low and intermittent investment over the past several decades, it is unclear if even an aggressive program would be able to develop an NEP system capable of executing the baseline mission. To clarify – we are not saying that it cannot – but rather that we do not have the data on which to base a good assessment. Our Committee recommends that NASA invigorate technology development associated with the fundamental challenge for NEP systems, which is to scale up each subsystem's operating power and develop an integrated nuclear electric system suitable for the baseline mission. Additionally, NASA should put in place plans for (1) demonstrating the operational reliability of an integrated NEP system over its multi-year lifetime and (2) developing a chemical propulsion system that can be used with the nuclear electric system. If NASA plans to apply NEP technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development.

Our findings and recommendations applicable to both NTP and NEP are:

First, our Committee found that recent, apples-to-apples trade studies comparing NEP and NTP systems for a crewed mission to Mars in general and the baseline mission, in particular, do not exist. To remedy this gap, NASA should develop consistent figures of merit and technical expertise to allow for an objective comparison of the ability of these systems to meet the requirements of the baseline mission.

Second, both NEP and NTP systems require, albeit to very different levels, significant maturation in areas such as nuclear reactor fuels, materials, and additional reactor technologies; cryogenic fluid management; modeling and simulation; testing; and regulatory approvals. Given those commonalities, some development work in these areas can proceed independently of selecting a particular space nuclear propulsion system.

Third, a comprehensive assessment of reactor fuels using high-assay low-enriched uranium (HALEU) vs. fuels using highly enriched uranium (HEU) for NTP and NEP systems that weighs the key considerations is not available. These considerations include technical feasibility and difficulty, performance, proliferation and security, fuel availability, cost, schedule, and supply chain as applied to the baseline mission. Our Committee recommends that in the near term, NASA and the Department of Energy (DOE), with inputs from other key stakeholders, including commercial industry and academia, conduct a comprehensive assessment of the relative merits and challenges of HEU and HALEU fuels for NTP and NEP systems as applied to the baseline mission.

Finally, we found that terrestrial microreactors, which operate at a power level comparable to NEP reactors, are on a faster development and demonstration timeline than current plans for space nuclear propulsion systems. Development of microreactors may provide technology advances and lessons learned relevant to the development of NEP systems. Similarly, technology advances within the Demonstration Rocket for Agile Cislunar Operations (DRACO) program of the Defense Advanced Research Projects Agency (DARPA) could potentially contribute to the development of NTP systems for the baseline mission. In light of these potential opportunities, our Committee recommends that NASA seek opportunities for collaboration with the DOE and Department of Defense terrestrial microreactor programs and the DARPA DRACO program to identify synergies with NASA space nuclear propulsion programs.

In summary, our Committee found that either nuclear thermal or nuclear electric propulsion systems would provide substantial benefits to human Mars exploration missions but that both systems have significant technical risks today. These risks are very different for NTP and NEP systems, and neither one is at a state of development suitable for selection. There is a need for significant investment in both systems before a data-driven selection between the two can be made.

Thank you for the opportunity to testify. I'm happy to address any questions the Subcommittee might have.

Dr. Roger Myers
Consultant, R Myers Consulting LLC
Woodinville, WA 98072

Experience Summary

Dr. Roger Myers has over 30 years of experience developing, testing and producing for flight space propulsion technologies and systems of all types for NASA, National Security, and commercial space missions. Additionally, he has spent years leading teams studying spacecraft mission requirements, capabilities, designs, and architectures for all space markets and developing strategies and tactics for engineering team leadership and program and business management. His experience ranges from hands-on research and development, to leading small innovative teams, to leading, as General Manager, the world's largest developer and producer of in-space propulsion technologies and systems, Aerojet Rocketdyne's 400+ person site in Redmond, Washington. His experience with chemical, electric, and nuclear propulsion system development and production as well as their integration requirements and challenges for all spacecraft sizes and applications provides a broad foundation for assessing new challenges and opportunities, and his extensive contacts in the U.S. and international space community enable him to facilitate new connections and create new opportunities. Dr. Myers is also the President of the Washington State Academy of Sciences and the Chair of Washington State's Joint Center for Aerospace Technology Innovation, as well as serving on the Boards for the Electric Rocket Propulsion Society (President 2013-2020) and Seattle's Museum of Flight. Additionally, Dr. Myers supports his community serving on National Academies committees and giving speeches and lectures.

Education

BS Aerospace Engineering, summa cum laude, University of Michigan, 1984
Ph.D, Mechanical and Aerospace Engineering, Princeton University, 1989

Experience

July 2016 – present: independent consultant, R Myers Consulting, LLC
2013-July 2016: Executive Director, Advanced In-Space Programs, Aerojet Rocketdyne
2011 – 2013: Executive Director, Electric Propulsion and Integrated Systems, Aerojet
2010 – 2011: Deputy Lead, Space and Launch Systems and Exec. Director, Electric Propulsion & Integrated Systems, Aerojet
2006-2010: General Manager, Aerojet Redmond Operations
2005-2006: Executive Director, Systems and Technology Development, Aerojet
2002-2005: Director, Systems and Technology Development, Aerojet
1996-2002: Director, Electric Propulsion and Space Electronics, Olin Aerospace, Primex Technologies, and GD Space Propulsion
1988-1996: Research Engineer and Group Supervisor (Sverdrup and Nyma) at NASA Glenn Research Center (then Lewis), conducting and overseeing in-space propulsion research

Awards and Honors

Stuhlinger Medal for Outstanding Achievement in Electric Propulsion, Electric Rocket Propulsion Society, 2017
Wyld Propulsion Award, American Institute of Aeronautics and Astronautics, 2014
Member (elected), Washington State Academy of Sciences, 2012
Fellow (elected), American Institute of Aeronautics and Astronautics, 2010
European Space Agency Award for "Outstanding Contribution to SMART-1 Mission", 2003
NASA Award for "Turning Goals into Reality", for outstanding contributions to and exceptional progress toward NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) Team, 2001

NASA Group Achievement Award for the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) Team, 1999
NASA Award for Exceptional Contributions to the Space Station Alpha Photovoltaic Test, 1995
NASA Award for Outstanding performance in support of NASA's Space Propulsion Technology Division, 1994
NASA Award for Outstanding support of NASA's On-Board Propulsion Branch, 1992
NASA Award for Outstanding contributions to the Space Station Freedom Photovoltaic Array Test, 1992
NASA Award for Attaining highest power and performance levels achieved with MPD thrusters, 1991

Boards and Other Service to Aerospace, Science, and Engineering Community
2020 – Present: President, Washington State Academy of Sciences; Board member since 2016
2012-Present: Board of Directors and Chair, Joint Center for Aerospace Technology Innovation (Appointed by Washington State Governor)
1995-Present: Board of Directors (Founding member) and President (2013-2020), Electric Rocket Propulsion Society
2015 – Present: Board of Trustees, Museum of Flight, Strategic Planning Committee Chair and member of Education and Spaceflight Committees
2006-Present: Visiting Committee, University of Washington, Dept. of Aeronautics and Astronautics
2020 – Feb 2021: Co-Chair: National Academy of Sciences, Engineering and Medicine Committee "Space Nuclear Propulsion for Human Mars Exploration"
2014-Sept 2020: Member, National Academy of Sciences, Engineering and Medicine Space Technology Industry-Government-University Roundtable
2012: Panelist and In-Space Propulsion (TA02) lead, National Academy of Sciences, Engineering and Medicine, "NASA Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space"
2011-July 2016: Board of Directors, Aerojet Rocketdyne Foundation
2010-2012: Advisory Board, Seattle Science Fair
2006: Panelist, National Academy of Sciences, Engineering and Medicine; "High Energy Power and Propulsion and In-Space Transportation"
1993-2008: Associate Editor, Journal of Propulsion and Power
1998-2000: Chair, AIAA Electric Propulsion Technical Committee
1995-2006: Instructor, AIAA Electric Propulsion Short Course
1994: Organizer, Electric Propulsion Sessions, AIAA Joint Propulsion Conference
1990 – Present: Session chair at most Joint Propulsion and International Electric Propulsion Conferences

Invited Speeches, Presentations, and Panels
Invited Speaker/Lecturer (examples only): Graduation Commencement Speaker at Washington State University (5/2013); Banquet speaker, American Junior Academy of Sciences, 2020; Plenary Speaker at 2013 IECEC "Power Generation and Processing Challenges for Near-Term High Power Solar Electric Propulsion"; Pacific Northwest Aerospace Association (5/2015) "The Business of Space in Washington State"; Graduation speaker for Washington Aerospace Scholars program (2014, 2015, 2016); Univ. Washington Jackson School of International Studies "Space in Washington State"; Testimony to Washington Lt. Governor's Summit on Space (12/2015), "Aerojet Rocketdyne in Washington State"; MIT Enterprise Forum Seattle "Human Mars Exploration: How do we do it affordably?" (12/2015); NRO Technology Seminar "Enhanced Mission Affordability thru Advanced In-Space Propulsion" (1/2013) ; NRC Human Spaceflight Committee "Affordable Human Space Exploration Architectures" (6/2013); NASA ASEB "High Power Solar Electric Propulsion" (10/2013); **Invited Panelist** (examples only): Space Propulsion 2016 "Primes and Operators vs. Suppliers Views on Space Propulsion: Spacecraft"; U.S-Japan Space Forum (3/2016); Propulsion and Energy Conference Forum 360: "Government Investments Enabling Advancement of In-Space Propulsion"

(7/2015); AIAA Propulsion and Energy panel on "Keeping it Going: Sustainability and Growth in Technology and Workforce" (7/2014); Seattle Museum of Flight "The Future of Space" (1/2014); AIAA Propulsion and Energy Conference IECEC Panel on Human Exploration (7/2015) "In-Space Propulsion for Exploration"; "International Partnerships" (Space 2013, 9/2013); "U.S. Space Propulsion" (Space Propulsion 2013, 5/2013); "Space Propulsion in the Puget Sound Region" (WashingtonSTEM, 2/2012); "Pushing the Limits of Knowledge" for NASA 50th Anniversary Forum, (2008); Aerospace Lectures @ U of WA (annual from 1997 – present); "Evolution and Future Directions for Space Transportation" (2003); and at many other locations including Cornell, JPL, LANL, LLNL, Michigan Tech., Ohio State U., ORNL, Princeton U., U of Michigan, U of Tennessee Space Institute, and Worcester Polytechnic Institute

Patents

- Helicon Hall Thruster, Brian E. Beal, Roger M. Myers, Kristi H. de Grys and Alfred C. Wilson, U.S. Patent 7,436,122 Oct. 14, 2008
- Uniform Gas Distribution in ion accelerators with closed electron drift, U.S. Patent 6612105, Arnie Voigt, Kristi de Grys, David King, and Roger Myers, Sept. 2, 2003
- Three axis pulsed plasma thruster with angled cathode and anode strip lines; U.S. Patent 6,173,565; R. Joseph Cassady, Roger M. Myers and Robert D. Osborne, 1998
- Pulsed Mode Cathode; U.S. Patent 5,357,747; Roger M. Myers and Vincent K. Rawlin, Oct 25, 1994

Sample Career Accomplishments

Department of Defense Space missions:

Advanced Extremely High Frequency Mission (AEHF): led team that developed and produced the 4.5kW Hall thruster propulsion system (thrusters and power processing electronics) used for orbit raising and station keeping, including development of the world's first zero-erosion long-life Hall thruster (which led to today's magnetic-shielding concepts).

Global Positioning System: Led team that developed and produced propulsion system for all GPS IIF spacecraft

Wideband Gapfiller Mission: led team that produced GEO insertion bipropellant engines for all of these spacecraft

Coriolis: led team that developed propulsion system for the Navy spacecraft

NFIRE: led team that developed and produced propulsion system for Missile Defense Agency spacecraft

Many classified missions

NASA Space Missions:

Mars Science Laboratory: led team that developed and produced the lander engines with continuous 100:1 throttling capability (7 to 700lbf thrust) enabling the Curiosity Rover to land successfully on Mars, and recently used for Perseverance rover landing.

Pluto/New Horizons: led team that developed and built the propulsion system for APL-led mission to Pluto and beyond – providing extraordinary instrument pointing accuracy during high-speed fly-by.

STEREO: led team that developed and built the propulsion systems for the twin spacecraft

Mars Phoenix Lander: led team that produced the lander engines for first ever controlled soft-landing using pulsed-mode throttling.

THEMIS: led team that developed and built the propulsion systems for the 5-spacecraft constellation of small spacecraft

GOES-R: led team that developed and produced the arcjet system for orbit acquisition and control

Earth Orbiter 1: led team that developed and built both hydrazine and pulsed plasma thruster propulsion systems for the New Millennium program demonstrator spacecraft.

Orion: led team developing all the engines for both the Crew and Service modules, including both new monopropellant and bipropellant engines (2005-2011)
Ares: led team that developed 700lbf Roll Control Engines for the Ares launcher
Deep Space 1: performed early lifetests on NSTAR ion thruster and designed plume diagnostics used in initial spacecraft interface assessments. This same engine was used on NASA's **Dawn** mission to the asteroids Vesta and Ceres.
Green Propellant Infusion Mission: led team that designed, developed and produced AF-M31E propellant thrusters and integrated propulsion system for this successful technology demonstration mission.

International Civil Space Missions
European Automated Transfer Vehicle: led team that qualified and produced 100lfb thrust primary orbit adjust engines for the Jules Verne and subsequent ATV vehicles
H-II Transfer Vehicle: led team that qualified and produced 25lbf thrust ACS engines for the HTV vehicle
Smart-1: led team that developed and produced hydrazine attitude control system for European mission to the moon.
DRTS and WINDS: led team that developed and produced the arcjet systems for these two Japanese communications satellites

Commercial Missions
GeoEye-1: led team that developed propulsion system for highest resolution commercial imagery spacecraft
A2100: Led team that developed and continues producing all chemical and electric engine systems (thrusters and power electronics) for Lockheed-Martin's A2100 series of spacecraft (1996-2010)
Star-2: Led the team producing all the chemical and electric attitude control engines for Orbital's (now Northrup Grumman) Star series of commercial spacecraft (2006-2010)
FS 1300: Led the team that developed, qualified and produced the bipropellant apogee engines for Loral's commercial satellites (2006-2010)
Boeing 702: led team that developed and produced bipropellant apogee engine for Boeing's commercial satellites
Eurostar 2000/3000: Led the team producing the bipropellant engines for EADS/Astrium's commercial satellites (2006-2010)

Technology Development – but not yet flown
Led teams which:
- wrote winning proposals for NASA Advanced Electric Propulsion System (AEPS), the NASA Evolutionary Xenon Thruster (NEXT), and the 100kW Nested Hall Thruster System demonstration (NextSTEP) programs. The NEXT ion thruster is currently being integrated onto NASA's DART mission as a flight demonstration.
- demonstrated highest performance 100lbf thrust class NTO/Hydrazine bipropellant engine with Isp of 334s (NASA AMBR program, 2008)
- demonstrated highest thrust-to-power ratio Hall thruster (USAF HPPS program, 2008)
- built the NEXT 7.5kW high performance ion thruster (NASA NEXT program, 2007) – in 2015 awarded flight contract
- developed and qualified a 620s I_{sp} arcjet propulsion system (2002)
- highest power U.S. steady state magnetoplasmadynamic thruster (225kW, 1993)

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4. "NASA Small Spacecraft Technology Program", Science and Technology Policy Institute, February 2017

Chairman BEYER. Dr. Myers, thank you very much, and perfect timing. In the meantime, I'm in trouble because I neglected to recognize the Chair of the Full Committee, the wonderful Congresswoman E.B. Johnson, for her opening statement. So, Dr. Lal, if you'll allow me to pivot back to the Chair of our Committee, I recognize Congresswoman Johnson for her statement.

Chairwoman JOHNSON. Thank you very much, Mr. Chairman. I really appreciate you holding this hearing. For decades the space community has identified nuclear propulsion as a required and enabling technology for our human exploration goals. Even the best chemical propulsion capabilities of today mean long travel times to and from Mars, and a long stay on the red planet for our astronaut crew. Space nuclear propulsion is a capability that can help address the safety of our astronauts by reducing their exposure to in-space radiation with shorter trips. Reducing the length of time that the first crew stays on Mars and—would make the mission more feasible and likely to succeed.

We've talked about this technology for a long time. It has been the subject of many studies by NASA, the Department of Defense (DOD), and external advisory committees, including one led by retired Air Force Lieutenant General Tom Stafford in 1991. I want to know what we need to do to move from studies and talk to meaningful progress. Whether it's R&D investment, developing safety standards, or building a STEM (science, technology, engineering, and mathematics) pipeline in nuclear expertise, I hope our expert witnesses can identify the necessary actions for advancing space nuclear propulsion, and doing so safely. This capability will help our Nation lead the inspiring and ambitious effort of sending humans to Mars. Further, it will keep the United States and our industry partners at the cutting edge of nuclear research, development, and applications. I look forward to hearing from our expert witnesses this morning on the state of the technology and what we need to do to move it forward. I thank you, and yield back.

[The prepared statement of Chairwoman Johnson follows:]

Good morning. Thank you, Chairman Beyer, for holding this hearing.

For decades, the space community has identified nuclear propulsion as a required and enabling technology for our human exploration goals.Even the best chemical propulsion capabilities of today mean long travel times to and from Mars, and a long stay on the red planet for our astronaut crew.

Space nuclear propulsion is a capability that can help address the safety of our astronauts by reducing their exposure to in-space radiation with shorter trips. Reducing the length of time that the first crew stays on Mars would make the mission more feasible and likely to succeed.

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I look forward to hearing from our expert witnesses this morning on the state of the technology and what we need to do to move it forward.

Thank you, and I yield back.

Chairman BEYER. Thank you, Chairwoman Johnson, very much. I now recognize Dr. Lal for your opening statement. Dr. Lal, you are muted at the moment.

Dr. LAL. One second. I saw someone be muted——

Chairman BEYER. Yes, that—we can hear you now.

Dr. LAL. OK.

TESTIMONY OF DR. BHAVYA LAL,
SENIOR ADVISOR FOR BUDGET AND FINANCE,
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Dr. LAL. Good morning. Chairman Beyer, Chairwoman Johnson, Ranking Member Babin, and distinguished Members of the Subcommittee, it is an honor to again appear before Congress, this time on behalf of NASA, to talk about nuclear propulsion. Serving under Administrator Nelson and Deputy Administrator Melroy at NASA has been a dream come true for me. I hope I can convey to the Committee the excitement the whole NASA team feels about the future of exploration, a future that assures continued American leadership throughout the solar system and beyond.

As you know, on the Artemis Program, NASA is endeavoring to return humans to the Moon, but our goals don't stop there. Far from it. With the direction from Congress to expand human presence into the solar system, our eyes are on Mars, and beyond Mars. If we want to explore the cosmos with humans and with robots, we need to develop mass efficient high energy solutions that can power space vehicles, operate in harsh radiation environments, and increase mission flexibility. Nuclear fission systems can provide such solutions, delivering the high-powered levels needed to conduct exciting activities on the surface of the Moon, reduce trip time of crewed missions to Mars, and carry large payloads with expanded maneuverability for robotic missions into space.

Dr. Myers has already introduced nuclear electric and nuclear thermal propulsion systems. When combined with a chemical stage and NEP, nuclear electric propulsion system, can provide fast transit to Mars. A shorter trip, as many of you have mentioned, would reduce crew exposure both to harmful galactic and cosmic radiation, and to a reduced gravity environment. NEP reactors can also provide extensibility to higher power surface reactors, and are considered the lowest mass solution for a fast transit to Mars.

And NTP, nuclear thermal propulsion system, works differently, but can similarly enable a smaller and more versatile transport, along with faster trip times. The ability of an NTP system to generate high thrust on demand could provide greater mission flexibility, including mission abort and return to Earth options, if vital crew systems are not functioning properly. As with NEP chemical systems, the shorter trip enabled by NTP would reduce crew time and reduce gravity and space radiation.

As Dr. Myers said, both [inaudible] nascent, and face steep developmental challenges. The National Academies study has concluded that the best path forward is to execute early dual path technology investments for both NEP and NTP, and to make more informed decision in the next few years. To date, NASA has prioritized nuclear funding for fission surface power, which is a key capability for both lunar and Martian surface mission needs. Congress continues

to signal to—appropriations that NTP is a priority. As such, NASA's development in Fiscal Year 2021 and prior years has focused on NTP. NASA's Space Technology Mission Directorate has been leading both surface power and propulsion activities. We are working with DOD and DOE to procure low enriched uranium fuels from American industry. We recently funded three American companies to develop space-capable reactor designs. NASA is also sharing its space expertise—our space nuclear expertise to support DARPA on their NTP flight demonstration, which is planned for the mid-2020's.

Nuclear power systems for use on the Moon could be developed within the decade. Nuclear propulsion capabilities will cost more, and take longer. Indeed, realizing these capabilities will require sustained commitment and substantial investment over the next 10 to 20 years. It would demand working in lockstep with other government agencies, industry, and academia to ensure cost sharing and innovative development of systems.

Let me conclude today by reiterating that nuclear power and propulsion applications in space are key to enhancing U.S. leadership in space. Strategic competitors to the United States recognize this edge, and are investing in fission systems themselves to fulfill their own ambitions. Development of space nuclear systems will also advance the state-of-the-art for smaller and safer terrestrial nuclear power plants, helping to reduce greenhouse gas emissions. NASA's discovery of—everything that we do is fueled by persistence to solve hard problems worth solving. The decisions we make now will have ramifications for centuries. Doing great things when others cannot is the definition of what it means to be a leader. No one has said it better than President Kennedy, "We do these things not because they are easy, but because they're hard."

Thank you for the opportunity to testify. We look forward to working together on doing great and hard things, and I look forward to your questions.

[The prepared statement of Dr. Lal follows:]



National Aeronautics and
Space Administration

Hold for Release Until
Presented by Witness

Oct. 20, 2021

Committee on Science, Space, and Technology
Subcommittee on Space and Aeronautics

U.S. House of Representatives

Statement of:
Dr. Bhavya Lal
Senior Advisor for Budget and Finance
National Aeronautics and Space Administration

117th Congress

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Statement of
Dr. Bhavya Lal, Senior Advisor for Budget and Finance
National Aeronautics and Space Administration

before the

Subcommittee on Space and Aeronautics
Committee on Science, Space, and Technology
U.S. House of Representatives

Good morning. I am Bhavya Lal, the senior advisor for budget and finance at NASA, and I am delighted to be here to talk about space nuclear propulsion.

Distances in space are vast. You may remember, it took the New Horizons spacecraft over nine years to reach Pluto, and when it arrived, it did not have the propulsive ability to stop and take a more extensive look. The spacecraft flew past Pluto, collecting what data it could on its speedy fly-by. And it took over a year to send all that data back to Earth. All this was because we were both power- and propulsion-constrained. Just imagine what else we could have learned if we'd had the capability for a longer stay.

To date, chemical rockets and solar power have served our Nation well, but both have limitations, especially as we go deeper into the solar system. Mass-efficient, high-energy solutions to power space vehicles, operate in harsh radiation environments, and increase mission flexibility would open up new opportunities for space exploration.

Nuclear fission systems can provide such solutions, delivering the high power levels needed to conduct exciting activities on the surface of the Moon, reduce trip times of crewed missions to Mars, and accommodate larger payloads with expanded maneuverability for robotic missions into deep space.

Nuclear propulsion systems are not needed to get to the Moon, but could be valuable in sending payloads to Mars and more distant destinations. There are two ways fission reactions can power propulsion systems, although neither of these has yet been developed. When combined with a chemical stage, a Nuclear Electric Propulsion (or NEP) system could provide faster Mars transit capability, which leads to reduced crew exposure to galactic and cosmic radiation, as well as their exposure to a reduced gravity environment. NEP reactors could also provide extensibility to higher-power surface reactors, and are considered the lowest-mass solution for a fast transit to Mars.

A Nuclear Thermal Propulsion (or NTP) system, would provide both high thrust and high specific impulse, which may enable a smaller and more versatile system, along with faster trip times. The ability of an NTP system to generate high thrust on demand could provide greater mission flexibility, including mission abort and return-to-Earth options if vital crew systems are not functioning properly. As with NEP, the shorter trip provided by NTP would reduce crew time in a reduced gravity environment and lower exposure to space radiation.

Despite their potential and investment, especially in NTP systems in the 1950s and '60s, both technologies face steep developmental challenges. NASA-internal and external studies, including a 2021

assessment performed by the National Academies of Sciences, Engineering, and Medicine, have concluded that the maturity and readiness of both systems are low, and additional long-lead development is needed to mature either.

To date, NASA has prioritized nuclear funding for fission surface power, which is a key capability for both lunar and Martian surface mission needs. Congress continues to signal through annual appropriations that NTP is a priority. As such, NASA's development in FY 2021 and prior years has focused on NTP.

The Space Technology Mission Directorate at NASA has been leading both of these efforts. In all areas of research and development, NASA is working closely with academia, industry, and other Government agencies to explore nuclear-propulsion-related options and capabilities. For instance, we are working with the Department of Defense and the Department of Energy to develop a source of low-enriched uranium fuels from industry, and recently funded three companies to develop space-capable reactor designs. NASA is also sharing its expertise in cryogenic fluid management to support the Defense Advanced Research Projects Agency (DARPA) on their NTP flight demonstration planned in the mid-2020s.

Let me end my testimony by reiterating that nuclear power and propulsion applications could help to enhance U.S. leadership in space. They represent the type of investment that could help the U.S. maintain its global technological edge at a time when more countries around the world seek to fulfill space exploration objectives. Development of space nuclear systems would also advance the state-of-the-art for smaller, more efficient, and safer terrestrial nuclear power plants, to help reduce greenhouse gas emissions.

Nuclear power systems that could be used on the Moon could be developed within the decade. Nuclear propulsion capabilities will cost more and take longer – realizing these capabilities would require sustained commitment and substantial investment over the next 10-20 years. I also cannot emphasize enough the importance of collaborating with other Government agencies as well as academic and commercial stakeholders in ensuring cost-sharing and innovative development.

Thank you for the opportunity to discuss how space nuclear propulsion could support us in exploring Mars and beyond. We look forward to working with Congress on these important priorities. I look forward to your questions.

Dr. Bhavya Lal, Senior Advisor for Budget and Finance, NASA

Dr. Bhavya Lal serves as the senior advisor to the NASA Administrator for budget and finance. She was the seniormost White House appointee and Acting Chief of Staff at NASA for the first 100 days of the Biden Administration, the agency's transition under the administration of President Joe Biden. Before that, she served as a member of the Biden Presidential Transition Agency Review Teams for both NASA and the Department of Defense.

Lal brings extensive experience in engineering and space technology, serving as a member of the research staff at the Institute for Defense Analyses (IDA) Science and Technology Policy Institute (STPI) from 2005 to 2020. There, she led analysis of space technology, strategy, and policy for the White House Office of Science and Technology Policy (OSTP) and National Space Council, as well as federal space-oriented organizations, including NASA, the Department of Defense, and the intelligence community. She has applied her expertise in engineering systems and innovation theory and practice to topics in space, with recent projects on commercial activities in low-Earth orbit and deep space, in-orbit servicing assembly and manufacturing, small satellites, human exploration, space nuclear power, space exploration, and space science. She has published more than 50 papers in peer-reviewed journals and conference proceedings.

Before joining STPI, Lal served as president of C-STPS LLC, a science and technology policy research and consulting firm in Waltham, Massachusetts. Prior to that, she served as director of the Center for Science and Technology Policy Studies at Abt Associates Inc. in Cambridge, Massachusetts.

Lal is an active member of the space technology and policy community, having chaired, co-chaired, or served on five high-impact National Academy of Sciences, Engineering, and Medicine (NASEM) Committees including, most recently, one on Space Nuclear Propulsion Technologies released in 2021. She served two consecutive terms on the National Oceanic and Atmospheric Administration (NOAA) Federal Advisory Committee on Commercial Remote Sensing (ACCRES) and was an External Council member of NASA's Innovative Advanced Concepts (NIAC) Program and the Technology, Innovation and Engineering Advisory Committee of the NASA Advisory Council (NAC). She co-founded and is co-chair of the policy track of the American Nuclear Society's annual conference on Nuclear and Emerging Technologies in Space (NETS) and co-organizes a seminar series on space history and policy with the Smithsonian National Air and Space Museum. For her many contributions to the space sector, she was nominated and selected to be a Corresponding Member of the International Academy of Astronautics.

Lal earned Bachelor of Science and Master of Science degrees in nuclear engineering, as well as a Master of Science degree in technology and policy, from the Massachusetts Institute of Technology, and holds a doctorate in public policy and public administration from George Washington University. She is a member of both the nuclear engineering and public policy honor societies.

Chairman BEYER. Thank you, Dr. Lal, very much. It does sound like NTP and NEP will be hard. So let's move on to our leader from the FFRDC (federally funded research and development center), The Aerospace Corporation, Mr. Meholic. The floor is yours.

TESTIMONY OF MR. GREG MEHOLIC,
SENIOR PROJECT LEADER, THE AEROSPACE CORPORATION

Mr. MEHOLIC. Thank you. 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 testify on this exciting topic that has received more interest in the past few years than in the last half century. During my 20 years at Aerospace, supporting technology programs from the Air Force, Space Force, DARPA, NASA, and other agencies, I served as a subject matter expert for a project leader evaluating the design development, and operation of space launch systems (SLS), as well as for advanced emerging propulsion technologies. In my current role I am the technical coordinator, excuse me, for most of the aerospace activities, supporting cross-agency projects associated with fission-based space nuclear propulsion and power, or SNPP for short. There are three main points I would like to make to the Committee regarding fission-based SNPP.

My first point is that SNPP could offer enhanced mission capabilities. During the Nova Program 50 years ago, nuclear thermal propulsion, or NTP, engines demonstrated twice or more the cycle efficiency of traditional high thrust chemical rocket engines. This means an NTP system can deliver the same amount of total propulsive energy, thrust, and acceleration to the spacecraft as a chemical system, but with roughly half as much onboard propellant. So, for a given total vehicle mass, an NTP spacecraft can carry more payload mass than its chemical counterpart, or, in other words, more science for less propellant. With electrical power, a space nuclear electric system would offer long term, continuous, megawatt class electrical power that would be insensitive to line of sight or distance from the sun. If coupled to an electric propulsion system, otherwise known as nuclear electric propulsion, low level ultra-efficient thrusts could be produced continuously for perhaps months, depending on the mission. In short, SNPP could enable military and civil missions or capabilities not practically achievable using traditional means, and its adoption may therefore bolster U.S. space national security and leadership.

My second point is that SNPP technology maturation would benefit from the government-funded—or a government-funded, government led collaboration with industry and academia. In order to realize the potential benefits of SNPP, there are a number of technical, operational, and implementation challenges that must be addressed. Uranium fuel form development, materials technology, system modeling, tests and integration, and a whole host of other aspects are at the hearts of current government and industry projects that are closely engaged with academic research. But due to the uncertainty of—for SNPP customers and missions, these projects are always concerned with funding, objectives, personnel, capability, development, and a variety of other things. A series of multi-year government-funded, government-led efforts built upon

SNPP maturation plans, and dedicated to addressing these challenges, would greatly benefit technology development and risk reduction to allow for timely implementation. Potential opportunities exist now to mature and advance space nuclear technology, which would establish the U.S. as a world leader in such systems.

My third and final point is that U.S. regulations and policies for space nuclear systems should be tailored for SNPP. Today policies and regulations for space nuclear material are centered around the uses of plutonium and other materials inside of radioisotope thermoelectric generators, or RTGs, which have been commonly used for sub-kilowatt levels of power for deep space missions. RTGs are always radioactive, and so the policies introduce strict compliance guidelines to ensure the safety and security of personnel and the environment. Fission based SNPP reactors, in contrast, are—emit negligible levels of radioactivity until commanded to active in space, thus significantly reducing safety concerns.

50 years of technological advancements in nuclear materials and science have further reduced the risk to public safety, and are essential to the reactors being envisioned today. Therefore, regulations written for RTGs may be unnecessarily restrictive for SNPP development, ground test, launch, and in-space operations. Consideration of fission-based systems into policy and regulatory language is where the government could have a profound near-term positive influence to inform technology maturation, and could help more rapidly establish U.S. capability and leadership in this area.

In closing, space nuclear propulsion and power has 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. Both government and industry are beginning to re-examine potential capabilities of SNPP as feasible options for unique science, exploration, and national security missions. These heightened interests are supported by a robust nuclear industry base, heritage programs, technology advancements, and interests of Committees like this that may be highly influential toward developing near-term national capabilities. My sincerest thanks to this Committee for holding this hearing, and for your generous attention. I look forward to your questions.

[The prepared statement of Mr. Meholic follows:]

Statement of

Mr. Gregory Meholic

Senior Project Leader – Civil Systems Technology

The Aerospace Corporation

Before the

Committee on Science, Space, and Technology
Subcommittee on Space and Aeronautics

U.S. House of Representatives

"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.

[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
Mr. Greg Meholic
Senior Project Leader, Civil Systems Technology
The Aerospace Corporation

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.

Chairman BEYER. Thank you, Mr. Meholic, very much. We'll now hear from Mr. French. Mr. French, the floor is yours.

TESTIMONY OF MR. MICHAEL FRENCH, VICE PRESIDENT, SPACE SYSTEMS, AEROSPACE INDUSTRIES ASSOCIATION

Mr. FRENCH. Thank you, Chairman Beyer. Chairman Beyer, Chairwoman Johnson, Ranking Member Babin, and Members of the Subcommittee, thank you for the opportunity to testify today. The Aerospace Industries Association represents the largest and most diverse coalition of aerospace companies in the United States. We represent over 300 companies across the aerospace supply chain, from family owned small businesses to large system integrators, and from publicly traded, to privately held, to venture-funded startup companies. This morning I'll focus on three policy areas important to accelerating space nuclear propulsion, as Chairwoman Johnson said in her opening remarks, how we move from study to action. I'll focus in particular on those areas where the Subcommittee is, and continue to be, a key enabler.

I'll begin with recent changes in executive branch policy. Nuclear systems have been a part of America's space program since the beginning of the space age. The process for improving the launch—systems was recently updated to reflect this legacy. Under this change, the launch of a nuclear thermal propulsion flight demonstration would likely be considered a mission under the approval authority of a NASA administrator. This would not change the host of safety and regulatory requirements for the launch, but would focus and expedite the overall process.

Another recent executive branch policy development was the issuance of Space Policy Directive 6, or SPD–6. SPD–6 directs the whole of government approach to advanced nuclear space systems development, and provides a road map with specific agency roles and responsibilities. Maintaining interagency coordination, and defined agency milestones, are important to policies for accelerating nuclear propulsion development. This takes us to the first enabling action. Affirmity—affirming these executive branch policy updates is a key action the Subcommittee can take as it considers future authorizing activities.

Let me turn next to funding. Stable, sufficient funding is critical to accelerating the development of nuclear propulsion technology. Here Congress deserves praise. Congress has consistently funded the NASA budget on a bipartisan, bicameral basis, with eight consistent years of—consecutive years of appropriation increases. That number is nine consecutive years if you count the pending Fiscal Year 2022 House and Senate appropriation marks. Importantly, this support has been balanced across the NASA portfolio, supporting aeronautics, education, exploration, science, and space technology. Within these consistent, balanced appropriations, Congress has funded nuclear thermal propulsion on a multi-year basis. Congress's funding aligns directly with the timelines established in NASA's technology roadmaps.

Congress has also recognized the importance of a flight demonstration to move this capability forward, and has consistently included direction for a nuclear thermal propulsion flight test along with its funding. The President's Budget Request (PBR) has not

aligned as directly with the technology roadmaps. Finalizing the Fiscal Year 2022 marks and test direction, and continued support in Fiscal Year 2023 and on, is a second key policy action Congress can take to accelerate the development of this technology.

Finally, and of particular relevance to the Subcommittee, is the NASA reauthorization. In the previous Congress this Subcommittee passed language directing the NASA administrator to "develop a plan, including a cost estimate, to achieve an in-space flight test of a nuclear thermal propulsion system within 10 years of the enactment of this act." The Senate-passed NASA authorization included similar direction, with an accelerated flight demonstration timeline. Passing a NASA reauthorization is the third key policy action Congress can take to accelerate the development of this technology. It would also provide important direction across the NASA portfolio. The Subcommittee should again consider authorizing nuclear thermal propulsion activities, establishing a flight demonstration date, and endorsing accelerated partnership and coordination between NASA, the Department of Energy, the National Security Agencies, and industry on nuclear thermal propulsion development.

In sum, Congress and the Subcommittee have been key enablers to accelerating the development of this technology, and can continue to do so by finalizing Fiscal Year 2022 funding and direction, providing direction in the NASA reauthorization, and continuing its support in Fiscal Year 2023 and beyond. Thank you for the opportunity to testify today, and I look forward to answering any questions.

[The prepared statement of Mr. French follows:]

Testimony of Michael French
Vice President, Space Systems
Aerospace Industries Association
before the
Subcommittee on Space and Aeronautics
Committee on Science, Space, and Technology
U.S. House of Representatives

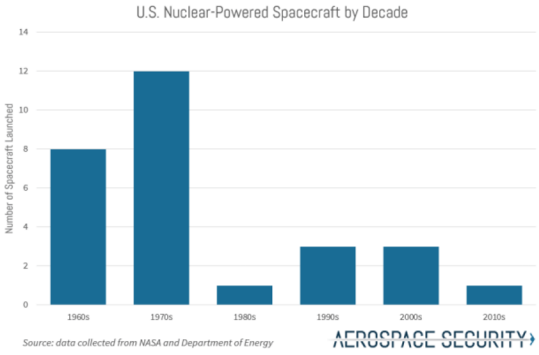
Chairman Beyer, Ranking Member Babin, and distinguished members of the Subcommittee, thank you for the opportunity to provide testimony today on the policy and budgetary enablers to accelerate deep space travel with space nuclear propulsion.

The Aerospace Industries Association (AIA) is proud to represent the largest and most diverse coalition of aerospace companies in the United States, an industry that generates $909 billion in economic output and supports 2.1 million employees across the country. With over 300 member companies from across the aerospace and defense supply chain, AIA members range from family-owned small business component manufacturers to large system integrators, and include publicly traded, privately held, and venture funded entities. AIA member companies design, manufacture, operate, and launch space vehicles across the commercial, civil, and national security space sectors with missions from low Earth orbit to cislunar space and beyond.

Congress has been a consistent supporter of nuclear propulsion activities, particularly nuclear thermal propulsion, through both NASA funding and direction. As outlined further below, Congress's continued investment coupled with authorizing legislation will serve as key accelerants to developing this capability for Mars and other deep space exploration.

Government Policies to Match Technology Maturity

The use of nuclear technologies in space is not new and has been a critical enabler of our nation's space-based accomplishments since the beginning of the Space Age.



Graphic Source: Center for Strategic and International Studies [i]

Early communications and weather satellites used nuclear technology as power sources, as did the Apollo Lunar Surface Experiment Packages, instruments left on the moon by the Apollo astronauts to collect and transmit scientific data back to Earth.[ii] The use of nuclear technologies to provide power to space science missions has continued, including on NASA's Mars rovers Curiosity and Perseverance, and on recent NASA missions to Jupiter, Saturn, and Pluto.[iii]

Nuclear propulsion systems, particularly nuclear thermal propulsion (NTP), would provide a new set of capabilities for deep space exploration. Nuclear thermal propulsion is three times more efficient than today's chemical systems, enabling more efficient human missions to Mars or scientific exploration in deep space. This technology does not replace chemical rockets but enhances our exploration capabilities by providing a more efficient means of propulsion for elements chemical rockets initially put into space.

While the concept of nuclear propulsion was explored in the past, technological advancements now make it practical. First, and importantly, today's nuclear propulsion systems use low-enriched uranium (LEU). This allows for safer systems not possible in the past. Second, modern analytics allow for detailed digital analysis and design with less extensive ground testing than historically required. Given these technological changes, the United States is not alone in pursuing this technology for exploration. China and Russia have also announced nuclear in-space propulsion plans.

U.S. government policies need to leverage this successful legacy of activity, the significant technology developments behind next generation nuclear propulsion systems, and the advancements in computer modeling and simulation techniques. Fortunately, policy improvements have already taken place within the Executive Branch that considers these factors, beginning with a recent update to the policy for launching nuclear payloads, National Security Presidential Memorandum-20, Launch of Spacecraft Containing Space Nuclear Systems.

Nuclear Launch Policies

In 2019, the Administration issued National Security Presidential Memorandum-20, Launch of Spacecraft Containing Space Nuclear Systems.[iv] This update created a tiered, risk-based approach for approving the launch of nuclear systems, replacing a singular approach developed in the 1970s. Under the prior framework, all launches of nuclear systems required the assessment of an interagency working group and approval from the President. The President's approval was delegated to the Director of the White House Office of Science and Technology Policy or made by the President directly at the Director's recommendation.[v]

Under the new system, the characteristics of the nuclear system, the level of potential hazard, and national security considerations determine the required approval process. The prior system remains for the highest risk launches, designated as "Tier III" in the new policy. Lower risk launches, Tier I and II, allow delegation of approval at the head of the sponsoring agency level, following interagency review and other safety assessments detailed in the policy. For example, the NASA Administrator would likely be the approval authority for a NASA science mission using heritage nuclear power systems as a Tier I launch under the policy. A nuclear propulsion flight demonstration would likely be considered a Tier II mission under the policy given technology heritage and the expected use of low enriched uranium. This policy change is an important enabler to a near term flight demonstration of nuclear thermal propulsion systems needed to achieve a human rated system in the 2030s.

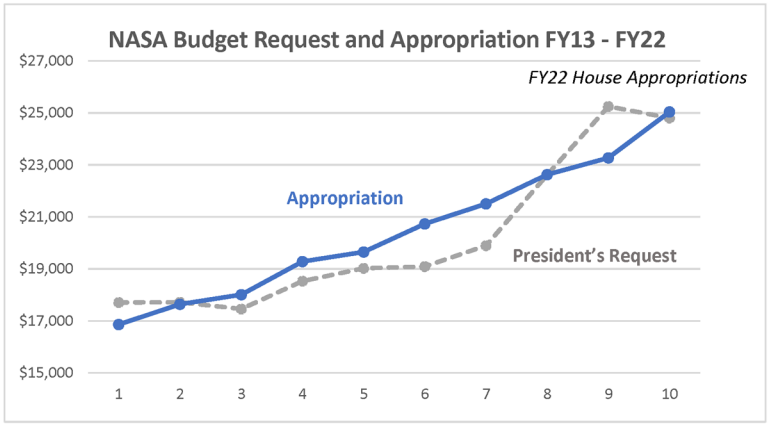
Space Policy Directive 6

A second recent policy development of note is Space Policy Directive 6, National Strategy for Space Nuclear Propulsion and Power ("SPD-6"), signed in December 2020.[vi] SPD-6, "outlines high-level policy goals and a supporting roadmap that will advance the ability of the United States to use [space nuclear power and propulsion] systems safely, securely, and sustainably."[vii] SPD-6 acknowledges and creates a whole of government approach to leverage and advance nuclear space systems. An example of the coordination outlined by SPD-6 is taking place between the Defense Advanced Research Projects Agency (DARPA) and NASA's Marshall Space Flight Center, with support from NASA Headquarters and other national security agencies, to establish joint working groups to achieve common goals in their respective nuclear thermal propulsion activities.

SPD-6 also provides a roadmap for the further development of nuclear space systems with specific agency roles and responsibilities. Particular to advancing nuclear thermal propulsion, SPD-6 directs, "[b]y the late-2020s, establish the technical foundations and capabilities — including through identification and resolution of the key technical challenges — that will enable NTP options to meet future DoD and NASA mission needs." Maintaining interagency coordination and defined milestones is an enabling policy for accelerating nuclear propulsion capabilities and should be maintained.

Consistent Congressional Support

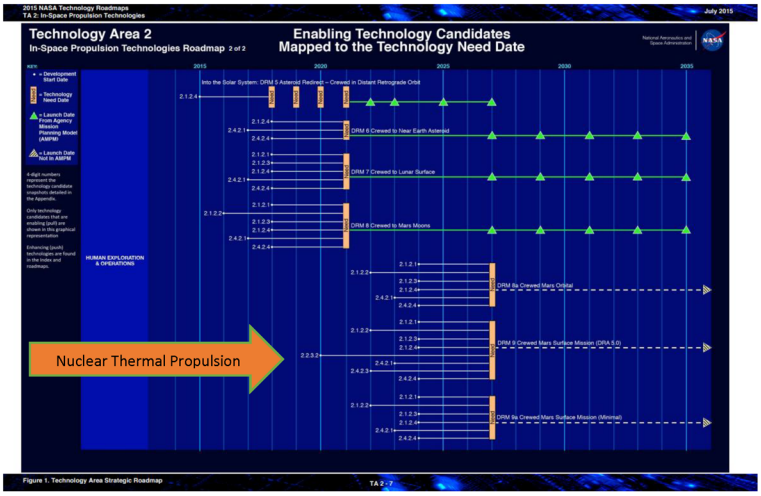
Stable, sufficient investment is critical to accelerating the development of nuclear thermal propulsion technology for a Mars mission in the 2030s. Here, Congress deserves recognition. Congress has shown consistent support for the overall NASA budget on a bipartisan, bicameral basis – with eight consecutive years of appropriation increases (nine considering the pending FY22 House Appropriations mark).



Importantly, this support has been balanced across the NASA portfolio, not only recognizing NASA's contributions to human exploration, but supporting NASA's aeronautics, education, science, and space

technology missions. Within this consistent, balanced series of appropriations, Congress has funded nuclear thermal propulsion activities on a multi-year basis at significant levels. Congress has also recognized the importance of a flight demonstration to move this capability forward, regularly including flight demonstration direction with the funding it provides.

Congress' funding aligns directly with timelines established in NASA's technology roadmaps for the development of needed capabilities for future human transportation to Mars. For example, NASA's 2015 Technology Roadmaps determined the need to develop nuclear thermal propulsion technology in the first half of the 2020s for a technology need date of 2027.[viii] Nuclear thermal propulsion remains an enabling technology in NASA's updated 2020 technology taxonomy.[ix]



Source: July 2015 NASA Technology Roadmaps TA 2: In-Space Propulsion Technologies[x]

Congress has similarly indicated its support for nuclear thermal propulsion, including a flight demonstration, through recent NASA reauthorization efforts. This Subcommittee in the previous Congress passed language directing the NASA Administrator to, "develop a plan, including a cost estimate, to achieve an in-space flight test of a nuclear thermal propulsion system within 10 years of the enactment of this Act." The Senate-passed NASA authorization included in the U.S. Innovation and Competition Act directs the NASA Administrator to develop a similar nuclear thermal propulsion plan and conduct a flight demonstration, "[n]ot later than December 31, 2026."

While Congress has consistently provided funding and direction for nuclear thermal propulsion, the President's Budget Request has not aligned as directly with NASA's technology roadmaps.

NASA Nuclear Thermal Propulsion Funding		
	President's Budget Request	**Congressional Appropriation and Report**
FY2017	Study funding requested; no specific funding line	$35M
FY2018	Study funding requested; no specific funding line	$75M
FY2019	Some activity funded within Space Technology; no specific funding line	$100M/$70M for design of a flight demonstration by 2024
FY2020	Some activity funded within Space Technology; no specific funding line	$110M/$80M flight demonstration
FY2021	$100M for both surface power and nuclear propulsion	$110M/$80M flight demonstration
FY2022	$0[xi]	$110M/$80M flight demo (House Appropriation)

A Portfolio Approach

As is recognized in SPD-6, accelerated nuclear space activity requires the coordination and contribution of multiple Federal agencies partnered with industry. The Department of Energy and NASA are key players, but overall technology development also includes the Department of Defense. DARPA's Demonstration Rocket for Agile Cislunar Operations (DRACO) program is an important example. This program is partnering with industry to advance nuclear thermal propulsion technology, particularly focused on advancing methods for modeling and simulation. DRACO is not a substitute for NASA's activities, but complementary. As noted by the National Research Council, "NASA could benefit from lessons learned by the DRACO flight demonstration (currently planned for late 2025) and could work collaboratively with DARPA to develop technologies and subsystems that contribute to the mission needs of both agencies."[xii]

SPD-6 and the President's FY22 Budget Request also seek to accelerate nuclear surface power technologies. These technologies are important to future Moon and Mars exploration, particularly long-duration activities, however, these activities are separate from the nuclear propulsion development activities and not "trades" from an exploration needs perspective.

Needed Congressional Actions

As outlined above, the Congress has been a consistent supporter of the investments and direction needed to accelerate space nuclear propulsion. Additionally, the Executive Branch has made important recent updates to U.S. Government policy to align with the accelerated use of nuclear space systems. AIA is pressing the current Adminstration to reaffirm these policy updates.

Congress can further accelerate the development of space nuclear propulsion by:

- Finalizing FY22 funding for nuclear thermal propulsion with flight demonstration direction;
- Adopting the NASA infrastructure investments included in pending infrastructure legislation;
- Continuing to consistently fund nuclear thermal propulsion development and a flight demonstration in FY23 and beyond; and
- Passing a NASA reauthorization that includes language authorizing nuclear thermal propulsion activities, establishes a 2026 nuclear thermal propulsion flight demonstration date, and

endorses accelerated partnership and coordination between NASA and the national security agencies on nuclear thermal propulsion flight demonstrations, common fuels, and operational systems production.

Thank you for the opportunity to present this testimony today, and we look forward to continuing to work with the Subcommittee to ensure the growth and health of the U.S. space industry.

[ii] "What Does the Trump Administration's New Memorandum Mean for Nuclear-Powered Space Missions?," Aerospace Security, Center for Strategic and International Studies, available at https://aerospace.csis.org/what-does-the-trump-administrations-new-memorandum-mean-for-nuclear-powered-space-missions/ (visited 10/15/21)

[ii] The History of Nuclear Power in Space, U.S. Department of Energy, available at https://www.energy.gov/articles/history-nuclear-power-space (visited 10/15/21)

[iii] Mars 2020 Launch Nuclear Safety, NASA, available at https://rps.nasa.gov/resources/81/mars-2020-launch-nuclear-safety/ (visited 10/15/21)

[iv] National Security Presidential Memorandum-20, Launch of Spacecraft Containing Space Nuclear Systems, 2019, available at https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-launch-spacecraft-containing-space-nuclear-systems/ (visited 10/15/21)

[v] 1977 nuclear launch memorandum available at https://fas.org/irp/offdocs/pd/pd25.pdf (visited 10/15/21)

[vi] Space Policy Directive 6 available at https://www.federalregister.gov/documents/2020/12/23/2020-28457/posting-of-the-presidential-policy-directive-6-space-policy-national-strategy-for-space-nuclear (visited 10/15/21)

[vii] Id.

[viii] July 2015 NASA Technology Roadmaps, TA 2: In-Space Propulsion Technologies, NASA, available at https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf (visited 10/15/21)

[ix] NASA Technology Taxonomy, 2020, available at https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf (visited 10/18/21)

[x] July 2015 NASA Technology Roadmaps TA 2: In-Space Propulsion Technologies, available at https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf (visited 10/15/21)

[xi] NASA FY22 President's Budget Request Congressional Justification, ST-68, available at fy2022_congressional_justification_nasa_budget_request.pdf (visited 10/17/21)

[xii] National Academies of Sciences, Engineering, and Medicine 2021. Space Nuclear Propulsion for Human Mars Exploration. Washington, DC: The National Academies Press. https://doi.org/10.17226/25977 (visited 10/15/21)



Mike French
Vice President, Space Systems
Aerospace Industries Association

Mike French is Vice President for Space Systems at the Aerospace Industries Association. As the lead of the Space Systems policy division, Mike works with AIA's membership to advocate for policies, regulations, and investments that ensure American leadership and strong industry partnership across the civil, commercial, and national security sectors.

Mike's experience in the space industry ranges from advising senior government leaders on space policy, to developing market forecasts and assessments for industry executives, to analyzing major space investments for companies and banks. He previously served as the Senior Vice President for Commercial Space at Bryce Space and Technology, a market analysis and management consulting firm. At Bryce, he advised major aerospace industry clients on management, policy, and investment decisions.

Mike has also held several federal government positions, most recently serving as NASA's Chief of Staff, advising the NASA Administrator, White House, and other government leadership on national space policy issues. He received NASA's Distinguished Service Medal for his service. Prior to serving in government, he practiced law in the defense and aerospace sector in Los Angeles where he advised clients on matters regarding aircraft and aerospace weapons systems.

Mike holds a Bachelor of Science in business administration from the Haas School of Business at the University of California, Berkeley and a J.D. from Harvard Law School.

Chairman BEYER. Mr. French, thank you very much. And now, finally, we'll hear from Dr. Franklin Chang-Diaz. Dr. Chang-Diaz, the floor is yours.

TESTIMONY OF DR. FRANKLIN CHANG-DIAZ,
FOUNDER AND CEO, AD ASTRA ROCKET COMPANY

Dr. CHANG-DIAZ. Thank you, Mr. Chairman, and Chairwoman Johnson, Ranking Member Babin, and distinguished Members of the Subcommittee. I am very honored to be called to testify before you on this important topic for our Nation, and for our civilization. Space travel beckons humanity even more today than it—I think it did in the 1960's, and—not to abandon our planet, but to care for it, to preserve it, to protect it, by providing an opportunity for all humans to thrive and prosper in a universe of possibilities. To do that, we must secure a safe, and robust, and a fast means of transportation, and nuclear power offers us that opportunity, but there is homework to be done.

In rocket propulsion, the faster the rocket exhaust is, the better the rocket. To make the exhaust fast, we have to make it hot. The best chemical rocket runs at thousands of degrees, and has an exhaust velocity of about 4,500 meters per second. Nuclear rockets come in two flavors, nuclear thermal and nuclear electric. The goal is the same for both, to heat the propellant to high temperature and expel it. In nuclear thermal, the reactor is a contact heater to heat hydrogen and expel it. In nuclear thermal rockets, you could increase the exhaust velocity to about 9,000 meters per second, but higher temperatures are constrained by materials limitations.

In a nuclear electric rocket, temperatures of millions of degrees are accessible because at those temperatures the exhaust is an electrically conducting plasma, a soup of charged particles which responds well to electric and magnetic fields. In the VASIMR engine, for example, we take advantage of that feature by using a magnetic field to hold and guide the plasma, keeping it away from any material surface as we heat it. The heating is done with electromagnetic waves, so nothing physical touches the plasma. In these devices, exhaust velocities of 30,000 to 50,000 meters per second are measured, an order of magnitude greater than chemical rockets, and higher velocities are technologically feasible.

The nuclear reactor here is not a heater, but is an electrical power plant, and the big challenge is to develop powerful, compact, and efficient nuclear electric power source, and an electric rocket capable of handling all that power. This is the homework. We must do it if we want to lead. The potential payoff is extraordinary. For example, with a power and propulsion package weighing about three to four kilograms per kilowatt, and operating about 20 to 30 megawatts, human Mars transits of less than 3 months would be possible. Nuclear electric also extends the departure and return windows from Mars from days to weeks, and provides a variety of in-flight abort options if they were needed.

So in space, power is life, and with nuclear electric, the reactor also provides an abundant supply of electrical power for the ship. The Nation has made investments in nuclear thermal. We need to invigorate the nuclear electric option as well. It is the right time. Our own VASIMR engine recently achieved a major milestone with

an 88-hour high power continuous endurance test last July, a project supported by private investors and NASA. Other high-powered technologies are also poised for development. It is also the right time, as nuclear electric draws on advances in fusion energy innovation, now also with private sector investment, and advances in power electronics for electric vehicles. To lead in space propulsion, we must invest in disruptive innovation.

Mr. Chairman, Members of the Subcommittee, as our Nation moves to explore deep space with humans, we must be able to travel fast, to reduce the debilitating effects of space on the human body, the reduce the burden of consumables, life support, to be less constrained by the planetary alignments and tight launch windows, and to expand our capability to recover from unforeseen contingencies en route. In short, this is the problem punch list we need to solve to give our astronauts a fighting chance in deep space. The development of high powered nuclear electric propulsion is critical to checking those boxes, and to meeting our Nation's goal in space. Thank you, and I'm happy to take your questions.

[The prepared statement of Dr. Chang-Diaz follows:]

Statement by Dr. Franklin Chang Díaz
CEO, Ad Astra Rocket Company
For the Committee on Science Space and Technology, Subcommittee on Space and Aeronautics
U.S. House of Representatives

October 20, 2021

Accelerating Deep Space Travel with Space Nuclear Propulsion

Mr. Chairman and distinguished members of the subcommittee, I am honored to be called to testify before you on this important topic for our nation and for our civilization.

Space travel beckons humanity even more today than it did in the 60s, not to abandon our planet but to care for it, preserve, and protect it by providing an opportunity for all humans to thrive and prosper in a universe of possibilities. But to do that, we must secure a safe, robust, and fast means of transportation. Nuclear power provides us with that opportunity – but there is homework to be done.

In rocket propulsion, the faster the exhaust the better the rocket. To make the exhaust fast, we must make it hot. The best chemical rocket runs at thousands of degrees and has an exhaust velocity of ~4500 m/sec.

Nuclear rockets come in two flavors: nuclear thermal and nuclear electric. The goal is the same for both, however, to heat the propellant to high temperature and expel it.

In nuclear thermal, the reactor is a contact heater to heat hydrogen and expel it. Nuclear thermal rockets could increase the exhaust velocity to ~9000 m/sec. Higher temperatures are constrained by materials limitations.

In the nuclear electric rocket, temperatures of millions of degrees as accessible, because at those temperatures the exhaust is an electrically conducting plasma, a soup of charged particles which responds to electric and magnetic fields.

In the VASIMR engine, for example, we take advantage of that feature by using a magnetic field to hold and guide the plasma, keeping it away from any material surface as we heat it. The heating is done with electromagnetic waves so nothing physical touches the plasma. In these devices, exhaust velocities in the 30000 to 50000 m/sec are measured (an order of magnitude) and higher velocities are technologically feasible.

The nuclear reactor here is not a heater but an electrical power plant and the big challenge is to develop a powerful, compact, and efficient nuclear electric power source and an electric rocket capable of handling a lot of power.

This is the homework we must do if we want to lead. The potential payoff is extraordinary. For example, with a power and propulsion package weighing 3-4 kg/kW and operating at 20-30 MW human Mars transits of less than 3 months could be possible. Nuclear electric also opens the departure and return windows for Mars from days to weeks and provides a variety of in-flight abort options (if needed) while enroute.

In space, power is life and with nuclear electric the reactor also provides an abundant supply of electrical power for the ship.

The nation has made investments in nuclear thermal. We need to invigorate the nuclear electric option as well.

It is the right time. Our own VASIMR® engine recently achieved a major milestone with an 88-h high-power continuous endurance test last July, a project supported by private investors and NASA. Other high-power technologies are also poised for development.

It is also the right time as nuclear electric draws on advances in fusion energy innovation (now also with private sector investment), and advances in power electronics for electric vehicles. To lead in space propulsion, we must invest in disruptive innovation.

Mr. Chairman and members of the subcommittee, as our nation moves to explore deep space with humans we must be able to travel fast, to reduce the debilitating effects of space on the human body, to reduce the burden of consumables, life support, to be less constrained by planetary alignments and tight launch windows and to expand our capability to recover from unforeseen contingencies enroute. In short, this is the problem punch-list we still need to solve to give our astronauts a fighting chance in deep space. The development of high power nuclear electric propulsion is critical to checking these boxes and to meeting our nation's goals in space.

Thank you and I am happy to take your questions.

(end of opening statement)

Additional material submitted for the record

The VASIMR® engine works with plasma, an electrically charged gas that can be heated with electrical power to extreme temperatures (2-3 million degrees) by radio waves and controlled and guided by strong magnetic fields. The magnetic field also insulates the rocket casing from the hot plasma. In rocket propulsion, high exhaust temperature leads to high exhaust velocity and hence high fuel efficiency. Plasma rockets have exhaust velocities 10x greater than conventional rockets, so their propellant consumption is extremely low. The high efficiency allows a range of missions that are not possible with conventional chemical rockets.

Other important features of the VASIMR® engine include:

- Scalable from ~50 kW to multi-MW in a single engine
- Electrodeless design, implies long component life
- Multiple, low cost, abundant propellants, such as argon (~$5/kg) and krypton (~$300/kg), as compared with other electric thrusters, which operate with rare and expensive xenon (~$1000/kg).
- Variable thrust and specific impulse, can "shift gears" to better adapt to the gravity "hills and flats" of the mission.

Potential applications

The VASIMR® engine could provide primary propulsion for robotic SEP and eventually NEP spacecraft in many venues, with more capability and economy than chemical rockets. Examples:

1. A commercial multiuse solar-electric space tug for orbital debris mitigation, satellite support and cislunar cargo transport.
2. Drag compensation or reboost of orbital space stations in low Earth Orbit (LEO)
3. The VASIMR® engine could propel a re-usable high-power solar electric propulsion (SEP) deep-space catapult to deploy robotic missions to the Jupiter and Saturn systems faster than conventional rockets.
4. With advanced nuclear electric power, the VASIMR® engine provides nuclear electric propulsion (NEP), enabling fast (less than 90 days) human Mars transfers. These reduce radiation exposure and other space-induced debilitating effects on humans. It also relaxes the departure windows on NASA's Design Reference Architecture 5.0 (DRA-5.0).

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Dr. Franklin Chang Díaz @franklinchangd is Chairman and CEO of Ad Astra Rocket Company, a US Delaware Corporation domiciled in Webster, Texas developing advanced plasma rocket technology. Ad Astra also owns and operates a subsidiary in Guanacaste, Costa Rica that focuses on green hydrogen energy storage and fuel-cell electric transportation.

A former NASA astronaut, Dr. Chang Díaz is a veteran of 7 space missions and has logged over 1,600 hours in space, including 19 hours in three space walks.

Dr. Chang Díaz initiated the VASIMR® rocket engine project in 1980. Throughout his 25-year NASA career, in conjunction with astronaut duties and training, he and his team at the Advanced Space Propulsion Laboratory (ASPL) at the Johnson Space Center developed the controlling physics of the VASIMR®. In 2005 Dr. Chang Díaz retired from NASA and founded the Ad Astra Rocket Company to continue to mature the VASIMR® technology through the private sector.

In the corporate world, Dr. Chang Díaz also serves on the Board of Directors of Cummins Inc. (NYSE-CMI), a global power leader headquartered in Columbus, Indiana, and EARTH University, an international sustainable development educational institution in Costa Rica. He also leads the "Strategy for the XXI Century, a master plan, aimed to transform Costa Rica into a fully developed nation by the year 2050.

Dr. Chang Díaz received a PhD degree in applied plasma physics from MIT and a bachelor's degree in mechanical engineering from the University of Connecticut. He holds six US Patents including four key patents on the technology of the VASIMR® engine.

Dr Chang Díaz is a four-time recipient of NASA's Distinguished Service Medal, the agency's highest honor and was inducted in the US Astronaut Hall of Fame on May 4, 2012. He holds honorary doctorates from several universities in the United States and Latin America and has continued to serve in academia as an Adjunct Professor of Physics at Rice University and the University of Houston.

Chairman BEYER. Thank you, Dr. Chang-Diaz. That concludes our presentations from our five expert witnesses. We'll begin the round of questions. I get to go first, by virtue of the history right now.

So, Dr. Chang-Diaz, this VASIMR engine that you worked on—you say you have a Ph.D. in plasma physics——

Dr. CHANG-DIAZ. That's correct.

Chairman BEYER [continuing]. And it seems like you're using tokamak-type ideas, electromagnetic fields to hold the high plasma in, very parallel to what they're doing in the fusion research here on Earth.

Dr. CHANG-DIAZ. Right.

Chairman BEYER. When you talk about 30,000 to 50,000 meters per second, is—obviously much faster than the 9,000 meters per second that NED—NTP would give you, but is that still fast enough to get there in a reasonable amount of time?

Dr. CHANG-DIAZ. It is if you run the engine long enough. These electric rockets are low thrust, but continuous thrust, so you are accelerating all the time. And so what you end up doing is you go halfway to Mars, and then you start turning around and decelerating so that you don't, you know, overshoot the planet. But yes, in the end, you go faster than with a nuclear thermal, or even a chemical rocket.

Chairman BEYER. OK. Thank you. Mr. French, one of the most obvious questions is, if we can't get to Mars using the traditional chemical stuff, and we have to turn to some type of nuclear propulsion, why the zero request in the President's budget for this? And why so little—if we look at your chart about FY '17, '18, '19, '20, no specific funding at all, 100 million in 2021, and then zero in 2022. What's been missing from NASA's request to the President's request?

Dr. LAL. I could jump in with that, Mike, if you'd like? So——

Chairman BEYER. Or both, please.

Dr. LAL. Yes.

Mr. FRENCH. Thank you, Mr. Chairman. And so I'll—you know, I'll—I can't speak to what—you know, what happened within NASA in Fiscal Year 2022. I will say, from my experience both at the White House and NASA in prior administrations, what I often encountered is that NASA would have important technology needs, and develop technology roadmaps, and sometimes the budget for those requests didn't quite make it through the full budget process at the end of the day. And so—sometimes you could find something where a technology need may not necessarily, at the end of the day, be reflected in the final PBR. That's in general. You know, I'd really have to turn to NASA to explain what occurred, you know, in Fiscal Year 2022. But I'll certainly say, can't understate the—what the Congress has done so consistently here, with its support in recognizing the need of this technology.

Chairman BEYER. Hooray for Congress, but Dr. Lal, where is NASA on this?

Dr. LAL. So—thanks, Mike. So nuclear propulsion, as we just discussed, is critical to America's future in space, there's no doubt, however, with the limited resources available to NASA for tech development efforts, our priority has been to focus on surface power,

fission surface power, first, which is not only a near-term requirement for long duration surface mission on the Moon, but has extensibility to nuclear electric propulsion. That's an important thing to point out.

The Fiscal Year 2022 budget does include many technologies that apply to propulsion systems. One of the most important ones is cryogenic fluid management systems, which are critical for propulsion, for long term storage of hydrogen and other volatiles in space, and—not just for in space, but also on the surface of Moon, Mars, and other bodies, we are also continuing work, in terms of the budget, on space-related power conversion systems, LEU, low enriched uranium, moderator materials, and lighter weight radiation shielding, all of which apply to propulsion. NASA, of course, looks forward to working with Congress and the administration to develop a balanced, schedule driven investment strategy for our nuclear portfolio.

Chairman BEYER. Thank you, Dr. Lal. Mr. Meholic, you really talked very much about tailoring regulations to the SNPP, and you compared it to the RTGs, the plutonium radioactive—is this parallel to the efforts on Earth to distinguish fusion energy from fission energy? You know, having—given the fundamental difference that these are very different power systems, with very different dangers and advantages?

Mr. MEHOLIC. Yes, absolutely. You know, the RTGs, as I mentioned, are always on, as far as—you know, even from their manufacture, they have to be carefully handled in proper facilities and so forth. And even during launch, you know, the RTG device is actually one of the last things to be loaded onto the launch vehicle before, you know, all personnel leave the pad. With a nuclear fission system, though, that is not the case, right? These are basically just giant hunks of metal with some uranium in it, for all practical purposes, and, you know, it is not critical in any way, shape, form, or manner. It can be handled safely, and so forth.

What I meant by the policies, to kind of touch on that a little bit more, is there is, you know, the Presidential Memorandum Number 20, that talks about launch approval for these types of reactors, but there's also other policies associated with DOE and DOD on perhaps the testing of these types of things. A number of the folks here in the testimony mentioned about ground test, the need for ground test, the value of ground test, but, you know, there are really no current regulations that would allow that in such a way that would not be prohibitive, or take years to try to overcome from environmental studies and things like that.

So the point I was trying to make on that was to be able to streamline that process and look at—really look at the safety aspects of these new types of reactors, as opposed to 50 years ago, and determine if the policies and regulations in place that would cover ground test and operation may have to be tailored in some way. And granted, you know, RTGs and that type of testing is a different realm as if we were to try to test a nuclear thermal propulsion system in the open aid like they did for NOVA—NERVA. So, you know, NASA right now has a dedicated task to look at, ground test options, facilities, and so forth for one of their space nuclear propulsion projects, nuclear thermal propulsion centric

right now, and, you know, those types of policies need to be looked at a little bit deeper.

Chairman BEYER. Thank you very——

Mr. MEHOLIC. Thank you very much for the question, sir.

Chairman BEYER. Yes, yes. Thank you, Mr. Meholic. And let me now recognize the Ranking Member of our Space Subcommittee, Dr. Babin of Texas.

Mr. BABIN. Thank you, Mr. Chairman. I appreciate it. Dr. Lal, in May China became the only non-U.S. country to successfully deploy a rover on the surface of Mars, and shortly afterwards China announced that it intends to conduct crewed missions to Mars in 2033. The head of the China Academy of Launch Vehicle Technology indicated at the time that to shorten the travel time, spacecraft would have to tap energy released from nuclear reactions in the form of heat and electricity in addition to traditional chemical propellants. What insight do we have—and please keep this as short and abbreviated as you possibly can. What insight do we have into China's current capabilities regarding space nuclear propulsion? How much are they spending, are their schedules realistic? Are they focusing on NEP or NTP? And if they're focused on both, what technology is farther along, and could they develop and deploy space nuclear propulsion before we do?

Dr. LAL. Thank you, Ranking Member Babin. Our strategic competitors, including China, are indeed aggressively investing in a wide range of space technologies, including nuclear power and propulsion, to fulfill their ambitions for a sustained human lunar presence, as well as Martian and deep space science missions. So there is no question that there is investment at the level that we do not understand. Data is hard to come by, and I can take some of your specific questions for the record and come back to you. On space nuclear, we have seen long term planning on part of China for human missions using nuclear systems in the late 2030's, similar to our plans. The United States needs to move at a fast pace to stay competitive and to remain a leader in the global space community.

Chairman BEYER. Brian, you're——

Mr. PERLMUTTER. Brian, you muted yourself.

Chairman BEYER. Yes.

Mr. BABIN. There we go. Thank you. I'm sorry. Extensibility—this is for Dr. Lal as well. Extensibility is the concept that technologies developed in the near term will be useful for the future exploration as well. Extensibility prevents the development of dead-end capabilities. Nuclear surface power will be required for crewed operations and missions on the Moon. Surface power generation would presumably be extensible to nuclear electric propulsion development for a mission to Mars as well. NTP is already being developed by the Department of Defense to meet their needs, and Congress has appropriated hundreds of millions of dollars for NTP over several years. Referring to a mission to Mars, the Academy report stated, "If NASA plans to apply nuclear electric propulsion, or NEP, technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development." How is NASA supporting the development of NEP? Which is critical, in my opinion.

Dr. LAL. So we are—as per congressional direction, we are focusing our effort on NTP. However, as you noted, NEP is a critical—we must achieve. Our investment in surface power is—does have extensibility to NEP, although I should point out that, depending on the wattage of the surface power, that NEP may be more applicable for deep space science missions, which are extremely important for us, and over time they can go up to the power level that would be required for an NEP human mission. So, you know, we are looking at about, you know, 10 kilowatts to 40 kilowatt-like systems for surface power for the moment. We need to be looking at higher levels. For a human mission to Mars, we should be looking at—that NEP system is more like two megawatts, so there's a lot of extensibility that needs to happen from surface power to NEP.

Mr. BABIN. Got you. OK. Well, thank you so much. And real quickly, Dr. Myers, there have been exceptional advancements in high power electrical propulsion, or EP, accelerated by recent investment from the private sector, such as in the NASA next step public/private partnerships that led to the recent 88 hour endurance test of a VASIMR test engine by a constituent of mine. Additionally—who we are hearing from today. Additionally, electric propulsion innovation benefits from fusion energy development now also accelerating with private investment, and the great advancements in power electronics for transportation and industry electrification, yet high power electric propulsion development has suffered from low and intermittent investment over many decades.

The National Academy of Sciences panel recommended that the U.S. must accelerate a robust and sustained program to develop high power electric propulsion thrusters needed to maintain and advance our leadership in space propulsion. How should NASA prioritize investments in both incremental innovations, such as the Hall-Effect Thruster, and disruptive innovations, such as the VASIMR engine?

Dr. MYERS. I think at this point—thank you for the question, and——

Mr. BABIN. Yes, sir.

Dr. MYERS [continuing]. At this point our committee recommended a balanced approach, focused on leveraging the capabilities of well-established technologies, while at the same time maintaining a portion of the investment in the breakthrough technologies. Having a balanced portfolio of technology investments is the best way to mitigate program risk, and, at the same time, you really want to leverage—we found that you really want to leverage the capabilities—the established capabilities, and, frankly, the engineering know-how, and the deep understanding, on the Hall thrusters and the MPD thrusters.

For example, the lithium MPD thruster has actually fired for 500 hours at 500 kilowatts. So that's—you know, we commend the progress. We were excited to read about the progress that VASIMR had made—had demonstrated, that Franklin and his team have demonstrated. Excellent progress, and we certainly should continue. At this point, we do not have enough data to make a good decision between the different technologies for this very high power—nobody has invested much money in the very high-power

systems, and we need a more sustained investment in those very high-power systems.

Chairman BEYER. Thank you, Dr. Myers, and thank you, Dr. Babin.

Mr. BABIN. OK. Thank you very much. I wanted—I had another question, but I see that we're out of time, Mr. Chairman. Thank you.

Chairman BEYER. Great. Thank you——

Mr. MEHOLIC. Dr. Babin? Dr. Babin? May I interject for a second, sir?

Mr. BABIN. Sure.

Mr. MEHOLIC. Building off of Dr. Myers's comments, and thank you for allowing this, you know, I agree with his points 100 percent. I read the National Academies report, and they identified also, as is well known the number of critical subsystems associated with nuclear electric power, right? A—the electric power thruster, as was pointed out, is a technology that's decades old, all right?

There's advancements that may need to accommodate these—you know, to accommodate these types of Mars missions, but these other subsystems, like the power generation system, the actual reactor, the cooling, and the heat rejection, and all the other subsystems are absolutely critical in order to provide the power to those electric thrusters. And those actually just come into—as—what I described in my testimony as just the space nuclear power part. Those also need dedicated development programs that have yet to be realized in any great form, especially for the power and the durations expected for these high—these highly——

Chairman BEYER. OK, let's——

Mr. MEHOLIC. Thank you.

Chairman BEYER. Let's move on, because we have lots of people in the queue.

Mr. BABIN. All right. I really wanted to hear what Dr. Chang-Diaz had to say about it, but——

Chairman BEYER. Well, he—and, Brian, hang in, we can do a second round too.

Mr. BABIN. OK. All right, thanks.

Chairman BEYER. But now let me recognize the Chair of the Full Committee, Congresswoman Johnson.

Chairwoman JOHNSON. Well, thank you very much. Dr. Myers, in the National Academies report your panel found that NASA needs to accelerate its development programs in nuclear propulsion, whether nuclear thermal or nuclear electric, in order to meet the requirements for a Mars mission in the 2030's. Is achieving this capability primarily a question of adequate resources, or are there other factors?

Dr. MYERS. I would say that the—thank you for the question, and I would say that the primary factor is adequate resources. As was noted, there has been some significant investment over the past 8 years in nuclear thermal propulsion, but there has not been a commensurate investment in nuclear electric propulsion, and so we found that we do not have the information that—the data which are needed in order to make informed decisions about all of those subsystems that Mr. Meholic just mentioned, for example.

There are, however, some very fundamental questions about both nuclear thermal and nuclear electric. The risk associated with achieving the temperatures and lifetimes in the reactor fuels for nuclear thermal is a fundamental materials challenge that we think is quite likely solvable, which is why we came to the conclusion that it was possible to meet the timeframe for the baseline mission, but we're not 100 percent sure. There's real technical risk there, and some fundamental materials work that needs to happen on the reactor fuels for nuclear thermal.

Nuclear electric is more of a scaling question. They—it does not have exactly the same kind—it has very different challenges, in fact, and so it's—I would say it's primarily a resource question, but there are some fundamental materials—some fundamental science questions that need to be addressed immediately, as we say in the report, in order to really get to the point where we can be sure.

Chairwoman JOHNSON. Well, thank you. Now, the National Academies report, that you co-chaired, of course, noted challenges in the STEM education and work force pipeline——

Dr. MYERS. Um-hum.

Chairwoman JOHNSON [continuing]. For advancing space nuclear propulsion. The report identified three key challenges, a lack of gender and ethnic diversity, competition for talent, and export control and classification regulations. How do these challenges affect the space nuclear propulsion sector, and what needs to happen to address these challenges?

Dr. MYERS. Thank you for—that's an excellent question, and it's one of very—it's very relevant in today's society. I would say that the resources need to be put on these technologies in order to attract the students and set up the pipeline that is needed for—to get the students and—the students excited and interested, and we need the programs at the universities, and then we need the programs even further down to get people excited about all the different aspects of space exploration and space nuclear propulsion. We've got to fill that pipeline with smart kids who are excited, and a diverse population of kids, and we can't do that without resources. So we really need a balanced portfolio of work to support a broad engagement of students across the Nation. I hope that answered your question. I—missed part of it.

Chairwoman JOHNSON. Yes, it's a challenge. Thank you, Mr. Chairman. I yield back.

Chairman BEYER. Thank you, Madam Chair, very much. Now recognize the Congressman from Cape Canaveral, Mr. Posey.

Mr. POSEY. Thank you, Chairman Beyer, for holding this hearing on space nuclear propulsion for enabling deep space exploration. Mr. French, in your written testimony you mentioned policy improvements have already taken place for launching nuclear payloads with the National Security Presidential Memorandum 20 in 2019. Why was the National Security Presidential Memorandum 20 so important?

Mr. FRENCH. Thank you, sir. What it did is it looked—the—it updated a policy that had essentially been unchanged since the late 1970's, and in that time we've certainly had quite a bit of experience launching nuclear space systems. What it does is—it's very important—it doesn't change the overall safety and regulatory re-

quirements that would have to take place to approve a launch, but what it does is it shifts the final approval for certain launches, including likely what would be a nuclear thermal propulsion launch, from being led by a Presidential approval to one by the NASA Administrator. Now, again, it doesn't change the safety and overall regulatory requirements, but what that would do is if—in a NASA mission, it would allow more focus in driving the process, and ensuring that all the gates were met in a timely fashion. And so that's the primary positive thing there.

Dr. LAL. Could I add to that response?

Mr. POSEY. Sure, sure.

Dr. LAL. I would just like to add to that that everything Mike said was absolutely accurate, but I think one big innovation in the Presidential Memorandum was that the analyses are based on the characteristics of the system, the levels of the potential hazard, and national security considerations, and all of those are made quantitative. So the process that existed before since the 1970's was very open to interpretation, and a lot of discussion, and it was just very expensive, because there was no sort of level of safety to which you were trying to aim for. With this update, there are quantified risks that we aim to address, and that's a good thing all around. That makes safety better, it makes costs lower, and it increases the speed at which we can achieve our objectives.

Mr. POSEY. Thank you. Mr. French, how would that policy change be an important enabler for thermal propulsion systems that would be needed for deep space?

Mr. FRENCH. Yes, sir. So, under the—as Dr. Lal talked about, there's three differed tiers under the new policy, and as the policy is designed, a flight demonstration of nuclear thermal propulsion system would fall likely under tier two, which would gain the benefits that Dr. Lal just discussed.

Mr. POSEY. OK. And is there anything Congress could do to expand upon the memorandum to keep America a preeminent leader?

Mr. FRENCH. Yes, sir. I'd say that, on the policy side, affirming these positive improvements through authorization activity would be very important, as well as, you know, affirming the nuclear—the language that the Committee—Subcommittee considered last Congress would be a very positive step.

Mr. POSEY. Thank you. Mr. Meholic, whenever a launch includes a payload with a nuclear reactor, there's a huge process to safeguard threats to life and the environment. In your written testimony you stated fission-based SNPP, space nuclear power and propulsion, systems are manufactured and launched in the off state, that would dramatically reduce any threats to the environment or life. Can you give us an example of how that might protect lives, let's say, on the Space Coast, for example?

Mr. MEHOLIC. Sure. Thank you for the question. Yes, so, as I mentioned in the—in my earlier words here, you know, RTGs are always hot, given the nature of plutonium, right? It's always radiating, there always has to be shielding and so forth, and if there was a launch accident, you know, those—that material inside of that reactor would still remain in that active state, and, you know, would fall down into the oceans, and in the—into the—onto the land, depending on where the accident occurs, and potentially have

to get, you know, analyzed and assessed for what kind of damage would be produced.

With a uranium-based nuclear fission system, the uranium is actually not fissioning. It is very, very negligibly radioactive at the time during manufacture, during the fuel formation, during its insertion into the reactor, and basically is a giant chunk of metal that weighs several tons, not unlike a normal spacecraft. So, you know, if an accident were to occur, this metal would come down, you know, possibly as a single piece, but unless there is some form, or command, or significant consequence that would cause it to go critical, it would otherwise remain as a giant chunk of metal, and just splash down into the ocean with no results. But, obviously, the analysis would have to be done for—you know, the criticality analysis, and everything that accompanies any kind of a normal launch when you're dealing with this type of thing. So that would still continue.

Mr. POSEY. All right. Thank you, Mr. Chairman. I yield.

Chairman BEYER. Thank you, Mr. Posey, very much. Now recognize the Congressman from Mars, Mr. Perlmutter.

Mr. PERLMUTTER. Thank you, Mr. Chairman. I appreciate that. Just a couple thoughts. The good news and bad news for us in Congress is we have one of the top nuclear physicists in the country on this panel, Dr. Bill Foster. So the good news is he can interpret all of the things you all are talking about, nuclear fission, and nuclear fusion, and plasma containment, and all that stuff. Bad news is we have to listen to that all the time too. So what I want to talk about is—every one of you has addressed the need for stable and sufficient resources, and that's really what Congress must and can—that's our responsibility, as the board of directors here, sending out a mission.

So let me begin with—just assume that, between the Defense Department, the intelligence agencies, the Department of Energy, and NASA, the budget is sufficient, and you know where I'm going with this, to get our astronauts to Mars by 2033. Dr. Myers, your report is pretty sobering, quite frankly, for an exuberant guy like me, and maybe I'm being unrealistic, but are there any fundamental scientific limitations to us being able to get to Mars by 2033, if you had sufficient resources? I mean, does it just take that much time to do the kinds of research and testing that's necessary?

Dr. MYERS. Yes, unfortunately, it likely does. There are some—as I mentioned earlier, the materials challenges for nuclear thermal propulsion may really limit its capabilities, but when you look at the overall mission architecture, and the propellant that—the launches that you need, the—you know, the cargo—the precursor cargo missions, the—just the normal Mars orbital dynamics, right, the sonotic cycle, when you look at all of that, and you ask about the technology development requirements from a—you—from where we are today to launching a crewed mission, we saw that as a tremendous challenge, and possibly—likely unobtainable by 2033.

Mr. PERLMUTTER. All right. So——

Dr. MYERS. Of course——

Mr. PERLMUTTER [continuing]. I guess—I'm the kind of guy that thinks that, between the scientific community, the engineering community, the technical community, we can do that. I know you

guys can do it. And the reason that we said 2033, or that's become so—I've become so obsessed with it is 4 years ago, or 5 years ago, we had a couple senior people from NASA, I think it was probably 2016, 2017, saying 2033 the orbital mechanics is good. That gives us a 15-year lead time, and, yes, we can do it. So, Dr. Lal, can we do it?

Dr. LAL. So I agree with everything Dr. Myers said, but I would like to add some other things to it. So deep space transport is just one piece of getting to Mars. There's also the entry, descent, and landing, which is very, very difficult, and we have not invested much in it at all. We've landed small rovers and landers, which is not at all like human landers, right? So that's a second piece. The third piece is environmental control. I mean, we have to take these—you know, our best humans, you know, the best Americans, our heroes, you know, in these vessels, and we need to make sure that the environmental control and life support systems can keep them alive for 2 to 3 years. I mean, nuclear cuts the travel time by maybe a year, but it's still about 2 years.

And the last but least—not least piece is radiation protection. So, you know, there's huge amounts of galactic and cosmic radiation the astronauts would be exposed to, and we need to understand the impact of the radiation on the human body, so transportation is just one element. There's all these other elements as well, and funding everything together, while we are also interested in——

Mr. PERLMUTTER. I—OK. I know it's going to be a challenge. I've been listening to this for 5 years, and I know you people can do it, so I'm going to turn to Mr. Meholic right now, and I wanted to give Dr. Chang-Diaz a chance too, as—and I wanted to talk about SPD–6, but—Mr. Meholic?

Mr. MEHOLIC. Yes, I also wanted to—thank you very much for the question. As far as resources go, there's also the resources of launch acquisition and launch vehicles to get to orbit to put these types of things together. One area that's not touched on very much is the advancements that are needed in on-orbit and automated assembly in space of these types of large spacecraft, regardless of what the propulsion system is, and how to launch those systems, and the availability of those systems, and qualification of those systems, by the timeframe you're talking about, sir. That's all. Thank you.

Dr. MYERS. So I—conclude and wrap that up by saying, when the committee looked at all of those issues that Dr. Lal and Mr. Meholic mentioned, that's why we came to the conclusion that we did.

Mr. PERLMUTTER. All right. Well, I'm going to keep—I'm going to push you, because I know you can do——

Dr. MYERS. Excellent. We look forward to having the resources to do our best.

Chairman BEYER. And, Congressman Perlmutter, unless the Committee overrules me, we're going to try to do a second round too, so hang in there. Now let me recognize the original Daniel Webster from Florida. Congressman Webster, the floor is yours.

Mr. WEBSTER. Thank you for putting this on, Chairman, and—really appreciate it. This is technologically challenging for all of us, I guess. Especially me. I was wondering, is there a—any thought

to where the launch point should be? Should it be on the Earth, or should it be external to the Earth? And I'm not sure who would be the right person to answer that question.

Dr. MYERS. I'm happy to jump in——

Mr. WEBSTER. OK. Mr. Myers?

Dr. MYERS [continuing]. And then I'm sure other—others of our witnesses have useful—have good things to say. I would say that the bottom line is that, right now, everything starts on the surface of the Earth, so we have to get to space. The departure—and then, actually, as Mr. Meholic mentioned earlier, there's an assembly point in Earth orbit where you bring all of those resources together, and then the mission to Mars will depart from Earth orbit. So there's—you launch from Earth into orbit, do a vehicle assembly process in orbit, and then go to——

Mr. WEBSTER. And the initial launch is a whole bunch of stuff with them? It's—you're only taking people, and parts, and all kinds of other things, and then it's assembled in space?

Dr. MYERS. Yes. Yes, it's assembled in orbit, in space, and then it goes to Mars from that point.

Mr. WEBSTER. Is there a—is it a deep orbit, or a shallow orbit, or——

Dr. MYERS. Frankly, that's been—that has not been finalized yet. There are—we, in fact, looked at two options. One—and we had presentations—we had lots of people providing us input, but there are options to do a low Earth orbit assembly, and for a high Earth orbit assembly, or, frankly, even assemble around the Moon. There—NASA has done some mission architectures using lunar orbit as an assembly stage point.

So we've looked at all of those, or the community has looked at all of those options, and one of the findings of our Committee was that we really need an apples to apples comparison of these different mission—what we call mission architecture options, different ways of performing these missions, in order——

Mr. WEBSTER. So does that——

Dr. MYERS [continuing]. To finalize one.

Mr. WEBSTER. So does that affect the timing, you know, talking about particular years orbiting that, or whatever? Is there a—does that change the timing, or the—of the actual distance after you get into space? Is it——

Dr. MYERS. It does——

Mr. WEBSTER [continuing]. Really matter?

Dr. MYERS. It can change the amount of time that the astronauts are in space, but it doesn't change it dramatically, because the Moon is bound to the Earth, and so fundamentally the orbits are guided by the Earth's orbit and Mars's orbit, for example. So it can affect it somewhat, but it does not affect it fundamentally.

Mr. WEBSTER. Is that—is there any change—well, you're—if you're doing it in space, does that change the type of energy used to propel the ship to Mars?

Dr. MYERS. Not—no, it doesn't, because, again, fundamentally you have to go from an Earth orbit, whether it—wherever you assemble in Earth orbit, be it—even at lunar orbit—the Moon orbits around the Earth, and so fundamentally it does not. It can have

effects on—it can have—it definitely does impact it some, but not dramatically. And other panelists, feel free to jump——

Dr. LAL. Yes, I guess I would just add to that, if I might, you know, the space station, low Earth orbit, is about 400 kilometers, Moon is 400,000 kilometers, Mars is 400 million kilometers, so being, you know, in Earth orbit versus Moon orbit really doesn't change a whole lot as—and it's about the same time regardless of where the assembly happens.

Mr. WEBSTER. Thank you both.

Mr. MEHOLIC. And if I may also, sir, you know, the assembly of these types of spacecraft, regardless of what the propulsion is, if it's nuclear electric or nuclear thermal, is going to require perhaps dozens of launches, depending on the launch vehicle, and how much each one of those rockets can carry to the assembly orbit, right? The further out you go away from Earth to assemble, the larger the launch vehicle you're going to need, depending on the mass that you're sending up, you know, which could be several tons, right, of payload. So being able to do that, acquire the launch vehicles, get all the launch approvals, you know, and send these things to the right orbits is critical. And I know that time is coming up.

Mr. WEBSTER. Is there any way to start now doing that?

Dr. MYERS. We really need the—to make some other decisions about technology approach. I think we need to make some fundamental progress on the technologies before we start the mission itself. So we do need to establish the infrastructure required to—you know, it—at the technology level, and then the ground infrastructure, and the in-space infrastructure before we can really start the mission, I would say.

Mr. WEBSTER. Thank you very much. I yield back.

Chairman BEYER. It's now my honor to recognize Dr. Foster, who, with Mr. Perlmutter and others, I thoroughly enjoy trying to keep up with the many different ideas that he has. Dr. Foster, floor is yours.

Mr. FOSTER. OK. Well—all right. Am I audible here?

Chairman BEYER. Yes.

Mr. FOSTER. OK. The—well, actually, just a follow up on the—just—the previous question, at what point, when you look at different assembly scenarios farther from Earth, at what point does the radiation burden on whatever humans are assembling stuff become a driving factor? You know, is that a—turning to be a problem for, for example, lunar assembly?

Dr. MYERS. The assembly would probably be primarily automated, as in—we talk about autonomous rendezvous and docking, for example, and autonomous assembly. It would need to be added to the in-space time of the astronauts, but those astronauts doing the assembly would probably not be the ones actually going on to Mars.

Mr. FOSTER. OK.

Dr. MYERS. So there probably—you know, in that scenario, there would probably be a way to balance all of that, and to end up, again, minimizing the radiation exposure of the——

Mr. FOSTER. Well, the worst case, for the ones that actually make the trip——

Dr. MYERS. Exactly.

Mr. FOSTER [continuing]. You're telling me. Yes.

Mr. MEHOLIC. And——

Mr. FOSTER. Let's see. What is the best understanding of the performance hit that you take in the—low enriched versus high enriched uranium? You know, both for nuclear thermal and for, you know, surface-based power reactors? You know——

Dr. MYERS. I can——

Mr. MEHOLIC. I can——

Dr. MYERS. I'll go first, and then Greg. So it turns out that at these power levels, and at these—either nuclear thermal or nuclear electric, there really isn't a significant power hit for highly enriched—I'm sorry, for HALEU, for low enriched uranium. The—you can design the reactor to operate just as well with HALEU or HEU. It is a different reactor design, you have to design it differently, but there is essentially no——

Mr. FOSTER. So you're limited by thermal transfer from whatever fuel assemblies you have, and it's—doesn't matter what's inside, pretty much?

Dr. MYERS. Pretty much.

Mr. FOSTER. And is there a different——

Dr. MYERS. At this scale. That's—I'm sorry. Let me just finish by saying that at small scales, so for some of these—the systems that Dr. Lal was talking about, for near term—near term surface fission power, the—there is much more of a penalty, so at 10 kilowatts there is a significant——

Mr. FOSTER. Right.

Dr. MYERS [continuing]. Penalty between the two—you can still build a HALEU reactor, it'll still work fine. It'll just be heavier than you want. But as you scale up in power, that penalty is dramatically reduced.

Mr. FOSTER. All right. And so the other effect that may be hard to quantify is the effect on mission cost, just because of the tremendous security. I'm sure most of you have been in a place that handles high enriched uranium. It's my understanding that the commercial enterprise interested in this are pretty much uninterested in high enriched uranium, is that——

Dr. MYERS. That is certainly what our committee—our committee was explicitly told that if industry is going to do it, it must be HALEU. It must be the——

Mr. FOSTER. OK.

Dr. MYERS [continuing]. High-assay low-enriched uranium, not HEU. HEU is a killer for——

Mr. FOSTER. Yes.

Mr. MEHOLIC. And if I may, that leads directly into, sir, the nonproliferation policies that the United States has with—you know, internationally, is the use of HEU. And also to touch back on Mr. Myers's points, and—as correctly described, you know, the performance hit is minimal with—between HALEU and HEU, but there is a mass change, right? You know, there have been a number of studies that showed that if you use a HALEU type of reactor for the power levels and thrust that are described in space nuclear propulsion and power, the core in the actual—the actual reactor core may only be about 15 to 25 percent heavier for a HALEU sys-

tem than for an HEU system. What that means to the overall spacecraft mass when you're talking 100 metric tons is very, very little, right, is the change in weight there. So the performance of the engines, as Dr. Myers stated, is going to be about the same regardless of the core.

Mr. FOSTER. All right. And so the mission impact, combined with the cost impact, and the fact that you basically have to go to weapons labs to—you know, to do an HEU design, and to test it, and everything else? Some—OK. That's interesting.

Dr. LAL. Could I add one more——

Mr. FOSTER. You know, the one corner that still made sense was the short-term low power surface reactors, which was—that was a prototype that was tested a few years back. And what's the status of that, and is there—are the—you know, what direction are we going in there?

Dr. LAL. So if I could take that question? So I just wanted to add one—another point to what Dr. Myers and Dr. Meholic said. Every single reactor effort we have had in this country in the last, you know, 50, 60, 70 years has been an HEU effort, so as we switch to HALEU, which we are—which we have, we really cannot leverage a lot of those lessons. So we cannot say, you know, doing "X" would be easier because we did that in the 1950's, because what we did in the 1950's was the system that's not really transferable. So I just wanted to make that point.

But to your question on the status of kilopower, it was a zero-power criticality test. It went very well, and since then NASA has determined, and I can get you details by e-mail—has determined to move from the HEU to a HALEU system, and those designs are underway. And NASA's currently looking at releasing an RFP (request for proposals) solicitation for reactor—power reactor systems this—the end of this year, and it would be asking for a HALEU design for surface power on the Moon.

Mr. FOSTER. Thank you. Sorry, my time is up, but it looks like there's no reason to reconsider and look back on that decision at this point. Good. OK. Thank you. I yield back.

Chairman BEYER. Thank you, Dr. Foster. I now recognize the Congresswoman from California, Representative Kim.

Mrs. KIM. Thank you very much, Chair. You know, one of the recommendations in the Committee on Space Nuclear Propulsion Technology's report on space nuclear propulsion is for NASA to develop consistent figures of merit and technical expertise to allow for an objective comparison of the ability of NEP and NTP systems to meet requirements for a 2039 launch of the baseline mission. Dr. Lal, I have a question for you. Has NASA officially adopted this recommendation and commenced demonstrates it can compare NEP and NTP systems, and if so, when can the Committee expect the results of this study?

Dr. LAL. So, Congresswoman, yes, NASA has accepted that recommendation. We are completing a study, and it is in review by external non-advocacy experts. The basic takeaway from the study I can summarize in three quick bullets. We found that both NTP and NEP—systems have the potential to fulfill the mission requirements for a fast transit to Mars in the 2030's. However, as we've been discussing, it's a different set of challenges for both, with NEP

advantage in lower mass and fewer launch vehicles. Those are kind of the big picture takeaways, and we will make sure that once the report is reviewed and updated, we can get it to you.

Mrs. KIM. Thank you, Dr. Lal. Maybe to any panelist, I have a question for one or all of you. How are departments and agencies collaborating on SNPP systems? Are they conducting regular technical exchanges among SNPP programs?

Dr. MYERS. I——

Mrs. KIM. Mr. Myers?

Dr. MYERS. I would say that, yes, they are working very closely together, to my knowledge. I'm not directly involved, but I have spoken to various people in the agencies, and they are actually directly engaging. The Department of Energy, the Department of Defense, and NASA are working very closely together, and Dr. Lal will probably be able to speak directly to this.

Dr. LAL. I'd be happy to. So as Dr. Myers said, DARPA is developing an NTP flight demonstration that is representative of a high thrust system needed for national security—near the Moon operations. Of course, such a system would provide NASA with valuable knowledge in the area, including things like launch regulations, reactor, and engine operation, and thrust control for future NASA and other missions. On this particular program, which is called DRACO, we have a memorandum of understanding (MOU) in place. NASA's Marshall Space Flight Center is supporting this effort. At DOE, the Idaho National Lab (INL) is getting upgraded, and that could be used, and INL is also handling some of the early design contracts.

Another part of DOD, we are—I'm struggling with what—stands for. It'll come to me. We are working together. So they are developing a ground-based reactor for forward bases, and we are working with them on fuel production, because they're also looking at HALEU. They're not identical fuels, but similar enough that we can collaborate. And, again, we have an MOU in place with the Pelley Program. DOE is, of course, integral to our efforts. At NASA we work with the Idaho National Lab, Los Alamos National Lab, Oak Ridge National Lab, and DOE tends to provide technical oversight, and support, and reactor, and fuel manufacturing, and providing testing facilities. So very strong relationships with the Department of Energy, and Department of Defense, and of course, private industry.

Mr. MEHOLIC. And Congresswoman, if I may also, The Aerospace Corporation is also intermingled with all of the programs that Dr. Myers and Dr. Lal mentioned, in addition to our connections with Space Command and the Space Force interests also in this type of technology for national security missions. We're also involved with launch acquisition for all of these projects as well, both for the NASA project and for DRACO, which have, you know, more "immediate"—well, shorter term requirements, or desirements, for a potential flight test of these types of systems.

Mrs. KIM. Well, since—I've got little time left here, but I do want to ask, how far along are other countries in advanced in space propulsion? You know, are there any key technology areas in which the U.S. does not lead?

Dr. MYERS. Well—perhaps—I mean, I can—so Russia has a nuclear—a significant nuclear electric propulsion development program, and they have been talking about launching in the 2030's a significant nuclear electric system. I could not comment on whether or not—on how far along they are. I don't have that kind of insight. It does seem to be more advanced than what we're doing today. And perhaps Dr. Lal, or other witnesses, have other insights.

Dr. LAL. I would add to that that Russia has been launching power reactors for the last 20 or 30 years, so they do have a huge base of—an operational expertise that we don't. We launched a power reactor in 1965, and since then we have not launched any nuclear fission systems. With respect to other countries, there are efforts in China to be developing space nuclear propulsion systems. They have similar goals as ours, to be getting to Mars in the 2030's. We don't have too many more details on the specifics, but we can say that China has a very aggressive space development program, and they are seeking to have global parity in this area.

Mrs. KIM. Well, I think my time is up, but, you know, asking the obvious question, so what can we in Congress do to make sure that the United States stays competitive and, you know, compete with Russia, China, and other countries that are—far advanced than us?

Chairman BEYER. Congresswoman Kim, since—I think we should move on, because the time's up, but we're going to do a second round.

Mrs. KIM. Thank you.

Chairman BEYER. You're most welcome to stay for that important question. And with that second round, let me first yield to our Chairwoman, Congresswoman Johnson, if she has any questions.

Chairwoman JOHNSON. Thank you very much. No, I do not have any questions at this time.

Chairman BEYER. Great. Thank you, Madam Chair. So let me begin with the second round, to be followed by Ranking Member Babin. First, for Dr. Chang-Diaz, it seems fairly clear, through this last hour plus, that without nuclear propulsion, it's going to be very difficult to get to Mars and back, and to manage the cargo, and to run the stuff that's on the planet itself. Is this actually true? Can we think about Mars just using the traditional chemical propulsion systems, or do we need to double down and understand that one of those versions of nuclear propulsion is—for going to Mars?

Dr. CHANG-DIAZ. Well, my personal opinion is that, you know, you can go to Mars today, if you want to, with chemical rockets. I mean, you—we know how to—the physics will allow you to do that, but it will be a very fragile mission, and it will be a mission that—you know, any contingency would be—would put the astronauts in peril, and then it could be a, you know, a really bad day. So, to me, it is important that we do the homework, and we do it right, and we take a little longer to, you know, to get to Mars, but do it with a very robust frame—you know, technology infrastructure.

And I was going to say, in all these discussions, that—I really believe the Moon is a crucial component of this whole architecture, and particularly for nuclear electric propulsion. When you're talking about multi-megawatt rockets, plasma engines, we're not going to test those engines on the Earth. Most likely you're not going to

test them in flight either. You probably will have to test them on the surface of the Moon, and we may have to set up a facility on the Moon to fire these engines for the full duration of their burn, which would be months, and verify that, in fact, they do work, and they're reliable, so——

Chairman BEYER. Dr. Chang-Diaz, is—that's a perfect pivot to my question for Dr. Myers, because I thought—one of the biggest things I took out of your testimony was the need to be thinking about testing these engines on Earth full scale, rather than trying to test them in space. Can you expand on that? And especially—I know—I guess—I don't know whether it was Mr. French or Mr. Meholic talked about the impossible regulations on Earth right now, but, you know, or Dr. Chang-Diaz's notion that we'd have to test them on the Moon.

Dr. MYERS. So we did not find it to be impossible to test on Earth, and I personally have spent months thinking about this, and doing the analyses with colleagues. I've led teams that have done these evaluations. It is a challenge, yes, but we're talking about human missions to Mars, which will be humanity's greatest endeavor. And—so we're talking about an enormous project. Building the ground test facilities, NASA has done studies, I've contributed to, other panelists have contributed to looking at nuclear thermal propulsion ground tests, and it is feasible to do. It's not cheap, but it is feasible to do. And our Committee did not find a way to avoid that kind of testing on the ground in order to demonstrate the reliability.

Similarly, with nuclear electric propulsion, we found that it was feasible, it is feasible, to test certainly the lithium MPD thrusters. It's one of their benefits, because they have condensable propellant. And so, in fact, right now there is an existing facility at the Jet Propulsion Laboratory which can be used to test a two-megawatt nuclear electric rocket—plasma rocket, the MPD—the lithium MPD thruster. Similarly, others—at NASA Glenn there's the Space Power Facility that is in Northern Ohio. That facility can be upgraded—can likely be upgraded to test the hull thrusters, and potentially VASIMR, depending on the scale, and the modularity, that is proposed for these different systems. One of the questions that we need to answer—one of the technical questions we need to answer is how do we—for nuclear electric propulsion, what is the level of modularity that is feasible, and how do we—do we have to test a multi-megawatt engine, or do we put multiple 500-kilowatt engines? And then we can test the 500-kilowatt engines, and do a different kind of test for the integration, for example.

And so we—the Committee had these debates, and got lots of input from the community, again, the government, academia, and industry, and our consensus was that it is feasible. It's not cheap. I didn't say it was cheap, I—but it is quite feasible, and in some cases with existing facilities, to do the ground testing required for the nuclear electric rocket. I think Mr. Meholic mentioned very—he made some excellent points about—remember the other subsystems, the reactor, the power conversion system, the radiator, the power management and distribution system. All of those systems have to be tested. A key difference between nuclear thermal and nuclear electric is that nuclear thermal is a much more inte-

grated—and—it's much more difficult to separate the subsystems so that you can do modular ground testing. You really need to test full scale, fully integrated systems for nuclear thermal. That was our committee consensus. Whereas nuclear electric you could break it up into modular pieces, and as long as the interfaces are very well defined and controlled, we found that we could likely—in fact, we were sure you can design test facilities on the ground.

Chairman BEYER. Thank you, Dr.——

Dr. MYERS. So I hope that answers——

Chairman BEYER [continuing]. Myers. Let's move back to our Ranking Member, who, the last time he spoke, was delving that exact question. So——

Mr. BABIN. Exactly.

Chairman BEYER [continuing]. Congress—Congressman Babin.

Mr. BABIN. Yes, sir, thank you very much. Mr. Chairman, if I may, I'd like to thank all the witnesses today, but I'd also like to give just a moment of special recognition to Dr. Franklin Chang-Diaz, because I believe the work that Dr. Diaz and his team at Ad Astra are accomplishing on their VASIMR engine will revolutionize space travel and transform the trajectory of our space industry. And so I want to thank you again. And just—back to my question that our Chairman just mentioned on the state of thruster technology, I know that there's been some significant success, as I just mentioned in the—since the Academy report came out, and I'd like to give Dr. Franklin Chang-Diaz a little bit of time to find out here what his thoughts on this is. And so if—I will just let you give us a few of your thoughts here, and whatever time you need to take up to the—my remaining time.

Dr. CHANG-DIAZ. Thank you, Dr. Babin.

Mr. BABIN. OK.

Dr. CHANG-DIAZ. Thank you very much for your comments. We are very happy with the results that we've obtained. The key on the work that we've been doing is to integrate, you know, to build the entire package, and test the entire rocket engine in the vacuum environment. Many of these electric thrusters that are being tested are tested in sort of—some parts of the thruster are inside the vacuum, other pieces are outside, and they are not quite ready to be vacuum compatible. And so we have endeavored to package it all, and to deliver a TRL–5, so a technology readiness level five, package that will have all the characteristics of something that you could actually fly. And that is something that we're very proud of, and has been accomplished thanks to private investment, and also NASA support.

So this combination of effort from the space agency, together with funding from the private sector, is changing the chemistry of things, changing the paradigm. Going back to the Moon is going to be also a commercial activity, lots of—there's going to be a lot of traffic to the Moon, and I think that we need to start thinking of the Moon as a place of real interesting work, like what we're doing today with the International Space Station, that, you know, began to—as a very, you know, collection of tests, projects, and experiments now has become a more commercial activity. And to do that we need to have an infrastructure of high-power electric thrusters

that can service that transportation path between low Earth orbit and the Moon.

So I'm trying to think of the entire architecture as we move further and further into the future, and not just about an isolated mission to Mars. I don't want to get us in the same, you know, sort of pitfall of the Apollo Program, where we just went and landed on the Moon, and then, you know, a whole half a century passed, and we didn't do any more because, you know, the race to the Moon had been won. We need to do this in a sustainable way so that it continues to progress, and move further and further out, with the private sector very much engaged.

Mr. BABIN. OK. Thank you so very much. And I also want to say congratulations on being selected one of Goldman-Sachs's 100 most intriguing entrepreneurs of 2021 as well——

Dr. CHANG-DIAZ. Well, thank you.

Mr. BABIN [continuing]. Dr. Franklin Chang-Diaz, good man. I also—I've got a little bit of time left here, so I'd like to direct a question to Mr. French, if I could. Highly enriched uranium, HEU, raises proliferation concerns, and restricts the number of private sector organizations that could contribute to development. Recent proposals have favored high-assay low-enriched uranium, or HALEU, to address these concerns. But according to the Academy report, technical feasibility, performance, safety, fuel availability, costs, and schedule considerations do not favor HEU or HALEU. Should NASA conduct a comprehensive assessment of the relative merits and challenges associated with HEU and HALEU, and should that assessment consider how such a decision impacts U.S. industry? Mr. French, if you don't mind?

Mr. FRENCH. Yes, thank you, sir. I'll defer to some of my other panelists here on some of the technical aspects of that, but I will say that NASA's activities already are on—looking at lower enriched uranium options, and that is what industry is responding to and working on. That also aligns very well with the new launch framework, and the testing regimes that increase feasibility. So industry is very much focused on a lower enriched uranium framework, and that is what our government partners are looking at, and what—the partnerships NASA is engaged in. And then maybe I'll hand it off to some of my other panelists on some of the technical aspects there.

Dr. MYERS. I would just say that I agree exactly with what Mr. French said. Since the Academy report, and even during the Academy report, NASA was reaching the conclusion that high-assay low-enriched uranium was fine. It worked fine, it met the performance requirements, and so NASA has—and as, you know, industry also has focused on high-assay, low-enriched uranium. And as we discussed, as Dr. Lal, I think, discussed, that helps with the proliferation concerns, and the launch regulation concerns as well.

Mr. BABIN. Excellent. Thank you——

Dr. MYERS. I think we may be beyond that question.

Mr. BABIN [continuing]. You bet. Well, I—my time has expired, Mr. Chairman, so I will—I'll yield back. Thank you.

Chairman BEYER. Yes, thank you, Dr. Babin. Thanks for hearing in the—hanging in there. Let me now recognize again our one nuclear physicist, Dr. Foster.

Mr. FOSTER. I'm actually a high energy particle physicist, so I don't have my, you know, neutron absorption cross-section memorized the way you all do. But—let's see, a couple of things. Well, first, I want to point out that the advanced reactor designs that are being pursued on the commercial front are almost uniformly highly-enriched low-assay uranium, and so I think there's a lot of commonality there that everyone will benefit from.

And so—now I'd like to change the subject completely, and this—it's my considered belief that this is going to work, that there is a good, very efficient solution for the high specific impulse, but low thrust, you know, design corner that you need to go from one—low Earth orbit to other planets, all right? I am less sanguine about progress that we're making on getting into low Earth orbit. And there are all kinds of—you know, of ideas out there. And so if I could, with some of my time remaining, maybe starting with Dr. Chang-Diaz, you know, if Congress was to put some money into some of these high risk, high payoff methods for getting stuff into low Earth orbit without, you know, just using the same chemical fuels that Wernher von Braun came to 60 years ago, then what is your—what—where would—where should we put our money?

Dr. CHANG-DIAZ. Well, you know, I really think that the chemical rocket is a pretty good way to get things into low Earth orbit, and it's hard to beat, particularly locks and hydrogen, which are nonpolluting, and it's a pretty nice technology that's been developed. But what I think needs to happen is that low Earth orbit is really a staging ground. It really needs to be a staging ground, and what we need to put money into is the infrastructure to get stuff from low Earth orbit to points beyond. And that is most likely going to start with solar—high power solar electric engines, which will then migrate into nuclear electric engines for deeper path into space.

But the solar electric option is also a good one for the vicinity of the Moon and the Earth, and our company envisions, essentially, a system of electric tugs, trucks, you know, to deliver all the cargo that needs to be delivered, to build that sort of railroad, you know, that will be able to support operations on the Moon, on the surface, and also in what we consider to be the lunar shipyard, which is where we think the ship to Mars will be built. But it's a whole infrastructure buildup that needs to be created, and I think the government has a strong role to play here with the private sector.

Mr. FOSTER. Um-hum.

Dr. LAL. So, to your question, Representative Foster, there's a lot of private investment going in launch to low Earth orbit, you know, many billions of dollars, and, of course, there has been a lot of government investment too, which is why we have, you know, companies like SpaceX, and Blue Origin, and Rocket——

Mr. FOSTER. Yes, I mean, SpaceX is using the same chemical fuels that——

Dr. LAL. Yes.

Mr. FOSTER [continuing]. Were explored in the 1950's, right? And so——

Dr. LAL. And I think the private sector is lowering costs by, for example, building the entire rocket with 3D printers. If we have to make an investment, I think a better investment, other than launch, would be on—what is it we do once we are in space? I

mean, we need to invest in real commercialization. We need to—if you're making things in space, to bring it back down on Earth, or if we are making things in space to take them deeper into space. I think we have a gap in that investment. Launch—but just to address your question at the core, there are some companies that are working on, you know, centrifugal methods, so there are—there is a variety of investment. And I don't think—if we are making a decision on where the government needs to put money, that would be the place to put money. I think we need to focus on active—activities in space.

Dr. CHANG-DIAZ. Exactly right.

Mr. MEHOLIC. And, if I may, this is—another area too is that these launch companies that Dr. Lal mentioned—well, some of the launch companies, as well as others, the capabilities that they're developing are actually for fairly low masses to orbit, right? So the kind of masses that we're talking about for these kinds of Mars missions and assemblies are, you know, tens of metric tons, which is very limiting to what kinds of launch vehicles will be available by the timeframe they're needed to actually deliver that. So we might have Starship, we might have Falcon Heavy, we might have SLS, right? Other than that, these other smaller launch vehicles just may not have the capability to launch the required masses to the assembly orbits.

Mr. FOSTER. OK. I was just thinking, 50 years out, are we going to be sitting there looking at, you know, kerosene and liquid oxygen for big boosters, or, you know, is—whether—you know, that's my reading on why the Apollo Program sort of ended up being terminal, is that there were not—you know, as the Lindbergh flight was followed by more and more efficient vehicles, that—you know, there isn't even a factor of two increase in the performance of heavy boosters since the Saturn booster.

Dr. MYERS. That——

Mr. FOSTER. And that's where——

Dr. MYERS [continuing]. Certainly is true——

Mr. FOSTER. That's what—the block I'm trying to see my way around here. Anyway, my time has expired.

Dr. MYERS. But the cost has come down by a factor of 100. The cost has come way down by changing the architecture——

Mr. MEHOLIC. Um-hum.

Dr. MYERS [continuing]. And changing the production methods, as Dr. Lal mentioned, and so, from a cost perspective, we have made progress.

Mr. MEHOLIC. And as just one final point, I think, is even at the terminal end of the Apollo Program there was a—there were some number of studies that said if they were to put a nuclear thermal propulsion stage on the upper stage of the Saturn, it could've delivered twice the payload to the Moon.

Mr. FOSTER. Um-hum. Yes. Yes.

Chairman BEYER. That—Congressman Foster, thank you very much.

Mr. FOSTER. Um-hum.

Chairman BEYER. By the way, we've gotten—we've expanded our narrow topic of nuclear propulsion to so much of space and NASA, so congratulations. This is great. And now I think we'll wrap up

with the distinguished Randy Weber, Congressman from Texas. Randy, thank you for your patience in coming in and out, but—floor is yours.

Mr. WEBER. Well, thank you, Mr. Chairman, and I appreciate all the witnesses today, the ability to hop on the Subcommittee here. My question is for all the witnesses, whoever wants to weigh in first. What is the power—and I'm in late, so I apologize if you all have discussed this. What is the power range for the current demonstration of a fission power system on the surface of the Moon, and how is that program aligned with mission needs for, and potential future government and commercial applications of in space power, NEP, as well as terrestrial nuclear power? And I'll open it up to whoever wants to answer first.

Dr. MYERS. So I'll go first. I spent a lot of—thank you for the question, because it's actually something I was going to try to interject later on. We—it did come up earlier——

Mr. WEBER. I'll——

Dr. MYERS [continuing]. As——

Mr. WEBER. I'll send you a bill in the mail.

Dr. MYERS. Exact—yes. So one of the things that we did discuss earlier was the need for scaling from the fission surface power, which is currently targeted at 10 to 40 kilowatts, or that range, to the megawatt class that we're really talking about for the space nuclear propulsion systems. That scaling is very challenging, and it—as Greg Meholic has commented, all of these different subsystems have to work together. You've got to have the reactor, the power conversion system, the power management and distribution system, the radiator. All of that for nuclear electric propulsion must work together with the electric rocket.

That scaling from 10 to 40 kilowatts to the megawatt class, factor of 100 or so, that's really hard to do unless we really think carefully about the subsystems that we choose to demonstrate and use on the fission surface power systems. So I would—you know, I would want to be sure that the subsystems approach that we use for the fission surface power are, in fact, relevant to the megawatt scale propulsion systems that we've been talking about. And it's—there are some options which are not scalable, they do not scale, and so we need to not choose those options for fission surface power, if we can avoid them. And I'm sure other of the witnesses—others of the witnesses have things to say as well.

Dr. LAL. I can add to that. Agree with everything Dr. Myers said, and Representative Weber, you have accurately recognized that there's connections between all four systems, right? So we have terrestrial fission systems—so we have all these companies developing new, improved ways of developing small modular reactors on Earth for, you know, reducing greenhouse gas warming. There are—we're talking about a fission reactor for Mars—sorry, for Moon and Mars, which is in the—you know, for—the consideration is in the 10 to 40 kilowatt range, but if you want to be doing industrial scale ISRU (In-Situ Resource Utilization), extraction of volatiles or water on either the Moon or Mars, you need to have much higher levels of power, so, you know, you're going to the megawatt range, so at some point we would need to go from, you know, tens of kilowatts to thousands of kilowatts.

Then there is NTP, where, again, the commonality is—you know, there's a reactor in all of these areas, so there are commonalities, and—especially if you want to move forward with NTP, does—you know, it gives a reason to be doing industrial scale ISRU on the Moon. So, for example, if you extract water, and you separate it into hydrogen and oxygen, now you have, you know, some—a mission pull for ISRU on the Moon, which for the moment we don't have. And, of course, I wanted to make sure that cryogenic food management, which is an area where NASA has a lot of investment, it's kind of critical to all of our space applications, right?

And then, of course, NEP, we—as Roger mentioned, it has extensibility from surface power. For the moment, for science missions, because, you know, if you're looking at 10 to 40 kilowatts, it's not a human rated—or human scale NEP system, but it's outstanding for doing science in the solar system, going to Neptune, going to Pluto, and instead of just doing these fly bys, where we don't collect a whole lot of data, we can go into orbit, right? We can collect more data. So they're all connected, and we really do need to keep this whole of enterprise approach as we think through our nuclear enterprise.

Mr. MEHOLIC. And just to—in the final closing seconds, I want to thank Dr. Myers for referring back to my comments as well, and for you, Congressman Weber. In addition to what Dr. Myers and Dr. Lal had said, you know, the subsystems that were referred to may have to take a different form for what there's—used on the Moon versus what's used on Mars, right, as far as reliability, mass, size, materials, capabilities. One has more gravity than the other, so how does that affect the physics of the process, fluid—so there's all those different things, but there is some level of extensibility across the range there, but each one is going to be very mission unique, and very, you know, very sensitive to those requirements.

Mr. WEBER. Well, thank you for that. I guess that's a broad scientific way of saying stay tuned. So thank you all so much. I yield back.

Chairman BEYER. Thank you, Congressman Weber. And we are now at the witching hour. Everyone has had a chance to speak at least once. Thank you very, very much. It's been a terrific hearing, with obviously an enormous amount of knowledge, background, and expertise, so thank you very much. The record will remain open for two weeks for additional statements from the Members, and for any additional questions the Committee may want to ask of the witnesses. So with that, witness are excused, the hearing is now adjourned, and we look forward to seeing you on many future NASA discussions.

VOICE. Thank you all very, very much for your time.

[Whereupon, at 12 p.m., the Subcommittee was adjourned.]

Appendix

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Roger M. Myers

Date: April 22, 2022

To: Members of the Committee on Science, Space and Technology
House of Representatives
Congress of the United States

From: Dr. Roger Myers
Co-Chair, Committee on Space Nuclear Propulsion Technologies
National Academies of Sciences, Engineering, and Medicine

Subject: Questions for the Record following testimony on October 20, 2021 hearing entitled *"Accelerating Deep Space Travel with Space Nuclear Propulsion."*

I have copied the original questions below, followed by my answers in *italics*. If you have further questions or want to follow-up in any way please let me know and I will respond quickly.

Submitted by Chairman Beyer

1. The long-term storage and transfer of liquid propellant in space, or cryogenic fluid management, is important for many space applications and propulsion technologies.

a. How do the requirements for cryogenic fluid management for nuclear thermal propulsion (NTP), in particular, overlap with and differ from those of other applications requiring cryogenic fluid management?

Answer: Nuclear Thermal Propulsion will require a minimum of 3 years of on-orbit storage of liquid hydrogen at 20 Kelvin (-423.6 degrees F) to enable both the Mars spacecraft assembly as well as the entire round trip mission to Mars. The capability to do this would also be over great value to chemical propulsion systems using liquid oxygen and hydrogen. Liquid oxygen must be stored at 90.4K (-297 degrees F). Other chemical propulsion systems such as the Starship system using liquid oxygen and methane propellants, also require long-term storage of cryogenic propellants, though the temperature requirement is not nearly so stringent, with liquid methane requiring 111.5K (-259 degrees F). All these long-term cryogenic storage technologies will require advanced insulation and cryo-cooler technologies to ensure that the propellant loss rate due to evaporation is low enough, though the cryocooler technologies will be different because of the different liquid temperatures required.

b. To what extent do the technology development investments NASA has made in cryogenic fluid management, through its Tipping Point program and elsewhere, directly apply to the multi-year storage of liquid hydrogen that would be needed for NTP systems?

Answer: The technologies investments made by NASA are critical stepping-stones along the way to meeting the requirements for NTP systems. Their investments in zero-boil-off liquid hydrogen storage are directly applicable to NTP, and their investments in the storage of either liquid methane

or liquid oxygen will assist in the development of advanced insulation capabilities that will be required. It is important to recognize, however, that liquid hydrogen will require much lower temperatures than either methane or oxygen, so there are differences in cryocooler technology requirements.

2. During the question-and-answer portion of the hearing, Dr. Lal discussed that all previous reactors in this country have used highly enriched uranium (HEU) and noted that, as the U.S. switches toward high-assay low enriched uranium (HALEU), we cannot use a lot of the lessons learned from the earlier years using HEU, as they are not transferrable. Do you agree with Dr. Lal's point? Why or why not? Is there any relevant knowledge from the Apollo-era Rover/Nuclear Engine for Rocket Vehicle Applications (NERVA) nuclear propulsion work that is transferable to modern efforts?

Answer: Yes – I agree with Dr. Lal's response. Use of HALEU requires a shift to a thermal spectrum moderated reactor design. This is a major design change from the HEU reactors and introduces new design challenges. Additionally, the enrichment level of uranium may have a significant effect on the material properties of the reactor fuel, as well as the amount uranium required in the reactor. While HALEU NTP reactor designs are different, there do not seem to be insurmountable problems introduced by the switch to HALEU from HEU.

The NERVA program was a highly successful but incomplete effort to demonstrate a nuclear thermal rocket and there are many important lessons to be gained from that program today. These include identifying many reactor fuels and designs that did not work, multiple tests of engineering (not flight) integrated systems that were successfully completed, and countless details of firing an engineering-class nuclear rocket with liquid hydrogen propellant. However, when examining the results of the NERVA program it is critical to recognize that not only did NERVA use HEU reactor fuel, but also that they never successfully demonstrated a nuclear thermal rocket with 900s specific impulse (they came close – 875s – but did not get there, and the difference is significant). So while there is considerable relevant knowledge to be gained from the NERVA program it does not include reactor design or fuel selection for a 900s specific impulse nuclear rocket.

3. What would you say are the biggest policy or regulatory hurdles for advancing space nuclear propulsion?

Answer: In my opinion the biggest regulatory hurdle for either nuclear electric or nuclear thermal propulsion will be getting the approvals for ground testing of the systems at full scale and thrust. This will be a much bigger challenge for nuclear thermal propulsion because it is an open cycle reactor (where the hydrogen coolant is the rocket exhaust) that is operating close to the material temperature limits of the reactor fuel. By contrast, nuclear electric propulsion, which is a traditional closed-cycle nuclear power system (albeit extremely high performance), will likely be able to follow a more traditional testing path using suitably modified but available facilities.

4. Did the Academies Committee on Space Nuclear Propulsion Technologies consider the level of investment needed to mature space nuclear propulsion to an operational capability for human missions to Mars? If not, do you have an opinion on what level of investment would be needed?

Answer: No – the Academies Committee on Space Nuclear Propulsion specifically did not consider the investment required. I do not have a well-informed opinion on the likely investment required

other than to say that including the development and qualification of the technologies and systems as well as the ground testing infrastructure required, based on my experience I would expect it to be between $3 and $10B for either nuclear thermal or nuclear electric propulsion systems.

5. Is nuclear propulsion the *only* way to enable crewed missions to Mars that are "opposition-class"—that is, with the ability to return any time, and not wait two years, when the orbits of Mars and Earth bring the planets close together again? How would the use of chemical propulsion affect crewed missions to Mars?

Answer: To my knowledge nuclear propulsion, either NTP or NEP, is the only way to accomplish short-stay opposition class missions to Mars. Chemical propulsion options need to use conjunction trajectories, and thus require long-stays on the Martian surface. Additionally, it is critical to recognize that some proposed chemical propulsion Mars mission architectures, such as the SpaceX Starship architecture, rely on in-situ propellant production on the Martian surface to enable trips back to Earth. In other words, not only would the crew need to wait through the 2-year long-stay on the surface, but they cannot return to Earth until a fully capable liquid oxygen/liquid methane propellant factory is operational on Mars and can fully refuel the Earth-return vehicle. Overall, because chemical propulsion requires three to 10 times the amount of propellant as either nuclear propulsion option (because the engine specific impulses is three to 10 times lower with chemical), chemical propulsion systems for crewed Mars missions will require a much larger number of mission critical launches and on-orbit operations to assemble the Mars transfer vehicle, and the spacecraft will be overall significantly larger than a nuclear propelled spacecraft for the same mission.

Submitted by Mr. Babin

1. How are the uranium fuel forms being developed to enable a range of terrestrial as well as space applications, including future commercial applications, and maximizing private-sector engagement and cost savings?

Answer: There are several factors that must be addressed in the development of uranium fuels for nuclear reactors. First, we need a domestic source of High Assay Low Enriched Uranium (HALEU) that our nuclear industry can use for either terrestrial or space applications. Private sector engagement and investment will only be possible with the use of HALEU (or other LEU fuel) because of the constraints on ownership of highly enriched uranium (HEU). Second, we need to establish the required reactor fuel forms and the associated reactor designs that will work for space nuclear propulsion systems and select those which maximize the commonality with terrestrial applications. Focusing on the second part of this question, it appeared to our committee that there may be significant commonality between reactor fuels for NEP systems and the emerging micro-modular reactor (MMR) developments for terrestrial applications, though the operational temperatures for NEP reactors are higher (1200 – 1400K) than those planned for MRRs (873-1073K) depending on design. In contrast, reactor fuels for nuclear thermal propulsion must operate at much higher temperatures, likely over 2850K, and therefore will require much more select and costly materials and manufacturing processes, likely limiting the commonality with terrestrial nuclear reactors.

2. What is the power range for the current demonstration of a fission power system on the surface of the Moon? How is that program aligned with mission needs for, and potential future government and commercial applications of, in-space power, NEP, and terrestrial nuclear power?

Answer: The current NASA solicitation for which industry proposals were due at the beginning of February had a target power level of 40kWe, with an additional goal of selecting technologies that could be scaled to much higher power levels to support future surface propellant production and nuclear electric propulsion systems. If NASA does indeed select proposals that meet both of these criteria, in particular the selection of technologies that can be scaled to much higher power levels, then this program will be well-aligned with potential government and commercial applications of both space and terrestrial nuclear power systems. Both in-situ propellant production on the Moon and Mars, as well as nuclear electric propulsion systems for crewed missions to Mars will require scaling a 40kWe system by over a factor of 30 times. Therefore, while NASA's investment in a scalable 40kWe system is well aligned with the need for future high-power systems, there is significant technology risk mitigation for the higher power systems that will need to be done in parallel with the 40kWe development if a much higher power system is to be ready by the late 2030s.

3. In August 2019, the National Security Policy Memorandum 20 (NSPM-20) was updated to establish safety guidelines and safety analysis and review processes for Federal Government launches of spacecraft containing space nuclear systems, including SNPP systems, and for launches for which the Department of Transportation has statutory authority to license as commercial space launch activities (commercial launches). How have these new guidelines improved the development of SNPP systems?

Answer: The creation of a 3-tiered approach to launch safety evaluations is a major step forward to enable development and launch of SNPP systems. Launching a "cold" fission reactor is much lower risk than launching a plutonium RTG, and the new NSPM-20 recognizes this difference and is a very positive move forward.

4. Which uranium fuel forms are needed to meet the nearest-term mission needs? How are they utilizing the same or similar materials, processes, designs, or infrastructure — across these fuel forms?

Answer: The development of SNPP systems requires a reliable domestic source of HALEU that can be used along with a reactor fuel matrix material. The selection of of the specific fuel form depends on whether NTP or NEP applications are targeted. Current research and development efforts are showing that the reactor fuels for NEP can be made using near-traditional approaches to reactor fuels, whereas nuclear thermal propulsion, because of its extreme temperature requirement to reach the full 900s specific impulse, will require new materials and new manufacturing processes. At present it appears unlikely that the extremely high temperature fuel forms required for NTP can use the same materials, processes, designs or infrastructure as the fuel forms required for either NEP or terrestrial MMRs.

5. Are the uranium fuel forms to meet near-term mission requirements maximizing private-sector engagement? Will these fuel forms be developed to enable a range of terrestrial as well as space applications, including future commercial applications?

Answer: I cannot speak to this in general, though I am aware of at least one company that is investing significant private resources in NTP reactor fuel development. At this point there is, to my knowledge, so such specific private sector investment in reactor fuels for nuclear electric propulsion, primarily because NASA does not have an active NEP program that would demonstrate US government interest in the technology, though several companies are investing private resources in

reactor fuels for terrestrial HALEU reactors and these very likely have significant commonality with NEP reactor fuels.

6. How are departments and agencies collaborating on SNPP systems? Are they conducting regular technical exchanges among SNPP programs?

Answer: The DOE is directly managing the reactor development contracts for NASA – so the two agencies are working very closely to ensure a successful outcome for both the on-going work on nuclear thermal propulsion and nuclear surface power with regular technical exchanges. Additionally, NASA is involved in the DARPA DRACO nuclear thermal propulsion program as advisors – NASA regularly participates in program meetings and technology reviews with the DARPA team. There is currently no active work on nuclear electric propulsion.

7. Commonality, such as reactor designs, nuclear fuels, infrastructure, and testing, among SNPP systems, and between SNPP and terrestrial nuclear systems, will greatly increase the development and advancement of SNPP programs. How are DoD and NASA working with partners to evaluate and use opportunities for commonality with other SNPP needs, terrestrial power needs, and reactor demonstration projects planned by agencies and the private sector?

Answer: To my knowledge, NASA and the DOE are actively working to maximize commonality between SNPP and terrestrial nuclear systems. Commonality can be found between terrestrial micro-modular reactors (MMRs) and both the new surface fission power program and NEP systems will be scaled from these surface power systems, so long as appropriate technologies are selected for the new surface fission power systems. There are some technology options which could be used for the near-term, low-power surface fission power that do not scale to the high powers required for either long-term surface power, nuclear electric propulsion applications or terrestrial power systems, so it will be important for NASA to select their technology investments carefully with commonality and extensibility in mind. Unfortunately, nuclear thermal propulsion requirements for extremely high temperature fuels to meet the 900s specific impulse requirement make finding commonality with other non-NTP systems very challenging – the materials, infrastructure and testing facilities required for nuclear thermal propulsion are highly specialized and do not lend themselves to other applications. There is of course significant commonality between the DoD DARPA DRACO NTP program and the NASA NTP program, though NASA has firm need for 900s specific impulse (due to their Mars mission requirements) which drives their fuel selection, and the DoD may have greater flexibility. It will therefore be important for NASA and the DoD clearly identify areas of commonality and differences as their programs mature.

8. "Extensibility" is the concept that technologies developed in the near-term will be useful for future exploration as well. Extensibility prevents the development of "dead-end" capabilities. How is NASA ensuring that its investments in space nuclear propulsion are extensible?

Answer: The answer regarding extensibility varies according to the particular program. As mentioned in my answer to question #7 above, the surface fission power program has a real opportunity to develop reactor fuels, power conversion technologies, and power management and distribution systems that will be directly extensible, through scaling, to the very high-power systems that will be required for surface production of rocket propellants on the Moon and Mars as well as for nuclear electric propulsion. This will only work if the right technologies are selected – there are "dead-end" technology options that will work well for this initial low-power program but which will not scale in power level and thus are not extensible. To ensure that the surface fission power

technologies are extensible I suggest that there be a parallel investment in the key technologies for high power nuclear electric, which will ensure that the investments are well coordinated. For nuclear thermal propulsion the reactor fuels, long-term hydrogen storage, and ground test requirements will be readily extensible from the current 12,500 lbf thrust engine to the 25,000 lbf thrust engine.

9. When will NASA need space nuclear propulsion capabilities? What architecture and strategic planning informs that schedule?

Answer: From my perspective, NASA will need nuclear propulsion capabilities when our nation decides that sending Americans to Mars on a regular basis (every few years) is a national priority. The alternative propulsion systems do not provide the robust safety margins or mission capabilities for fast transfers and quick Earth returns that nuclear propulsion provides. These benefits are independent of the particular date for the mission or specific mission architecture. To elaborate on this final point: there are alternative architectures that can get Americans to Mars for long-stay missions (>1.5 years on the Martian surface) with an Earth-return that is completely dependent on establishing an operational propellant production and fueling facility on Mars. This is the approach used by the SpaceX Starship – any crew will have to stay on Mars, no matter what, for at least 1-2 years and will not be able to return home to Earth until they have a fully operation propellant production and fueling capability, including mining and processing Martian ice. Another option is a high-power Solar Electric Propulsion (SEP) system, but power system limitations mean that the SEP approach likely only works for the most optimal long-stay missions which occur once every 10 – 15 years. Only nuclear propulsion systems (either NTP or NEP) have the performance capabilities to enable short-stay fast trips to Mars on a regular basis at every launch opportunity every 2 years.

10. How should the government synergize nuclear surface power generation and space nuclear propulsion development?

Answer: My assessment is that the government should chose its surface power generation technology investments carefully to ensure that all the critical reactor fuel, power conversion, power management, and heat rejection technologies are directly extensible (scalable) to nuclear electric propulsion and to next-generation high-power surface power systems. It is very important to avoid dead-end technologies in these areas. Luckily, there are technologies and system architectures that meet this extensibility requirement – the government just has to choose them.

11. How is NASA coordinating current investments in cryogenic propellant storage and transfer so that it could be applicable for space nuclear propulsion?

Answer: The same organization at NASA, the Space Technology Mission Directorate, is responsible for both cryogenic propellant storage and space nuclear propulsion investments, so these efforts should be well coordinated.

12. What kind of propellants do nuclear electric propulsion systems use and what are the costs and benefits? Are there any rare or exotic fuels under consideration that could entail supply risks?

Answer: There are two primary nuclear electric propulsion systems under consideration today: xenon-fueled Hall thrusters and lithium-fueled magnetoplasmadynamic thrusters. Both of these

technologies and propellant types have their advantages and disadvantages, and we do not have sufficient data to make a data-driven selection between them today – we need to do more testing with each of them to ensure we pick the best technology. Both of these propellants have good U.S. suppliers that could scale-up their production to meet the needs of human missions to Mars. Either propellant could be supplied for these missions and there are no major supply risks that I'm aware of currently, though production would have to be increased to meet the demand. Current costs for xenon range from $700 – $1000/kg, and lithium costs range from $70 – 100/kg. The price for both is driven by supply-and-demand, which would of course change as production scaled up for these missions.

13. The development of next generation nuclear propulsion involves advancing technologies associated with thrusters, power generation, power management, and cooling. What are the biggest challenges to scaling up the power or capacity of those subsystems?

Answer: For NEP systems the principle challenges are to 1) design a reactor to operate at the required temperatures (1200-1400K); 2) scaling up the Brayton power conversion system from the current 10kWe to between 500kWe and 1000kWe and demonstrating that it can last for the required 20,000 hours; 3) demonstrating the large deployable radiator technology required to reject the waste heat; and 4) scaling up the electric thruster and power electronics systems from the current 10kWe to over 100kWe (Hall thrusters will likely be scaled to ~100kWe, MPD thrusters will operate at 500kWe to 1000kWe) and demonstrating their lifetime meets the mission requirement. While there do not appear to be any fundamental barriers to this scaling, any such effort has significant technical risk and there will very likely be unforeseen results. Each of these scaling tasks has specific technical challenges that I would be happy to discuss in more detail if desired. For NTP systems the principal challenges are to 1) develop a reactor fuel that can operate at the required 2850K temperatures while meeting the 5 hour operating time requirement, with multiple restarts, without significant fission product release, 2) developing the technologies to store liquid hydrogen for 3 years, and 3) developing the ground testing infrastructure to test the NTP system at full scale and thrust.

14. How far along are other countries in advanced in-space propulsion? Are there any key technology areas in which the US does not lead?

Answer: Both China and Russia currently have significant on-going Nuclear Electric Propulsion programs. To my knowledge they are investing in all of the required NEP subsystems: reactor, power conversion, power management, heat rejection and electric propulsion. The U.S. has not had a significant NEP program in 20 years, we have no program currently underway and to my knowledge no significant program is currently planned. The US, Europe, Japan, China, and Russia all have active and successful low-power solar electric propulsion programs, but to my knowledge only China and Russia have NEP programs. I'm not aware of Chinese or Russian investment in nuclear thermal propulsion, whereas the US has two NTP technology programs – the DARPA DRACO program and the NASA NTP program.

15. Highly enriched uranium (HEU) raises proliferation concerns and restricts the number of private sector organizations that could contribute to developments. Recent proposals have favored high assay low enriched uranium (HALEU) to address those concerns. But according to the Academy report, technical feasibility, performance, safety, fuel availability, cost, and schedule considerations do not favor HEU or HALEU. Should NASA make significant investments in space nuclear propulsion

before conducting a comprehensive assessment of the relative merits and challenges associated with HEU and HALEU?

Answer: The Academy report found that, from a technical perspective, either HEU or HALEU could be used for a space nuclear propulsion program. This means that we have the opportunity to make a selection based on other, non-technical factors such as proliferation concerns. Therefore, I think that the timing of space nuclear propulsion investments should be based on whether or not the United States plans to send Americans to Mars in the next 10 to 20 years. If so, then investments in both nuclear electric and nuclear thermal propulsion technologies are needed now so that we can make a timely, data-driven selection between the two options, and we can make the reactor fuel selection based on non-technical factors because technically, either HEU or HALEU will work for these applications.

16. Are their non-governmental markets for space nuclear propulsion systems?

Answer: Yes – there are non-governmental markets for space nuclear propulsion systems if we have a sustained presence on Mars. The critical aspect of a sustained presence will be to have a robust transportation system for supplying the American Mars presence, and this will require propulsion systems that are robust, capable of rapid round trips, cost-effective, and provided by the private sector. If our vision for the U.S. space enterprise is to have Americans on the Moon and Mars on a sustained basis starting in 10-20 years, we will need to have a robust and highly capable private-sector-based transportation system to support them. There are several companies that want to fill this need, but the US Government needs to get the technology risk low-enough for them to justify the required investment.

17. In May, China become the only non-U.S. country to successfully deploy a rover on the surface of Mars. Shortly afterwards, China announced that it intends to conduct crewed missions to Mars in 2033. The head of the China Academy of Launch Vehicle Technology indicated at the time that to shorten the travel time, spacecraft would have to tap energy released from nuclear reactions in the form of heat and electricity, in addition to traditional chemical propellants. What insight do we have into China's current capabilities regarding space nuclear propulsion? How much are they spending per year? Are their schedules realistic? Are they focusing on NTP or NTP? If they are focused on both, which technology is father along? Could they develop space nuclear propulsion before we do?

Answer: While my insights into the Chinese space nuclear propulsion program are restricted to their public statements and publications, I will say that the Chinese have in recent years published several detailed analyses of megawatt-class space nuclear reactors and very high-power electric propulsion systems for nuclear electric propulsion. While they are actively building and testing the 100-500kW MPD thruster systems, I do not know if they are actually building test space nuclear reactors and power systems, and I do not know how much they are spending or whether or not their schedules are realistic. It does appear that they are following a credible technical path that could lead to a nuclear electric propulsion system in the next 10-15 years, assuming that they start building and testing the reactors and power systems that they are currently analyzing. They appear to be on-track with the very high-power electric thruster technology. If they continue on this path and we do not initiate an NEP program, they could certainly develop such a system before we do. They have not, to my knowledge, invested in nuclear thermal propulsion systems. It is also important to note that the

Chinese investments in large, megawatt-class space reactor technology could also be applied to large-scale surface power systems.

18. Dr. Myers, in the National Academies report, your panel recommended "NASA should invigorate technology development associated with the fundamental nuclear thermal propulsion (NTP) challenge, which is to develop an NTP system that can heat its propellant to approximately 2700 K at the reactor exit for the duration of each burn. NASA should also invigorate technology development associated with the long-term storage of liquid hydrogen in space with minimal loss, the lack of adequate ground-based test facilities, and the need to rapidly bring an NTP system to full operating temperature (preferably in 1 min or less)." Do you believe NASA is poised to do this? Why or why not? In the same report, your panel also recommended "If NASA plans to apply nuclear electric propulsion (NEP) technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development." Do you believe NASA is poised to do this? Why or why not?

Answer: NASA does not have the resources to required to develop either NTP or NEP technology in time to support human missions to Mars in the 2030-2040 timeframe. Recent work on NTP fuels has shown we do not yet have a reactor fuel capable of achieving either the temperature or lifetime requirements for NTP and there is no certainty that we can develop such a fuel. The challenge with long-term storage of liquid hydrogen appears more manageable and to my knowledge is receiving appropriate investment, though it is important to note that some of the investments made in storage of liquid oxygen and methane are not relevant to the challenge of liquid hydrogen storage. There is also a very large challenge of ground testing the NTP systems at full scale and thrust – facilities must be developed to fully contain and scrub (clean) the rocket exhaust and it is not clear to me if any work is proceeding on this front. Similarly, NASA has not had any resources for NEP system development for over 20 years, and currently only has a small team working on planning an NEP development program should funding be provided. Without adequate funding for NEP NASA cannot make progress.

19. Solar power is limited by available surface area and distance from the sun. In the future, missions will likely require more and more power, and U.S. government investment in developing space based nuclear electric generation would be a great step forward. How would missions with nuclear thermal propulsion produce electricity for missions where solar is not a viable option? How would you assess the benefits of using nuclear electric propulsion that could provide ample for missions as well as propulsion? How should that characteristic be weighted in architecture decisions?

Answer: This is an excellent question that highlights one of the critical architectural decisions that needs to be made between NTP and NEP. At present, if missions use NTP they will require a separate power system, either solar or nuclear, for power generation. While there are conceptual designs for "bimodal" nuclear thermal propulsion systems that can also generate small amounts of power, it is important to recognize that there are very big differences between reactor designs for thermal propulsion (>2850K for less than 5 hours total operating time) and the designs for long term electric power (1200-1400K for 3-10 years total operating time) and many subsystems for reactor control and thermal management would need to change. Therefore, it is unclear if these proposed bimodal nuclear systems will in fact work, and they would certainly not work for surface power generation. Therefore, choosing an NTP-based propulsion architecture will require the parallel development of nuclear power systems should solar power not be viable. By contrast, NEP systems naturally provide electric power for the mission duration, and it is simply a matter of switching the output from the propulsion system to other loads (or driving them in parallel to the propulsion

system). Additionally, the design of NEP reactor power systems will be the same as those for large scale surface power systems – all of the major subsystems will be common to both propulsion and power) if an NEP-based architecture is selected. Of course, there will be some difference in the heat rejection system if it is operated in an atmosphere such as on Mars.

20. There have been exceptional advancements in high-power electric propulsion (EP) accelerated by recent investment from the private sector, such as in the NASA NextSTEP public private partnerships that led to the recent 88 hour endurance test of a VASIMR test engine. Additionally, electric propulsion innovation benefits from fusion energy development (now also accelerating with private investment) and the great advancements in power electronics for transportation and industry electrification. Yet, high-power electric propulsion development has suffered from low and intermittent investment over many decades. The National Academy of Sciences' panel recommended that the U.S. must accelerate a robust and sustained program to develop high-power electric propulsion thrusters needed to maintain and advance our leadership in space propulsion? How should NASA (and the federal government as a whole) invest in both incremental innovations, such as the Hall Effect Thruster, and disruptive innovations, such as the VASIMR engine?

Answer: The creation of a well-balanced technology development program must consider both the opportunities and risks of any candidate technologies to ensure that the selection process is not biased or conducted without data. For good reasons, over the past 20 years the US electric propulsion program has focused on low-power systems which have broad commercial and civil mission applications – as you say there has been little recent work in high power EP other than the NASA NextSTEP program, and that program suffered from low funding levels that prevented either Hall or VASIMR thruster technology from fully achieving their goals. There are really four potential high power electric propulsion candidate technologies for MW-class NEP systems: 1) xenon-fueled Hall thrusters, 2) xenon-fueled ion thrusters, 3) lithium-fueled magnetoplasmadynamic (MPD) thrusters and 4) VASIMR. When assessing the risks for the first-generation NEP vehicle, it is important to recognize that incremental innovations, if they are capable for the first-generation system, are inherently less risky (and thus very likely less costly) than disruptive innovations, which may be well suited for future applications. For this reason, based on my experience developing many flight electric propulsion systems for a wide range of applications, I would recommend that a high power electric propulsion development program for MWe-class NEP vehicles be primarily focused two technologies: 1) xenon-fueled Hall thrusters, which have been operated at higher power than VASIMR (albeit for shorter times at powers >100kW) and have extensive in-space operation experience at low power, and 2) lithium-fueled MPD thrusters, which have operated at 500kW for 500hrs (in Russia, with current design experience at NASA's Jet Propulsion Laboratory and Princeton University), but for which there are questions related to thruster life beyond several thousand hours. These are both incremental technologies which appear will meet the mission requirements for the first several human missions to Mars, but for which there are still risks which must be evaluated before a data-driven selection can be made between them. VASIMR, as a disruptive technology, should continue be supported as a research program to address key questions about its performance, lifetime, and spacecraft system integration requirements to ensure that we obtain all the necessary data to ensure it is truly capable of performing future missions before initiating a VASIMR development program.

21. What is the technology readiness level for current U.S. capabilities in each nuclear thermal propulsion and nuclear electric propulsion? How much additional investment of resources would be needed to fully mature each capability, and how long would that take before we could leverage that into a human mission to Mars?

Answer: In my assessment I would say that both NTP and NEP are currently at Technology Readiness Level 3. As stated in the National Academy's report, the risks for the two technologies are very different – NTP has fewer subsystems but three major challenges (a capable reactor fuel, multi-year storage of liquid hydrogen, and ground testing), whereas NEP has less fundamental challenges but more of them (scaling each of the five major subsystems by over 10 times from their current capabilities). As shown in the National Academy report it will take the United States 10-15 years to develop and fully qualify either NTP or NEP for human missions to Mars – if we expect to send Americans to Mars in the late 2030s we must start a serious program now in order to ensure we have the data we need to select the right technologies to fully develop and qualify. The National Academy committee did not consider costs in our deliberations but based on other studies, our current state of knowledge, as well as my experience developing flight propulsion systems, I would expected the required investment to fully develop and qualify either NTP or NEP systems will be similar and range from $3 to $10 billion dollars. This large range is driven by the significant current uncertainties in the technologies – we need to make some real progress in order to increase the certainty of the budget estimate.

22. Dr. Myers: In the National Academies report, your panel recommended "NASA should invigorate technology development associated with the fundamental nuclear thermal propulsion (NTP) challenge, which is to develop an NTP system that can heat its propellant to approximately 2700 K at the reactor exit for the duration of each burn. NASA should also invigorate technology development associated with the long-term storage of liquid hydrogen in space with minimal loss, the lack of adequate ground-based test facilities, and the need to rapidly bring an NTP system to full operating temperature (preferably in 1 min or less)." Do you believe NASA is poised to do this? Why or why not? In the same report, your panel also recommended "If NASA plans to apply nuclear electric propulsion (NEP) technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development." Do you believe NASA is poised to do this? Why or why not?

Answer: NASA does not currently have the resources required to develop either NTP or NEP system technology in time to support human missions to Mars in the 2030-2040 timeframe. Recent work on NTP fuels has shown that while we are making progress, we do not yet have a reactor fuel capable of meeting the either the temperature or lifetime requirements for NTP and there is no certainty that we can develop such a fuel. The challenge with long-term storage of liquid hydrogen appears more manageable and to my knowledge is receiving appropriate investment, though it is important to note that some of the investments made in storage of liquid oxygen and methane do not apply to the challenge of liquid hydrogen storage (with requires 20K storage temperature). There is also a very large challenge of ground testing the NTP systems at full scale and thrust – facilities must be developed to fully contain and scrub (clean) the rocket exhaust. Similarly, NASA has not had any resources for NEP system development for over 20 years, and currently only has a small team working on planning an NEP system development program should funding be provided. Without adequate funding for NEP NASA cannot make progress.

23. Dr. Myers: You indicated that the MPD thruster operated for 500 hours at 500 kW. Could you elaborate on that test? Where was it conducted? Can you point us to the publication where the test results are presented?

Answer: This specific "500kW-for-500hr test" of a lithium-fueled MPD thruster was performed in Russia and the results published in "High-current stationary plasma accelerator of high Power," by V.P. Ageyev, V.P. Ostrovsky, and V.A. Petrosov, as paper IEPC-1993-117 in the 23rd International Electric Propulsion Conference, July 1993. It is available for free download from the Electric Rocket Propulsion Society webpage (www.electricrocket.org, under the IEPC article repository link). I have discussed the results with that research team and am confident they are highly qualified and have done excellent work. However, while very encouraging, it is important to note that 500hrs (or 88 hours) is a small fraction of what is required for the Mars mission (which will be over 10,000 hours). Projected lifetime for the 500kW thruster in the original test was several thousand hours. More recently, in 2019, Princeton University has collaborated with NASA JPL to develop multi-channel lithium MPD thruster hollow cathodes to further mitigate those lifetime concerns, which were successfully demonstrated at Princeton by testing a 30kW-class lithium-fueled MPD thruster. Additionally, Princeton and JPL have all the design experience required for MW-class lithium MPD thrusters, and JPL and has prepared a test facility capable of continuous (>5000 hour) testing of 1 MW lithium MPD thrusters. For all of these reasons, based on my experience, I believe that lithium MPD thrusters are a good candidate for the MW-class NEP systems, but there is still significant risk with the technology – we need more data before we can confidently select any EP thruster technology (Hall, MPD or VASIMR).

24. When NASA compares NTP to NEP it compares an NTP system that operates at hundreds of MW with an NEP system that operates at 1 MW plus a chemical boost. How can you achieve an "apples to apples" comparison of two nuclear systems that are so dissimilar in power? It would appear a-priori that the result would tend to lean in favor the NTP system. By the choice of this comparison, it would appear as if NASA were down selecting the NEP system to be made up of clusters of the 13 kW Hall thruster, the same thruster selected for the Gateway PPP. Why is NASA not considering higher power electric thrusters such as the VASIMR or the MPD in this comparison? Why does NASA not compare NTP and NEP systems of comparable power?

Answer: When comparing NTP and NEP it is important to remember that the total energy imparted by the propulsion system is the operating power multiplied by the operating time. In other words, while NTP would operate at 500MW it would only operate for less than 5 hours over the entire mission, with each burn lasting less than ½ hr. By contrast, the current expected NEP power ranges from 2 to 4 MW, but it operates for over 10,000 hours. This means that the total energy imparted by the NEP system is actually greater than the energy imparted by the NTP system – but it does so much more slowly, gradually imparting the energy to the vehicle. In aggregate, the net effect of all of this for the short-stay human mission to Mars is that either NTP or NEP can do the mission, but that the two systems do their jobs very differently. To my knowledge NASA assessments do not currently favor either NTP or NEP at this point – either system must perform the same mission (but in different ways). Of course, it is important to realize that NTP is receiving directed funding, whereas there is no current funding for NEP. The NEP technology options that NASA is including in their current trade studies include 100kW xenon-fueled Hall thrusters and 1MW lithium-fueled MPD thrusters. There is no consideration for using 13kW Hall thrusters for the MW-class NEP mission.

Submitted by Mr. Sherman

1. The use of nuclear propulsion in space holds great promise for enabling human exploration. However, previous nuclear propulsion programs, such as the SP-100 Satellite and the Jupiter Icy Moons Orbiter, were canceled due to difficulties in maturing nuclear propulsion technologies. Additionally, changes in NASA's priorities during different Presidential Administrations disrupted any continuity of purpose for the fielding of these cutting-edge nuclear programs. Does NASA now understand how to prioritize investments in nuclear propulsion technology such that we can get the ball over the goal line? Is there a focused purpose of effort to field and fly these systems? What is different today than in the past?

Answer: This is an excellent question and raises some important issues. In my opinion NASA's desired technical development plan, with a balanced technology assessment between NTP and NEP for 3-4 years followed by a down-selection to one of the two based on the results at that point, with full scale flight development and production of the selected system following the selection, is a good technical plan. We do not currently have the necessary data to make an informed selection between NTP or NEP to ensure we do not select a dead-end technology – we must be very confident that we can mitigate the key risks identified in the National Academy study before we make the selection.. Based on my experience this technical plan is a good one. However, NASA has not had the resources to support this technical plan, so the result is that little work is performed. At present the only significant work is for NTP, which has received directed funding, and while good progress is being made the NTP risks have not been mitigated to any significant extent. Almost no work is being done on NEP because there has been no funding. What is different today than in the past is that technically, technology has advanced, and we have far more sophisticated modeling and simulation capabilities than we did in the past, which has enabled us to do far more detailed design work without actually building a system. Advances in various technologies – including HALEU reactors and cryogenic fluid storage for NTP as well as power reactors, power conversion, power management and distribution and electric propulsion for NEP have decreased the risk for NTP and NEP, but there are still major risks to mitigated. From a programmatic perspective, the urgency of establishing capabilities for human missions to Mars has increased significantly with China's technology advances and stated intention to send taikonauts to Mars – the U.S. is no longer the only nation planning such missions.

Submitted by Mr. Crist

1. In the National Academies report, your panel recommended "NASA should invigorate technology development associated with the fundamental nuclear thermal propulsion (NTP) challenge, which is to develop an NTP system that can heat its propellant to approximately 2700 K at the reactor exit for the duration of each burn. NASA should also invigorate technology development associated with the long-term storage of liquid hydrogen in space with minimal loss, the lack of adequate ground-based test facilities, and the need to rapidly bring an NTP system to full operating temperature." a. Do you believe NASA is poised to do this? Why or why not?

b. In the same report, your panel also recommended "If NASA plans to apply nuclear electric propulsion (NEP) technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development." Do you believe NASA is poised to do this? Why or why not?

Answer to 1a and 1b: NASA does not currently have the resources required to develop either NTP or NEP system technology in time to support human missions to Mars in the 2030-2040 timeframe.

Recent work on NTP fuels has shown that while we are making progress, we do not yet have a reactor fuel capable of meeting the either the temperature or lifetime requirements for NTP and there is no certainty that we can develop such a fuel. The challenge with long-term storage of liquid hydrogen appears more manageable and to my knowledge is receiving appropriate investment, though it is important to note that some of the investments made in storage of liquid oxygen and methane do not apply to the challenge of liquid hydrogen storage (with requires 20K storage temperature). There is also a very large challenge of ground testing the NTP systems at full scale and thrust – facilities must be developed to fully contain and scrub (clean) the rocket exhaust. While there have been conceptual designs of such test facilities there has not been a detailed design or full environmental assessment, both of which will be necessary prior to securing funding for this major testing infrastructure. Similarly, NASA has not had any resources for NEP system development for over 20 years, and currently only has a small team working on planning an NEP system development program should funding be provided. The technical plan that the team is developing is a good plan that I support, but without adequate funding for NEP, NASA cannot make progress.

2. When NASA compares NTP to NEP, it compares an NTP system that operates at hundreds of MW with an NEP system that operates at 1 MW plus a chemical boost. How can you achieve an "apples to apples" comparison of two nuclear systems that are so dissimilar in power?

Answer: When comparing NTP and NEP it is important to remember that the total energy imparted by the propulsion system is the operating power multiplied by the operating time. In other words, while NTP would operate at 500MW it would only operate for less than 5 hours over the entire mission, with each burn lasting less than ½ hr. By contrast, the current expected NEP power ranges from 2 to 4 MW, but it operates for over 10,000 hours. This means that the total energy imparted by the NEP system is actually greater than the energy imparted by the NTP system – but it does so much more slowly, gradually imparting the energy to the vehicle. In aggregate, the net effect of all of this is that either NTP or NEP can do the short-stay (opposition) mission, but that the two systems do their jobs very differently. To my knowledge NASA assessments do not currently favor either NTP or NEP – either system must perform the same mission (but in different ways) and there is currently significant uncertainty with both systems. We need to make further technical progress before selecting one or the other systems to ensure we don't choose a dead-end technology. Of course it is also important to realize that NTP has received significant directed funding, whereas NEP has not.

Responses by Dr. Bhavya Lal

Questions for the Record to Dr. Bhavya Lal

U.S. House of Representatives Committee on Science, Space and Technology
Space & Aeronautics Subcommittee Hearing
Accelerating Deep Space Travel with Space Nuclear Propulsion
Wednesday, October 20, 2021

Submitted by Chairman Beyer

1. Your prepared statement noted that "realizing [nuclear propulsion capabilities] would require sustained commitment and substantial investment over the next 10-20 years."

a. Has NASA assessed what level of investment would be required?

A: Rough estimates in the tens of billions of dollars for an operational system have been proposed. However, NASA does not have a definitized cost estimate for nuclear propulsion at this time. Any projected estimates, whether by NASA or by external entities, would have a high degree of uncertainty due to the low maturity of key technologies and anticipated difficulty of advancing engineering solutions (for example, the need for a ground test facility and the cost of building it).

b. Under NASA's current funding for space nuclear propulsion, when would an operational capability be achieved?

A: NASA does not have a definitized schedule estimate for nuclear propulsion at this time.

2. Congress has appropriated more than $400 million over the past five years specifically for NASA to do nuclear thermal propulsion (NTP) work, toward an in-space demonstration.

a. What has NASA accomplished in that time? What have we learned?

A: NASA has made notable progress toward key technology challenges including identifying high-temperature fission fuels and reactor materials; establishing feasible reactor designs; and advancing cryogenic fluid management technologies. Providing engineering solutions for each of these areas is critical to reducing the risk to conducting a meaningful flight demonstration for NTP.

- In collaboration with the Department of Defense (DOD), NASA is establishing a commercial source for carbide ceramic fuel that can satisfy the fuel production needs for DOD's Pele project and NASA's nuclear propulsion project. Carbide ceramic fuels have the high operating temperature capability needed for an NTP rector.
- Fuel development and tests performed in FY 2020-2021 have yielded data that now informs the design needs of prototypical reactor subsystems. Successful tests on a solid core fuel element approach have been used to baseline a reference reactor design. The reference reactor design is now guiding additional reactor material developments, and was used to inform a solicitation for industry-led reactor designs.

- NASA conducted irradiation tests on a selection of reactor and turbine machinery materials, and is developing a materials property database. These efforts have resulted in two potential materials for a subscale chamber nozzle. These materials show high resistance to hydrogen embrittlement and tolerance against irradiation damage.
- NASA has funded commercial industry for the design of high temperature reactors. These industry-led efforts will produce prototype designs that have performance capabilities consistent with mission needs. Products delivered by industry will include preliminary reactor designs, reactor manufacturing approaches, and test approaches that demonstrate operational feasibility.
- NASA selected four industry-led partnership awards that will advance cryogenic fluid management (CFM) technologies, a critical capability for nuclear propulsion for long term storage of cryogens in-space and on the surface of the Moon, Mars and other planetary bodies, through flight demonstrations. Each of these development efforts will pave the way to the design and build of an engineering subscale engine.

b. When does NASA anticipate conducting an in-space demonstration of an NTP system under current funding levels?

A: NASA's near-term focus has been to address the critical NTP reactor design challenges that will enable an integrated demonstration while also pursuing separate flight demonstrations of long-term storage and transfer of cryogenic fluids in space. Cryogenic storage and transfer is a critical capability need for future NTP flight demonstrations. While more development remains, there has also been substantial progress in the development of critical NTP reactor technologies that begin to allow more detailed planning and development for integrated demonstrations, including consideration of collaborative efforts with DARPA. However, as mentioned previously, NASA does not have a definitized schedule estimate for nuclear propulsion at this time.

3. In July of this year, NASA, in partnership with the Department of Energy, selected three reactor design concept proposals for a nuclear thermal propulsion, or NTP, system at $5 million each.

a. What is the role of the Department of Energy in this program?

A: The Department of Energy provides knowledge of industry capabilities, subject matter experts for technical oversight, management of the contracted efforts, and application of its authorized indemnification policies for the industry performers. The full cost of the Department of Energy's support is reimbursed by NASA.

b. When the twelve-month award period ends, what will NASA do with the designs, and what are the next steps for the NTP program?

A: Industry will develop multiple preliminary reactor designs that can meet NASA's NTP requirements. These preliminary designs will be used by NASA to inform a potential follow-on solicitation to industry for a more detailed design and subsystem testing that can feasibly demonstrate predicted operation with high confidence.

4. The three NTP reactor design concept proposals NASA selected this summer for $5 million awards will pursue designs using high-assay low-enriched uranium (HALEU).

a. Has NASA made a firm decision on whether to use HALEU for nuclear propulsion systems moving forward, rather than highly enriched uranium, or HEU? If not, when will such a decision be made?

A: Based on guidance from Space Policy Directive-6 issued by the White House in 2020, NASA has decided that it will use High Assay Low-Enriched Uranium (HALEU) for space nuclear power and propulsion applications. Using HALEU for space nuclear applications will increase mass requirements and require solutions to additional challenges, but the technology approach appears to be viable. As discussed below, use of HALEU has some ancillary benefits as well.

b. Has NASA conducted the comprehensive assessment of the relative merits and challenges of HEU and HALEU for nuclear thermal and nuclear electric propulsion that was recommended by the National Academies report?

A: NASA had previously conducted studies on HEU versus HALEU designs for nuclear propulsion systems to meet the requirements of a human Mars mission. NASA has not shared these studies with the Academy given the export-controlled nature of their content and the open and public nature of the Academy's activities. These studies confirmed that reactor designs using HEU can be simpler, lighter, and smaller, but design studies on HALEU powered reactors show no practical limitation to pivoting to HALEU. HEU reactors will always be smaller and lighter, but the projected size and mass for a HALEU reactor is less than 15% greater than HEU designs. Predicted advances in moderated thermal fission reactor technologies and designs could offer capabilities that could make HALEU fueled systems mass-competitive, feasible and viable.

In addition, advancing HALEU designs allows for strong alignment with industry and the ability to leverage terrestrial commercial power technologies. Other considerations that support NASA's focus on HALEU include: the reduced security and regulatory burden and compliance with Space Policy Directive-6 which limits use of highly enriched uranium (HEU) to applications where it is clear that mission objectives cannot be met with other nuclear fuels or non-nuclear power sources. Regulatory requirements for HALEU reactors also provide opportunity for university engagements and commercial licensing with the Nuclear Regulatory Commission (NRC). Finally, HALEU-based designs open the trade space for facilities capable of performing integrated system tests and evaluations, which has the potential to reduce development cost and schedule.

5. Under the Artemis initiative, NASA is contracting with commercial industry on the development of solar electric propulsion thrusters for the Power and Propulsion Element (PPE) of the Gateway. To what extent can the PPE systems be leveraged to advance nuclear electric capabilities?

A: The 12 kW thrusters being developed for Gateway's PPE can provide a stepping stone to larger-scale thrusters needed for nuclear electric propulsion (NEP). Both solar electric propulsion (SEP) and NEP thrusters will operate at similar specific impulse (Isp), voltage and efficiency as the 100 kW-class thrusters envisioned for NEP. Also, flight operation of the SEP thrusters will help to validate design codes that can be applied to larger NEP systems.

6. You stated, during the question-and-answer portion of the hearing, that NASA has conducted the comprehensive, objective trade study between an NTP and nuclear electric propulsion (NEP) system, as recommended by the National Academies report, and that the study is currently under external review.

a. When does NASA expect the review to be completed, and will the study be made public?

A: The study is currently being reviewed by independent external experts, and NASA does not know the date of completion for this step.

b. When does NASA plan to decide on which method—NTP or NEP—will be the propulsion system for the first human mission to Mars?

A: NASA has not selected a specific propulsion system – nuclear or otherwise – for an eventual crewed mission to Mars. Despite the potential benefits for nuclear propulsion systems, both NTP and NEP technologies are nascent, and face steep developmental challenges. It is unclear at this time whether the benefits offered by nuclear propulsion in terms of reduced transit time to Mars outweigh their costs. NASA has identified a series of subsystem and integrated system tests that can be conducted on the ground that, if successful, provide the critical information needed to reduce the current level of uncertainty to selecting NEP or NTP. These tests would be used to demonstrate feasibility and collect critical performance data.

c. What will inform the decision, and will NASA make this decision, or will it be a cross-agency decision?

A: NASA is conducting a series of broad trade studies that evaluate various propulsion technologies (including SEP, chemical propulsion systems, NTP, and NEP) in the context of broader considerations related to a crewed mission to Mars, such as total time on the surface, surface systems required to support astronauts, human health and performance requirements, logistics requirements, and many others. An eventual decision on propulsion technologies will be made in light of these broader factors and will require extensive consultation across NASA. Given the expense and time required to develop an NEP or NTP system, agencies should work collaboratively to develop technologies and systems that are compatible with all potential government applications.

d. Does NASA intend to maintain development efforts for both NTP and NEP systems after choosing one for the first crewed Mars mission?

A: Notwithstanding the selection of a nuclear or non-nuclear propulsion system for a crewed Mars mission, NASA sees potential benefit in both nuclear capabilities when considering a range of missions that are of importance. Small NEP systems could potentially support advanced science at hard-to-get-to destinations deep in the solar system and beyond. Furthermore, the range of human exploration missions could benefit from both NEP and NTP systems, where each excels in unique applications: NTP for agile, quick response maneuvers for mission abort scenarios, and NEP for high delta-V missions and long-term, efficient transfer of large masses.

7. How is NASA engaging with commercial industry on advancing space nuclear propulsion? What roles do you see for industry in the development, testing, production, and/or operation of space nuclear propulsion systems?

A: NASA has contracted efforts with industry that will produce low-fidelity designs for high-temperature reactors that satisfy performance metrics consistent with mission needs. Products delivered by industry will include the preliminary reactor designs, potential manufacturing approaches, and proposed test approaches that prove operational feasibility.

NASA also has industry-led contracts that are advancing CFM technologies through flight demonstrations. Once completed, these industry efforts will be used to inform government and industry led efforts to establish and demonstrate an integrated capability.

8. During the question-and-answer portion of the hearing, Dr. Myers stated that the National Academies committee determined that "you really need to test full scale, fully integrated systems

for nuclear thermal [propulsion]" on the ground before going to space. What are NASA's perspectives on the appropriate stage in the development process for an in-space demonstration, and the need first, for full-scale ground testing?

A: Most experts believe that ground demonstrations, while expensive, are the preferred engineering approach to effectively manage a flight development with acceptable risk. NASA's perspective is that a flight demonstration has increased technical value when done following a successful ground demonstration of the completed design. Performing a flight demonstration first may be the right choice if key aspects of capability cannot be adequately captured by a ground test and results from a successful flight test are needed to feed a final design. NASA's current efforts are aimed at a subscale NTP engine design that could support a potential demonstration. A successful ground demonstration of the subscale engine would validate technology maturity and reduce engineering risk to scaling up that design to a full-scale engine. Future decisions on the ground demonstration of full scale, fully integrated system should follow and be driven by the outcome of sub-scale test results and strategic level decisions on mission architecture that have not yet been made.

9. During the question-and-answer portion of the hearing, you noted that NASA's work in surface power has extensibility to NEP and that NASA is looking at 10-40 kilowatt systems for surface power. You also discussed that for a human mission to Mars, NASA would need to look at two megawatts, "so there's a lot of extensibility that needs to happen from surface power to NEP."

a. What, in particular, would be needed to extend current capabilities in surface power to an operational NEP system?

A: A 40 kilowatt electrical surface power system is small in comparison to a megawatt-class fission power plant needed for a human mission to Mars that employs NEP, but there are features from the design that can inform requirements for scaling up the power level. We envision that we can take advantage of certain technologies used in the construction of a small surface power plant, such as the moderator material and fission fuel form, in the construction of a much larger megawatt level electrical system which will greatly reduce the design risks. Other potential opportunities for leveraging include the reactor primary heat transport, radiator heat transfer loop, radiator panel design and construction, and high-voltage power management and distribution systems. There are a number of intrinsic benefits as well. Those include qualified vendors for space power reactors, commercial-based fuel production and fuel qualification, reactor ground test facilities, and an established process for launch safety and approval that is directly applicable to NEP power reactors.

It is important to note that developing a humans-to-Mars-scale NEP power plant will need many more technological advances than just scaling up the reactor. High-risk components that will need additional development to apply specifically to NEP application include the power conversion system, active loops for the thermal working fluids, and the power management and distribution system. While a 40 kilowatt surface system is not expected to provide a design basis for these elements, evolution in the design of a higher power surface plants will likely have improved alignment with a NEP power system. A 40-kW power system has potential extensibility to a smaller, science-scale NEP system.

b. What are the power capabilities of solar electric propulsion technologies NASA is developing now, and to what extent could they scale or otherwise extend to the technologies needed for deep-space nuclear electric propulsion capabilities?

A: NASA is developing and qualifying a 12kW class electric propulsion system that will be qualified for flight and demonstrated on the Gateway Power and Propulsion Element. The solar power systems in SEP are distinctly different from the nuclear power systems used in NEP. SEP requires large solar arrays to collect sunlight that is converted to electricity using photovoltaic cells. The power produced by the solar arrays decreases at greater distances from the sun, so a Mars SEP power system must be oversized (more than double the number of arrays) to account for the approximate 65% reduction in solar flux at Mars, making this method of power supply increasingly impractical.

NEP requires a fission reactor and thermodynamic heat engines that generate electricity from the reactor heat energy. The fission power system can produce constant power regardless of sunlight or location, making it a useful option for missions to Mars and beyond. Nuclear power also offers an advantage relative to the amount of power that can be supplied to the thrusters.

There are some common technologies that will be used in SEP missions that can benefit future NEP missions. Both systems require high voltage, radiation tolerant electronics to manage and distribute the electric power; and the electric thrusters used in SEP missions provide a stepping-stone to the larger thrusters envisioned for NEP with similar design features, operating characteristics, and the same xenon propellant supply.

10. What is NASA's architecture and plan for the human exploration of Mars? Does it include space nuclear propulsion?

A: NASA's architecture and plans for the human exploration of Mars are in development. The high-level Moon to Mars concept includes human exploration of Mars after demonstrating critical hardware and operational scenarios around and on the Moon. This includes performing Mars analog missions at the Moon to understand the impact of the long duration transit time to Mars followed by a low gravity environment on the humans. NASA is evaluating alternative architectures for the first missions to Mars that would include an assessment of whether the mission should be a longer-stay conjunction class mission or a short-stay opposition class mission. We are also evaluating transportation options which include both chemical and space nuclear propulsion options. The timeline for developing these capabilities is strongly dependent on priorities and approved budgets.

Submitted by Mr. Babin

1. How are the SNPP programs within the USG coordinated by the White House?

A: In the last 5 years, the White House has developed four policy documents to direct and coordinate the development of space nuclear systems within the USG. In 2019 the White House released National Security Presidential Memorandum-20 – Launch of Spacecraft Containing Space Nuclear Systems – that describes the process for launching space nuclear systems by both commercial and government entities. In 2020, Space Policy Directive 6 – National Strategy for Space Nuclear Power and Propulsion – describes the strategy for the development of space nuclear systems. In 2021, the White House issued Executive Order 13972 – Promoting Small Modular Reactors for National Defense and Space Exploration. EO 13972 tasks NASA with developing a coordinated roadmap for its space nuclear power and propulsion systems. Lastly, the 2020 National Space Policy (NSP) notes that the United States will develop and use space nuclear

power and propulsion (SNPP) systems where such systems enable achievement of United States scientific, national security, and commercial objectives. The 2020 NSP also describes the roles and responsibilities of Federal agencies in the development, launch and operation of space nuclear systems. All four documents were developed in coordination with NASA and other relevant USG agencies to provide a framework for coordinating the development of nuclear systems within the USG.

2. What department is responsible for the development (and funding) of uranium fuel processing capabilities that enable production of fuel that is suitable to lunar and planetary surface and in-space power, nuclear electric propulsion (NEP), and nuclear thermal propulsion (NTP) applications?

A: The Department of Energy (DOE) is responsible for the processing and production of enriched uranium for NASA. NASA has the responsibility of using the uranium supplied by the DOE to advance high temperature fuel chemistries and fuel forms. NASA reimburses DOE for its support for reactor technology maturation efforts, industry engagements, contract management, and general expertise..

3. How are the uranium fuel forms being developed to enable a range of terrestrial as well as space applications, including future commercial applications, and maximizing private-sector engagement and cost savings?

A: In collaboration with DOD, NASA is working to establish a commercial source for a common fuel manufacturing capability that will be available to NASA, DOD, and industry. NASA's collaboration with DOD and industry has also funded reactor designs that would potentially use a common commercial fuel production source to maximize private-sector engagement. Successful development of materials and fuels, together with the reactor design, can result in smaller and more efficient terrestrial reactors and align with DOE Small Modular Reactors goals.

4. What is the power range for the current demonstration of a fission power system on the surface of the Moon? How is that program aligned with mission needs for, and potential future government and commercial applications of, in-space power, NEP, and terrestrial nuclear power?

A: NASA recently released a solicitation through the DOE asking American companies for design concepts for a minimum of 40 kWe fission surface power system for lunar demonstration. This capacity will provide power to run an In Situ Resource Utilization pilot plant along with other related surface operations, and the size and mass requirements also align with NASA stakeholder-informed needs for Mars. The system serves as a steppingstone to much higher power systems of interest to industry for extended lunar operations and related surface operations on both the Moon and Mars.

5. In August 2019, the National Security Presidential Memorandum 20 (NSPM-20) was updated to establish safety guidelines and safety analysis and review processes for Federal Government launches of spacecraft containing space nuclear systems, including SNPP systems, and for launches for which the Department of Transportation has statutory authority to license as commercial space launch activities (commercial launches). How have these new guidelines improved the development of SNPP systems?

A: The most significant benefits of NSPM-20 are the three tiers it defined, based on quantified exposure risks, that differentiate launch approval authority based on the risk associated with the

launch of the payload. These quantified risk tiers, and associated Safety Guidelines, provide a basis for mission planning and hardware design. Other benefits include a defined role for the Interagency Nuclear Safety Review Board with clear responsibilities that do not overlap with those of the executing program. NSPM-20 also describes how the private sector could safely develop and launch space nuclear systems with proper regulatory oversight.

6. In December 2020, the National Strategy for Space Nuclear Power and Propulsion (SPD-6) was issued by the White House. The memorandum established a national strategy to ensure the development and use of SNPP systems when appropriate to enable and achieve the scientific, exploration, national security, and commercial objectives of the United States.

a. How is NASA coordinating activities with other agencies like the Department of Defense, that are also looking into space nuclear propulsion?

A: NASA, the DOD, and DOE continue to collaborate on developing advanced space nuclear power and propulsion capabilities. NASA is partnered with DOD to establish a commercial fuel production capability for mobile terrestrial reactors and space nuclear systems. In addition, NASA participates with DARPA to establish National Environmental Policy Act processes that both organizations can adopt. NASA is directly engaged with technology development activities supporting DARPA's Demonstration Rocket for Agile Cislunar Operations (DRACO) program. NASA is also drafting design practices and standards that are shared with other stakeholder agencies. Though agency mission needs differ, interagency collaboration is focused on achieving common goals that can lead to a more unified and comprehensive approach to mature critical nuclear capabilities.

b. How is NASA coordinating activities with other agencies like the Department of Energy, that are also looking into nuclear fuel processing and reactor designs?

A: NASA has a long history of successfully working with DOE on space nuclear systems that include both radioisotope and fission systems. NASA relies on DOE as the Federal government's subject matter experts for fuel development and fission reactor design, and works to leverage this expertise through cost reimbursable agreements. While the formal inter-agency relationship relies on cost-reimbursement mechanisms, NASA has developed strong cooperative ties with DOE that include exploring coordinated solutions that leverage the resources and capabilities across both federal agencies and support engagements with industry organizations that will better position the eventual commercialization of emerging nuclear capabilities. DOE also offers technology and design experience gained from terrestrial nuclear power programs that could impact space power systems, such as the Advanced Reactor Demonstration program.

c. How is NASA cooperating with international partners to achieve the goals set out in this strategy?

A: NASA participates in international technical communities related to space nuclear power and propulsion, but due to the sensitive nature of the emerging capabilities and the competitive edge those capabilities are envisioned to provide, NASA has to date not sought collaboration with international partners with regards to nuclear power and propulsion. NASA is maintaining awareness of international efforts on space nuclear systems by participating in activities such as the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) and International Space Exploration Coordination Group (ISECG) Nuclear Power and Propulsion Gap Assessment Team.

d. How is NASA coordinating with the Department of State when seeking opportunities for international partnerships?

A: Due to the sensitive nature of the emerging technology and the competitive edge they are envisioned to provide, NASA has to date not sought collaboration with international partners with regards to nuclear power and propulsion.

However, the State Department serves as the head of delegation for the U.S. Government's participation in the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS). DOE and NASA are the primary U.S. Delegation participants in the UNCOPUOS Scientific and Technical Subcommittee Working Group on the Use of Nuclear Power Sources in Outer Space (NPS WG). The NPS WG is a useful forum open to all UN COPUOS Member States and observer international organizations to discuss the safe use of nuclear power in outer space.

7. In January, Executive Order 13972 tasked the NASA Administrator to define the requirements for NASA utilization of nuclear energy systems for human and robotic exploration missions through 2040 and analyze the costs and benefits of such requirements with 180 days (sometime in July). Has NASA completed this report? If so, when will the report be made public?

A: NASA has completed the report and is now conducting an internal review. The report will be shared with the public on the NASA website once it has been cleared for release in mid-2022.

8. Which uranium fuel forms are needed to meet the nearest-term mission needs? How are they utilizing the same or similar materials, processes, designs, or infrastructure — across these fuel forms?

A: The nearest term need is for an approximately 40 kWe reactor to operate on the surface of the Moon, in support of robust surface exploration activities. Such a space power reactor needs to operate for years but does not require the extreme temperatures of nuclear propulsion reactor, making fuel form and reactor design easier. NASA has no definitive requirements for a nuclear propulsion system in the near term. The nearest term potential mission utilizing a nuclear propulsion system would be an NTP or NEP system that could be used for a human mission to Mars.. For both applications, NASA is chiefly interested in ceramic carbide fuel chemistries due to the potential for higher temperature capability and having a manufactured form that directly aligns with fuel forms processed for terrestrial reactors. NASA is studying the potential to develop commonality in not just the fuel form, but in the fuel manufacturing facilities, and related infrastructure to maximize benefits and minimize investments for a range of applications.

9. Are the uranium fuel forms to meet near-term mission requirements maximizing private-sector engagement? Will these fuel forms be developed to enable a range of terrestrial as well as space applications, including future commercial applications?

A: Yes, NASA activities related to space nuclear systems are attempting to maximize private sector engagement. All three of the industry-led reactor design awards propose using the same terrestrial-based fuel manufacturing method as the government Test Reference Design. NASA, in collaboration with DOD, has made a partnered investment to establish a commercial source for a common manufacturing capability that will be available to NASA, DOD, and industry. NASA collaboration with DOD and industry funded reactor designs have the potential to use a common commercial fuel production source that will maximize private-sector engagement.

10. How are departments and agencies collaborating on SNPP systems? Are they conducting regular technical exchanges among SNPP programs?

A: Technical leaders at NASA, DOD, and DOE meet regularly to coordinate efforts and identify potential synergies to program goals and objectives. Where feasible, interagency collaborations focus on achieving these goals and objectives using leveraged resources. Technical exchange meetings also occur regularly through professional associations, conference attendance, and open invitation to program design reviews. DOD and DOE subject matter experts are often members of independent review teams at NASA reviews, and NASA experts serve in a similar role at DOD and DOE reviews.

11. Commonality, such as reactor designs, nuclear fuels, infrastructure, and testing, among SNPP systems, and between SNPP and terrestrial nuclear systems, will greatly increase the development and advancement of SNPP programs. How are DoD and NASA working with partners to evaluate and use opportunities for commonality with other SNPP needs, terrestrial power needs, and reactor demonstration projects planned by agencies and the private sector?

A: There is a concerted interagency effort to build partnerships and explore common solutions that effectively leverage the expertise and capabilities across stakeholder federal and commercial organizations. The goal is to encourage a more unified and comprehensive approach to maturing critical nuclear technologies. While the nuclear industrial base has traditionally been small, it is growing, and NASA has a strong desire to engage innovative companies that seek to join the growing commercial interest in a space economy.

12. "Extensibility" is the concept that technologies developed in the near-term will be useful for future exploration as well. Extensibility prevents the development of "dead-end" capabilities. How is NASA ensuring that its investments in space nuclear propulsion are extensible?

A: NASA space nuclear power and propulsion investments focus on satisfying defined mission needs that are both near-term (~10 years for lunar missions) and far-term (~20+ years for Mars missions and advanced science mission applications). The strategy used to implement and develop a mission nuclear capability is forward looking with envisioned growth to ancillary systems that can be derived from a near-term solution. NASA recognizes that one-size-fits-all technologies are rare and often accompanied with performance sacrifices (and the history of joint development of large systems shows many failures), but there are areas worth exploring, including establishing common manufacturing methods, fuel chemistries, moderator materials, radiation shielding, and power conversion systems where the greater benefit to space nuclear technology development can outweigh the need to optimize the performance of a point design.

13. When will NASA need space nuclear propulsion capabilities? What architecture and strategic planning informs that schedule?

A: NASA's Moon to Mars initiative includes human exploration of Mars after demonstrating critical hardware and operational scenarios around and on the Moon in the 2020s and 2030s. This includes performing Mars analog missions at the Moon to understand the impact of the long duration transit time to Mars followed by a low gravity environment on the humans. NASA is assessing several architecture alternatives including transportation options which do and do not include space nuclear propulsion. The timeline for developing these capabilities is strongly dependent on priorities and approved budgets.

14. How should the government synergize nuclear surface power generation and space nuclear propulsion development?

A: NASA's goal for developing a HALEU nuclear surface power plant is to have a small, low mass system that is simple and reliable. Many experts believe that moderated thermal reactors have the greatest potential to achieve to reduce and optimize overall system mass and volume. Developing a fission surface power system with low mass and sufficient lifetime can be applied to small NEP missions, such as those relevant to planetary science, and serve as a technology precursor for larger NEP systems that could support human exploration.

Both NEP and NTP are similarly required to have minimal size and mass reactors, and overlapping technology elements for fuel form, moderator material and design attributes are envisioned. Whenever possible and practical, NASA is emphasizing technology developments that share commonality and synergy across each nuclear capability. However, NASA requires surface power before propulsion, and, as such, the development of surface power should be prioritized.

15. How is NASA coordinating current investments in cryogenic propellant storage and transfer so that it could be applicable for space nuclear propulsion?

A: NASA and DOD have identified common high-level technology interests for cryogenic fluid management (CFM), fission fuels, and reactor designs. For example, one of NASA's CFM industry partners is also a contractor to DARPA for vehicle design and integration. Advanced on-orbit cryogenic fluid storage is needed by both NASA and DOD efforts to ensure long-term storage and transport of hydrogen propellant. Areas for collaboration include cryogenic coolers, high-efficiency insulators, and predictive modeling. These are areas where NASA has long-term investments and experience that can add value to DOD mission. NASA's has public-private CFM technology development efforts that also address capability interests of DOD, and the successful demonstration of these capabilities will retire several technology risks for both organizations, particularly since.

16. How much is NASA requesting in fiscal year 2022 budget for nuclear thermal and nuclear electric propulsion, including component systems?

A: The FY 2022 budget request did not include direct investments in nuclear propulsion. The budget request included funding for nuclear surface power because it is a nearer-term priority as compared with nuclear propulsion. The FY 2022 budget does include Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) related technology investments that also have a broader application to cis-lunar and lunar surface operations including:

- Cryogenic fluid management technologies, which are key for nuclear propulsion due to this technology's need for long term storage of cryogens in-space, and are also key to supporting other activities on the surface Moon, such as advanced human landers and In situ resource utilization.
- Fission surface power, which is a key capability needed for near-term lunar surface missions. NASA is prioritizing investments in this technology over Mars-related long-term technology investment such as nuclear propulsion, but it also shares common technologies with NEP for the reactor design, materials, and power conversion subsystems.

- Space-rated power conversion systems, power reactor materials, and lightweight shielding.

NASA looks forward to working with Congress to develop a balanced, requirements-driven investment strategy for our nuclear propulsion portfolio.

17. What kind of propellants do nuclear electric propulsion systems use and what are the costs and benefits? Are there any rare or exotic fuels under consideration that could entail supply risks?

A: For nuclear electric propulsion, there are multiple types of electric thrusters including Hall thrusters, ion thrusters, magnetoplasmadynamic (MPD) thrusters, and resonant induction (VASIMR) thrusters. Hall effect, ion, and VASIMR thrusters use noble gas as propellant, and MPD thrusters most commonly use Lithium. Xenon gas, which is most commonly used as propellant for Hall and ion thrusters, is a small percentage of the Earth's atmosphere, is extracted as a by-product from commercial air liquifaction plants, and with additional processing steps can have its production increased. The cost and schedule to modify infrastructure to produce an adequate supply of a propellant for an NEP Mars mission will need to be considered as part of overarching trade studies on whether or not to select such a propulsion system for a future Mars exploration campaign.

18. The development of next generation nuclear propulsion involves advancing technologies associated with thrusters, power generation, power management, and cooling. What are the biggest challenges to scaling up the power or capacity of those subsystems?

The subsystems that are the subject of this question are the primary areas that prove challenging when developing a Nuclear Electric Propulsion system. These challenges would also be seen should we develop a dual-mode NTP system where the fission reactor is used both as a heat exchanger to produce propellant thrust, and as a secondary loop to power the spacecraft.

- **A: Thrusters**: There are several candidate high-power thrusters that include Hall, ion, MPD and VASIMR. The important issue for any thruster is demonstrated reliability and credibility of high-power performance and lifetime Specific technical challenges include:
  - The need to demonstrate clustered operation of multiple electric thrusters.
  - Ion thrusters need advanced concepts to be considered a viable solution given the number of thrusters needed to achieve the NEP power level;
  - The need to demonstrate long life for the MPD thruster;
  - VASIMR has low maturity and is considered complex as a high-power electric thruster. A recent 88-hour test at 80 kWe shows progress, but the power level is much lower than needed for it to be mass competitive, and there is uncertainty related to effective thrust levels that needs to be resolved; and
  - The need to upgrade ground test capabilities to simulate the space environment for high power operation, relevant to all thrusters in consideration.
- **Power conversion**: Highly efficient power conversion systems are needed to reduce the amount of waste heat rejected to space. For a fixed electric load, the power conversion efficiency directly affects the power, size, and mass of the reactor and radiator panels. Closed-cycle Brayton convertors, operating at inlet temperatures that exceed previous testing experience, are needed to reduce the size and mass of the reactor and radiator panels. Currently there are no space-rated Brayton converter systems available at any power level, so critical development work is required to establish a qualified system.

- **Heat rejection**: The radiator is the largest component for an NEP system in terms of both size and mass. Based on expected power conversion efficiencies, the amount of rejected heat can be two or more times greater than the electric power produced. Radiators that are lighter weight and operate at higher temperatures are needed to reduce the mass and size of an NEP system, which has significant benefit to launch and integration requirements.
- **Power management and distribution**: The power management and distribution system manages voltage and current and transmits electric power to the thrusters. Specific challenges include higher voltage space electronics, higher power circuit protection, and advanced power magnetics.

19. How far along are other countries in advanced in-space propulsion? Are there any key technology areas in which the US does not lead?

- **A:** Based on published literature, efforts in China, Europe, Japan, and Israel have advanced thrusters at low to moderate power levels up to 20 kW. Most of the MPD thruster development was performed in the United States and former Soviet Union prior to early 1980, but the amount of work since has significantly decreased. A publication release in 1993 showed Russian results from a successful 500-hr test conducted on a high power 500 kW MPD electric thruster, which is more than 5 times the power and lifetime of anything demonstrated in the United States.
- Also in published literature, Russia and China have multi-megawatt-class NEP concepts reported in the literature at varying claims of development. China is conducting early-stage R&D into space nuclear propulsion. In line with how they are approaching other space technology areas, they appear to have projects across the board from 10-1000 kW, are exploring a variety of technical approaches, and the literature seems to suggest that they have proposed a suite of potential missions in the planning phases that may require the technology. Future missions to the outer planets and even crewed missions to Mars have been suggested as potential candidates.
- Finally, the literature indicates China is relatively nascent in its development compared to the U.S. and Russia, which have experimented and demonstrated space nuclear systems for decades. However, China's long-term public space strategy suggests they may pivot to space nuclear propulsion across multiple missions if safety concerns are mitigated, fuel sources are developed, and certain technical breakthroughs are achieved.

20. Highly enriched uranium (HEU) raises proliferation concerns and restricts the number of private sector organizations that could contribute to developments. Recent proposals have favored high assay low enriched uranium (HALEU) to address those concerns. But according to the Academy report, technical feasibility, performance, safety, fuel availability, cost, and schedule considerations do not favor HEU or HALEU. Should NASA make significant investments in space nuclear propulsion before conducting a comprehensive assessment of the relative merits and challenges associated with HEU and HALEU?

A: Advances in reactor fuels, reactor materials, and reactor designs have opened a potential competitive trade space for LEU systems which encompasses a high assay (HALEU) 19.75% enrichment. The availability of HALEU fuel is a separate consideration from the technical merits of using HALEU over HEU. The DOE has assured NASA that uranium 235 reserves are sufficient to satisfy the current HALEU fuel demands for space nuclear propulsion and power activities. In

addition, the security classification for HALEU is the same as commercially available 5% enriched LEU fuel that is regulated by the Nuclear Regulatory Commission. Systems using HEU will always be lighter and smaller, but the performance benefits of HEU over HALEU are projected to be modest in the power ranges of interest for human exploration. HALEU has strong synergy with emerging commercial nuclear power systems, and the technology advancements gained by developing HALEU-fueled space reactors can have direct benefits to terrestrial systems. NASA and DOE have performed reactor design studies for certain human Mars mission concepts where nuclear power is considered enabling, and the results of these studies show that HALEU systems can meet performance goals. The practical use of HALEU for space nuclear applications does require advancement in reactor materials and designs.

21. Are their non-governmental markets for space nuclear propulsion systems?

A: Not currently, but commercial space companies have a growing interest in nuclear power and propulsion capabilities for both lunar and cis-lunar operations. Power will be needed on the surface of the Moon and Mars for extracting valuable resources such as ice water and methane that can be turned into propellant and sold to government and private customers. Power will also be needed to support human habitats and other operations, and there may be non-governmental users of power on the Moon. There may also be need for high thrust propulsion (to tug spacecraft from one location or orbit to another) in the vicinity of the Moon, which could have private users. To the best of our knowledge, however, non-governmental markets cannot cover the full cost of developing or even using space nuclear power and propulsion systems.

22. In May, China become the only non-U.S. country to successfully deploy a rover on the surface of Mars. Shortly afterwards, China announced that it intends to conduct crewed missions to Mars in 2033. The head of the China Academy of Launch Vehicle Technology indicated at the time that to shorten the travel time, spacecraft would have to tap energy released from nuclear reactions in the form of heat and electricity, in addition to traditional chemical propellants. What insight do we have into China's current capabilities regarding space nuclear propulsion? How much are they spending per year? Are their schedules realistic? Are they focusing on NTP or NTP? If they are focused on both, which technology is father along? Could they develop space nuclear propulsion before we do?

A: To the best of our information, China is conducting early-stage R&D into space nuclear propulsion. In line with how they are approaching other space technology areas, they appear to have projects across the board from 10-1000 kW, are exploring a variety of technical approaches, and have proposed a suite of potential missions in the planning phases that may require the technology. Unclassified sources report that China is relatively nascent in its development compared to the United States and Russia which have experimented and demonstrated space nuclear systems for decades. However, China's long-term space strategy suggests they may pivot to space nuclear propulsion across multiple missions if safety concerns are mitigated, fuel sources are developed, and certain technical breakthroughs are achieved.

23. Dr. Lal, regarding nuclear thermal and nuclear electric propulsion capabilities, in which capability has NASA invested more? Why? Does the agency see the potential for both capabilities?

A: The agency sees potential benefits in both NEP and NTP that extend beyond the fact that both could be used to support a crewed Mars mission. The high propellant efficiency for NEP could potentially benefit long-duration, deep-space missions, and the high thrust for NTP has significant

benefits for non-NASA lunar and cis-lunar operations in addition to human missions to Mars. NASA has invested more in nuclear thermal propulsion consistent with Congressional direction

24. TO NASA- Over the last 10 years, how much money has NASA expended on technology development exclusive to nuclear electric propulsion? Over the last 10 years, how much money has NASA expended on technology development exclusive to nuclear thermal propulsion? How does NASA propose making R&D investments for NEP and NTP going forward? What would you consider to constitute high power, in making these investment decisions?

A: Over the last ten years, NASA technology advancements for NEP have included $16.5M toward advancing high-powered electric thrusters, along with a number of smaller early stage foundational technologies. Over the last ten years, NASA's NTP investments have been primarily driven by Congressional direction, and sum to $467M for reactor technology, fuel development and other crosscutting and foundational technologies (including cryogenic fluid management), which are needed to develop an operational NTP capability.

As noted in the hearing, each capability has its benefits and risks and the supporting technology needs maturation to ensure we truly understand the risks and performance trades before determining where to apply these systems to NASA missions.

25. Solar power is limited by available surface area and distance from the sun. In the future, missions will likely require more and more power, and U.S. government investment in developing space based nuclear electric generation would be a great step forward. How would missions with nuclear thermal propulsion produce electricity for missions where solar is not a viable option? How would you assess the benefits of using nuclear electric propulsion that could provide ample power for missions as well as propulsion? How should that characteristic be weighted in architecture decisions?

A: There are concepts for operating an NTP reactor to produce power separately from producing thrust by thermally adding energy to a propellant. This is referred to as a bi-modal operation for a NTP engine. The first priority for NTP is to develop and demonstrate a space nuclear reactor that can operate at extreme power density and at the extreme operating temperatures required to produce high specific impulse. NASA is focused on solving these major technical challenges with current investments. Once these challenges are solved, NASA can consider a reactor design that can be continuously operated at a much lower temperature with a secondary power conversion cycle to generate electricity. Establishing a bi-modal NTP capability requires more time to develop and engineering parameters of such a system are too uncertain to confidently inform architecture decisions. The electric power generated could be used to power the space vehicle, run avionics, manage communications, or drive electric thrusters. While a bi-modal NTP system could be utilized to provide ancillary power, this capability is not a primary driver for architectural decisions. An optimal NEP system would maximize the power levels necessary for the mission. A science class NEP system would typically be a few 10s of kilowatts.

26. There have been exceptional advancements in high-power electric propulsion (EP) accelerated by recent investment from the private sector, such as in the NASA NextSTEP public private partnerships that led to the recent 88-hour endurance test of a VASIMR test engine. Additionally, electric propulsion innovation benefits from fusion energy development (now also accelerating with private investment) and the great advancements in power electronics for transportation and industry electrification. Yet, high-power electric propulsion development has suffered from low and intermittent investment over many decades. The National Academy of Sciences' panel

recommended that the U.S. must accelerate a robust and sustained program to develop high-power electric propulsion thrusters needed to maintain and advance our leadership in space propulsion. How should NASA (and the federal government as a whole) invest in both incremental innovations, such as the Hall Effect Thruster, and disruptive innovations, such as the VASIMR engine?

A: Investments in NEP related technology have lagged NTP investment by over an order of magnitude. The Academies study concluded that greater investment in NEP would be required in order to develop an informed preference between NEP and NTP propulsion systems; the study did not evaluate other possible propulsion systems that could be used for a crewed mission to Mars. With differing degrees of maturity for Hall, MPD, and VASIMR thrusters, system level design options need ground test data to inform a system trade study. Each propulsion technology faces different technical hurdles to make the necessary advancements that lead to a better understanding of performance and system integration requirements. In order to address the technology gaps that remain, a comprehensive technology development effort would be required. Investment decisions would need to be guided by strategic criteria as well as the feasibility of overcoming key challenges confronting each capability. Until a better technical understanding is achieved s, NASA cannot determine the priority and potential for establishing each capability.

27. What is the technology readiness level for current U.S. capabilities in each nuclear thermal propulsion and nuclear electric propulsion? How much additional investment of resources would be needed to fully mature each capability, and how long would that take before we could leverage that into a human mission to Mars?

A: An independent examination of NTP and NEP was sponsored by the NASA Engineering and Safety Center to assess the Technical Readiness Level (TRL) and Advancement Degree of Difficulty (ADD). The NESC study concluded that the majority of critical technologies for both NTP and NEP are often overestimated in literature, and the TRL for both systems is relatively immature. The study also noted that the majority of critical technology needs for both NTP and NEP have relatively high levels of difficulty for advancement that would require a dual development approach to increase the probability that a capability will be successfully established. The National Academies also noted that both NEP and NTP systems and subsystems have low readiness levels, and it would take sustained and large investment for more than a decade to develop an operational nuclear propulsion system.

It should be noted that any projected estimates, whether by NASA or by external entities, have a high degree of uncertainty due to the low maturity of key technologies and anticipated difficulty of advancing engineering solutions.

28. For Dr. Lal, regarding nuclear thermal and nuclear electric propulsion capabilities, in which capability has NASA invested more? Why? Does the agency see the potential for both capabilities?

A: In accordance with Congressional appropriation and direction, NASA has invested more in NTP than NEP. The agency sees potential benefits in both NEP and NTP; the high propellant efficiency for NEP has a major benefit for long-duration, deep-space missions, and the high thrust for NTP has significant benefits for lunar and cis-lunar operations in addition to missions to Mars.

29. When NASA compares NTP to NEP it compares an NTP system that operates at hundreds of MW with an NEP system that operates at 1 MW plus a chemical boost. How can you achieve an "apples to apples" comparison of two nuclear systems that are so dissimilar in power? It would appear a-priori that the result would tend to lean in favor the NTP system. By the choice of this

comparison, it would appear as if NASA were down selecting the NEP system to be made up of clusters of the 13 kW Hall thruster, the same thruster selected for the Gateway PPP. Why is NASA not considering higher power electric thrusters such as the VASIMR or the MPD in this comparison? Why does NASA not compare NTP and NEP systems of comparable power?

A: There are several variables to consider in a comparison of NEP and NTP, but the mission architecture being considered determines the optimal parameters for each system, including power level. The comparative figures of merit are the cost, schedule, and confidence of developing the capability to meet a particular mission. Emphasizing schedule and cost can result in sacrificed performance and reduces the ability to accommodate the development of more beneficial, but lower TRL technologies. Conversely, emphasizing performance can make a system overly complex from a technical perspective, and potentially unaffordable.

NASA's conceptual NEP system would use 100 kWe Hall thrusters, but those thrusters would need to be scaled and tested to establish engineering confidence that they are ready for system integration and demonstration. NASA remains interested in higher power electric propulsion systems, such as MPD or VASIMR, but the lower maturity of these systems and the anticipated difficulty to advance solutions makes it uncertain they can meet performance goals in a similar time frame as lower power systems.

30. Dr. Lal: Is NASA considering a multi-MW MPD or VASIMR engine package in an NEP propulsion system of equivalent power as the NTP in this comparison? If so, when are these results going to become available? And if not so, can you explain why?

A: The low level of technical maturity for higher power electric propulsion devices, such as MPD and VASIMR, imposes a high level of uncertainty that those capabilities can be developed with meaningful estimates for schedule and cost. NASA recognizes that these thrusters could be enabling, but an objective and independent assessment of the technical readiness level, advancement degree of difficulty, development cost, and schedule would need to be completed in order to have a reliable comparison of each capability and the predicted impact to a potential Mars mission. An NEP system (without chemical supplementation) comparable to NTP at 500 MW or more may not be feasible for 50 or more years even with consistent and adequate funding.

Submitted by Mr. Brooks

1. NASA currently provides nuclear indemnity for its NTP work by utilizing the Battle Energy Alliance at the Idaho National Lab. If NASA had the ability to indemnify its nuclear propulsion work under Price Anderson Authority or used the national security exception, Public Law 85-804, could the program move faster and could the program spent more of the funds directly to the program?

A: NASA sees DOE's participation as valuable, and this partnership has not resulted in any significant procurement delays. While working with industry on initial designs of the system, NASA determined that unusually hazardous conditions did not exist, and therefore the work did not trigger the need for indemnification per the authorities given in P.L. 85-804. At the request of industry, NASA sought support from DOE to apply their indemnification policies (under Price Anderson) based on the prohibitive cost for them to gain insurance. The process NASA uses to

provide industry with indemnification through DOE's organic authority is efficient with little impact to the cost and schedule for industry contract efforts.

Submitted by Mr. Crist

1. **When NASA compares NTP to NEP, it compares an NTP system that operates at hundreds of MW with an NEP system that operates at 1 MW plus a chemical boost. How can you achieve an "apples to apples" comparison of two nuclear systems that are so dissimilar in power?**

A: The requirements of integrated vehicle designs for NEP and NTP would be very different, but each is optimized to the needs of a specific mission. The comparison of capability should not be made at the propulsion level. The comparison needs to be made based not just on power levels alone but also on how the system aligns with key mission needs, as well as cost, schedule, and confidence of developing the capability. The comparison also needs to be made with other systems that would be available in roughly the same timeframe.

2. Regarding nuclear thermal and nuclear electric propulsion capabilities, in which capability has NASA invested more? Why?

a. Does the agency see the potential for both capabilities?

A. In accordance with Congressional appropriation and direction, NASA has invested more in NTP than NEP. The agency sees potential benefits in both NEP and NTP; the high propellant efficiency for NEP has a major benefit for long-duration, deep-space missions, and the high thrust for NTP has significant benefits for lunar and cis-lunar operations in addition to missions to Mars.

Submitted by Mr. Norcross

1. NASA, in partnership with the Department of Energy, recently selected three companies to produce conceptual reactor designs for a nuclear thermal propulsion system. What are the key items you'd like to see in these proposals, and how is NASA planning to engage with industry on development once the designs are complete?

A: NASA objectives for the first phase of these industry engagements is to open the design to novel and innovative ideas and gain insight to industry's proposed solutions. The delivered product will be low-fidelity preliminary design information which offers NASA confidence that the proposed design is feasible and manufacturable. At the end of the performance period, NASA and INL will conduct design reviews of the reactor concepts and use the information to guide potential follow-on contracts that result in hardware design, development and test demonstration efforts.

2. Congress has expressed the need for a flight demonstration of a nuclear thermal propulsion system. What steps have to happen to get the technology to a place where it is ready for a flight demonstration? Approximately what year do you think a flight test will occur?

A: NASA is making good progress toward advancing the reactor technologies needed to inform the necessary detailed evaluation and development of integrated demonstrations. This includes industry contracts on potential engine designs and cryogenic fluid management technology demonstrations. To conduct an integrated flight demonstration with sufficient

fidelity to inform a potential operational design, several very difficult technology challenges must still be addressed, including:

- Fuel: A fuel form would have to be developed and tested that is extensible to future performance needs. NASA is working with industry to develop a stable manufacturing process for carbide ceramic fuels.
- Reactor Design: A robust design that enables the operation of a HA-LEU moderated reactor would have to be developed and tested. NASA has funded three commercial industry awards for the design of high temperature reactors. These awards are the first phase of an overall effort to produce a design with performance that is consistent with NASA needs.
- Cryogenic Fluid Management: The hydrogen propellant used by an NTP engine would have to be stored at 20 Kelvin to avoid boil-off and propellant loss. NASA selected four industry-led partnership awards that will advance CFM technologies through flight demonstrations. Each of these development efforts will provide key technical insights that could inform future NTP ground and flight demonstrations.

NASA is implementing efforts that could solve these key challenges, but the outcomes from these technology efforts need to be understood before the Agency will be able to provide a flight demonstration timeline with any level of confidence.

Responses by Mr. Greg Meholic

Questions for the Record to:

Mr. Gregory Meholic

By the

Committee on Science, Space, and Technology

Subcommittee on Space and Aeronautics

U.S. House of Representatives

Following the Hearing Entitled

"Accelerating Deep Space Travel with Space Nuclear Propulsion"

Held October 18, 2021

Submitted by Chairman Beyer

1. What funding would be required to achieve an operational space nuclear propulsion capability by 2033?

Response: Since space nuclear propulsion is envisioned to have applications ranging from small satellites to large, human-rated spacecraft for planetary exploration, estimating funding needs is extremely challenging for the following reasons, to name a few:

- Before development of the enabling technologies can begin, there are considerable costs associated with defining mission requirements and a validated development program, obtaining the buy-in of capable, consistent leadership, building cooperation from a strong industrial base and garnering broad government and public acceptance.
- Whatever combination of these emerge out of these endeavors, funding plans to support their realization should include critical considerations such as modeling, testing, subsystem and spacecraft development, launch acquisition, policy/regulatory compliance, and the establishment of a stable plan that promotes the continued maturation of the technology.
- Operational capability is often preceded by several years of successful outcomes from detailed technology development programs, system integration testing, exhaustive flight qualification and certification endeavors and mission assurance assessments, all of which significantly influence cost and schedule.
- It is conceivable that fission systems with modest capability for small satellite electric power and current generation electric thrusters can be built with little additional development cost. However, such systems would be designed around the expected capability of existing technology rather than seeking to develop the technology needed to achieve specific operational performance.

2. To what extent are existing safety regulations designed for radioisotope power systems sufficient for fission-based propulsion or power systems?

Response: Radioisotope power systems (which include radioisotope thermoelectric generators) and fission-based nuclear power are both considered space nuclear systems; however, they operate on different physics and utilize different componentry that are appropriate for their specific missions and required capabilities. But different technologies may require different regulations. To be as successful as radioisotope thermoelectric generators (RTGs), fission power systems may require their own regulations, safety features, and protocols.

- Existing regulations designed for RTGs have successfully and safely served space exploration power needs for 60 years and will continue to do so going forward. RTGs are designed with a complement of proven safety features with flight heritage including materials formulation and engineered safety mechanisms. RTGs are subjected to rigorous analysis, testing, and environmental compliance

assessment to ensure that public (and worker) safety and proper system performance are strictly maintained from manufacture through launch.

- The applicability of the regulations and policies around the design, manufacture, test, and launch of RTGs will need to be closely examined to ensure that the safety provisions for fission systems achieve equivalent levels of safety as those successfully demonstrated for RTGs. The assessment would also identify areas of regulatory consideration specific to fission-based systems and suggest avenues towards addressing those under the key tenets of safety and mission assurance as well as their influence on technology development and maturation.

3. To what extent are there synergies in the development activities and operations of terrestrial nuclear power with the requirements and development pathways for space nuclear propulsion?
a. What are the emerging trends or innovations in nuclear fuel fabrication that could be beneficial for space nuclear propulsion?

Response: There is little in the way of synergies between space nuclear propulsion (SNP) and terrestrial nuclear power; this is true for both traditional, large scale, commercial, fixed site terrestrial nuclear power plants and for terrestrial mobile nuclear power. However, there are some synergies between nuclear electric power (NEP) and terrestrial mobile nuclear power. In this response terrestrial mobile nuclear power refers to systems like the Strategic Capabilities Office (SCO) "Project Pele" mobile nuclear power concept.

Nuclear thermal propulsion (NTP) engines offer the most demanding environments of fission-based space nuclear applications. NTP engines heat a propellant passing through the nuclear core and expel it through a nozzle to produce a propulsive force (thrust). The fluid, often considered to be high-pressure gaseous hydrogen, is raised to temperatures in excess of 4500 degrees Fahrenheit in order to produce the thrust forces desired. These harsh environments present considerable challenges for the uranium fuels and materials from which the reactor and engine parts are made. By contrast, typical terrestrial nuclear power plants heat a working fluid that is used to drive a mechanical system to generate electricity. These types of nuclear power systems can efficiently operate at lower temperatures (for example, terrestrial plants convert water to steam at less than 1000 degrees Fahrenheit) which offers comparatively benign conditions for their internal materials and thus ease the burden of materials development.

NEP, extraterrestrial fission surface power (FSP), and terrestrial mobile nuclear power concepts like the SCO's Project Pele will probably all employ similar power conversion systems – that is the mechanical systems that convert nuclear heat into electric power. The likely candidates are Brayton and Stirling cycle power converters. These systems will have significantly different sizes, weights and power levels for these different applications, which means there is unlikely to be any commonality in their design or components, but the basic theory and industrial base will likely support all three applications.

The duration and temperatures of the fission process produces material degradation and gases inside the reactor core that could affect reactor lifetime. The envisioned application of NTP engines for a journey to Mars is to operate the reactor at high power for less than an hour followed by weeks or months shutdown. This type of operation results in very little burnup of the nuclear fuel over the life of the reactor, however the reactor must be designed to handle the rapid heat-up, extreme temperature, and subsequent cool down in this short period. NEP, FSP and terrestrial power plants operate for years and although they operate at lower temperature, the long periods at power and moderate temperatures drive material designs differently than NTP reactors. The duty cycles for space nuclear power systems have yet to be determined and will likely refine these issues.

Even though there are fundamental differences between NTP and terrestrial nuclear systems, there may be opportunities for common development in terms of uranium fuel forms. Two examples of this are the tri-layer isotropic (TRISO) or bi-layer isotropic (BISO) uranium fuel forms that resulted from decades of research into accident-tolerant fuel (ATF) options pioneered by the terrestrial nuclear industry. These fuel forms surround

the uranium kernel with several layers of other materials that protect the uranium from direct exposure to the environment if the reactor core structure becomes compromised. These layers also trap the radioactive fission biproducts mentioned earlier so that they do not escape to the environment. Layered fuel forms are being examined for use in space-based fission systems according to their temperature limits, production challenges and uranium enrichment options (Highly Enriched Uranium - HEU vs. High Assay Low Enriched Uranium - HALEU). The exact same design of encapsulated fuel kernel will not be used in the different applications, but the technology to perform this multilayer encapsulation may be one of a select few commonalities between SNP and terrestrial systems.

4. The subject of the National Academies study and most of NASA's work thus far has been with propulsion driven by nuclear fission reactors. What is the current state of technology for space nuclear propulsion with fusion reactors, and what, if any, development is NASA or the rest of the federal government supporting?

Response: Many start-up companies are exploring fusion for terrestrial power and a few are exploring it for direct space propulsion application. In most cases, the physics behind fusion has matured to a level of understanding where lab-scale, academic demonstrations of the fundamental aspects are being realized and supported from government-backed projects or commercial investments. Fusion propulsion would require overcoming many supplemental challenges that currently have little or no current development, so a demonstratable, fully-integrated engine system is not likely to materialize prior to the introduction of fission-based systems. As with any propulsion option, though, the potentially attractive payoffs of fusion propulsion will need to be traded against mission needs and other competing systems, which may also influence the development timeline. The second part of the question is best addressed by NASA.

5. What, in your view, are the biggest policy or regulatory hurdles for advancing space nuclear propulsion?

Response: There are several policy and regulatory aspects that should be closely examined to facilitate the timely development of fission-based space systems (NTP or NEP) leading to an in-space demonstration. The main hurdles are listed here but are certainly not complete:

- Ground test limitations: Compliance with the local, state and federal regulations surrounding the testing of nuclear experiments and components has become increasingly challenging since the NERVA/Rover programs from the 1960's where the ground tests and subsequent disassembly of NTP fission reactors revealed key information that informed future designs. If these policies were to be revisited and provisions made to account for today's technological advancements in nuclear fuel forms and reactor design, perhaps affordable and safe ground test options could be considered that would more readily help to advance the state-of-the-art. Doing so would also help to establish a national capability to test nuclear systems and perhaps perform critical flight certification campaigns for missions beyond initial demonstrations.
- Launch authorization process: Policy and regulatory compliance for this area often involves multiple commercial and government entities addressing their individual statutes which defers the launch date and increases program costs. The radioisotope power systems (RPS) community has established success in helping to clarify the considerations needed for the launch of nuclear material and methods by which compliance can be measured. Those policies may be a starting point from which to assess their compatibility with nuclear fission fuels and systems.
- HALEU Fuel availability: Currently, for HALEU fuel, HEU fuel must be obtained from national stockpiles, then transferred to labs or industry for down-blending and conversion into the fuel types needed for SNP applications. Opportunities may exist to streamline the process without compromising safety, security, supply control and transport protocols.

6. The Academies study provided roadmaps for maturing nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) systems to meet the requirements of a crewed Mars mission in 2039, preceded by cargo deliveries to Mars starting in 2033.

a. In your view, would those roadmaps, if followed, get us there?

b. What, if anything, is missing?

c. What do you think the biggest challenges might be in implementing these roadmaps?

Response: Each part of the question is addressed separately below:

- Part a: The findings and recommendations of the Academies report regarding the development roadmaps for both NTP and NEP propulsion technologies are reasonable and justified, but significant challenge lies in achieving the timely readiness for all of the other crucial elements for the baseline missions. Some of these were briefly mentioned, but it was not the objective of the report to address items not affiliated directly with the propulsion technologies. While the propulsion systems may be ready for flight in time for their respective missions, many other mission elements may not be.
- Part b: Presuming that the NTP and NEP propulsion maturation plans lead to their mission readiness, other elements may require equally aggressive development roadmaps and substantial support to keep pace. These include:
  - Cryogenic fluid management (CFM) for long-term, in-space storage of cryogens: CFM impacts both NTP and the chemical propulsion (oxygen/methane) elements of NEP missions to ensure the spacecraft have the propellants needed to perform the entire mission. This critical technology must eventually be flight demonstrated at various scales leading to reliable, mission-qualified systems.
  - Launch system qualification: The launch system(s) needed to loft the spacecraft elements to the assembly orbit must reliably perform as expected. Validating this usually takes several years after first flight and may be even more challenging due to the sheer size and capabilities of the heavy-lift systems needed for the baseline missions. Vehicle performance deviations or qualification set-backs could delay mission opportunities.
  - On-Orbit Servicing, Assembly and Manufacturing (OSAM) to assemble the elements into a spacecraft: Autonomous, in-space assembly, check out and flight prep of the mission vehicle(s) is necessary to reduce the negative impacts of long-term spaceflight to human health. This technology is actively being explored, but at a smaller scale than what would be required for the baseline spacecraft. Developing the robotic/autonomous hardware, systems and interfaces to carry out the complex assembly of the baseline vehicles is not even at the conceptual stage and will need to be flight tested before being put to use for the baseline vehicles.
  - Chemical Propulsion Supplement for NEP vehicles: This item was missing from the NEP development roadmap in the report and could be considered a critical system depending on the mission. The report asserts that the oxygen/methane rocket engine suitable for the NEP missions might be developed in parallel with a similar engine envisioned for the Artemis lunar lander ascent vehicle or may be a derivative of that engine. Either way, rocket engines typically take years to advance from concept to demonstrating the required in-flight reliability for crewed missions.
  - Payload design, development and test: Even though the notional Mars mission opportunities estimate "days on the surface", there may not be a plan for what will actually be accomplished or what kinds of tasks would be performed. Configurations of the spacecraft elements to support crew habitation are also uncertain as are the necessary life support subsystems and other vehicles. This hardware will need to be fully developed and tested years before the mission to allow time for launch vehicle integration as well as on-orbit assembly and check out.
- Part c: In terms of the propulsion development roadmaps proposed in the Academies report, some of the primary challenges include review and compliance with the regulatory processes for the launch and operation of space nuclear systems as well as the timely development and certification of ground test facilities for such systems (specifically NTP). From a mission perspective, one of the most dauting challenges is to develop and coordinate realizable technology maturation plans for <u>all</u> the critical mission elements such that the baseline or similar missions can be addressed. Given the current state of most of these enabling technologies and other supporting elements, there exists an elevated risk of not meeting the timelines mentioned in the report.

7. How do the current capabilities and activity levels in space nuclear propulsion of U.S. government and industry compare to the capabilities and activities around the world? Are we among the leaders? To what extent would advancing space nuclear propulsion contribute to our international competitiveness?

Response: Several articles have been released describing the plans by some foreign countries to develop fission-based space nuclear propulsion or power concepts for lunar or Mars missions. Some countries may have the engineering capabilities required, but may lack experience, while others may have the know-how, but it is unknown if their space nuclear projects have the internal priority to secure the needed resources. While these plans seem notional and perhaps unvalidated, it's clear that other space-faring countries are beginning to understand the benefits of Space Nuclear Power and Propulsion (SNPP) and may be actively striving towards achieving global leadership roles along with the US.

It is likely that the first nation to successfully demonstrate SNPP in space will set the global pace and objectives for the continual development of such a critical enabling technology. This was envisioned during the NERVA program in the 1960's and still holds true today. The number of government and commercial projects in the US with near-term demonstration objectives has the country well poised to become the world leader in SNPP; however, the US should not take for granted the uncertainty of other countries' plans or priorities to achieve the same thing. For that reason, domestic SNPP tech maturation plans should factor in the presumption that other countries have realized the strategic advantages of SNPP for both scientific and national security missions so that the US has the best chance of firmly establishing the leadership role.

Submitted by Mr. Babin

1. How are the uranium fuel forms being developed to enable a range of terrestrial as well as space applications, including future commercial applications, and maximizing private-sector engagement and cost savings?

Response: There are few synergies between Nuclear Thermal Propulsion (NTP) for space applications and terrestrial nuclear power primarily due to the differences in how they operate. NTP engines heat up gaseous hydrogen to temperatures in excess of 4500 degrees Fahrenheit in order to produce the thrust forces desired. Terrestrial power systems, however, boil water to steam, can do so for years and have very different duty cycles. These differences stem directly from the uranium fuel form and the other materials used inside the reactors.

Even though there are fundamental differences between NTP and terrestrial nuclear systems, there may be opportunities for common development in terms of uranium fuel forms. Two examples of this are the tri-layer isotropic (TRISO) or bi-layer isotropic (BISO) uranium fuel forms that resulted from decades of research into accident-tolerant fuel (ATF) options pioneered by the terrestrial nuclear industry. These fuel forms surround the uranium kernel with several layers of other materials that protect the uranium from direct exposure to the environment if the reactor core structure becomes compromised. These layers also trap the radioactive fission biproducts mentioned earlier so that they do not escape to the environment. Layered fuel forms are being examined for use in space-based fission systems according to their temperature limits, production challenges and uranium enrichment options (HEU vs. HALEU). Their performance needs for space applications must first be examined before definitive engagements with private-sector production and potential cost savings could be addressed.

2. What is the power range for the current demonstration of a fission power system on the surface of the Moon? How is that program aligned with mission needs for, and potential future government and commercial applications of, in-space power, NEP, and terrestrial nuclear power?

Response: The Request for Proposal (RFP) released to industry by Battelle Energy Alliance at Idaho National Laboratory (INL) on 19 November for a Fission Surface Power (FSP) system design stipulated a minimum target power of 40 kilowatts (electric) with potential extensibility to 1 megawatt (MW). These levels span a broad range of potential in-space applications ranging from small satellites in cis-lunar space that need either power or propulsion (via electric thrusters) to the envisioned NEP mission concepts for large-scale (crewed), scientific exploration beyond earth orbit. The FSP power range is significantly lower than the 1-10 MW Small Modular Reactors being considered for terrestrial use.

3. In August 2019, the National Security Policy Memorandum 20 (NSPM-20) was updated to establish safety guidelines and safety analysis and review processes for Federal Government launches of spacecraft containing space nuclear systems, including SNPP systems, and for launches for which the Department of Transportation has statutory authority to license as commercial space launch activities (commercial launches). How have these new guidelines improved the development of SNPP systems?

Response: The NSPM-20 guidelines primarily address the categorization of space nuclear missions and identify the responsible authority to approve the launch of nuclear material. Since there has not yet been a definitive direction within any SNPP project to advance to a flight demonstration, spacecraft and mission designs do not yet exist on which to base categorization or launch authority according to the guidelines. Until such information becomes available, the impacts of the guidelines to technology, spacecraft or mission development remain uncertain. Although NSPM-20 has not yet been put into practice for the fission-based SNPP community, the radioisotope power system (RPS) community may have missions under consideration.

4. Which uranium fuel forms are needed to meet the nearest-term mission needs? How are they utilizing the same or similar materials, processes, designs, or infrastructure — across these fuel forms?

Response: Although the requirements for a "nearest-term mission" for SNPP have yet to be defined, the primary HALEU-based fuel forms being explored for use in SNPP systems are TRISO, BISO, cermet (ceramic-metal) and cercer (ceramic-ceramic). Each of these has its challenges and opportunities depending on the desired operating temperature (thermal power) and allowable operating time as needed by the mission as well as for availability and manufacturing costs. Since these parameters vary widely across the notional missions envisioned for NTP and NEP, preliminary efforts trading fuel form options indicate a likelihood that the fuel form may have to be tailored to the specific mission. They also show that the performance of the fuel forms is sensitive to the mission needs and that they might not perform as expected for other missions or even in different reactor designs. Since some of these fuels are still being characterized at the fundamental level, the commonality of materials and manufacturing processes across the fuel form options is still being explored.

5. Are the uranium fuel forms to meet near-term mission requirements maximizing private-sector engagement? Will these fuel forms be developed to enable a range of terrestrial as well as space applications, including future commercial applications?

Response: Since the requirements for a "near-term mission" for SNPP have yet to be defined, the fuel forms under development are being examined at the fundamental levels of manufacturability, nuclear physics, material compatibility, and so on, to determine for what applications the fuel forms would be best suited. The performance of the fuel forms has been found to be sensitive to the mission needs and may be compromised if used for other missions or even in different reactor designs. Since most of the fuel forms being examined for SNPP are of the HALEU variety instead of HEU, the few commercial players involved that have the capabilities, facilities and licensure to work with HALEU have prioritized efforts to explore opportunities on how to grow the industrial base to meet anticipated demand.

6. How are departments and agencies collaborating on SNPP systems? Are they conducting regular technical exchanges among SNPP programs?

Response: As of today, NASA and DARPA are the only two agencies with active SNPP projects. They have recently agreed to exchange information as well as determine common needs and development paths despite the differences in objectives. The Department of Energy (DOE) and several national labs have dedicated support to these projects from the very beginning and have provided significant experience, resources and guidance for fuel development/testing, reactor design and concept performance evaluation. As the FFRDC for space, The Aerospace Corporation has been actively and deeply engaged with the NASA project at technical and programmatic levels and has been increasingly supporting DARPA's effort in some areas. Aerospace is also assisting to facilitate communication and engagement between other DoD interests in SNPP from Air Force Research Lab (AFRL), Space Command, US Space Force/Space Systems Center, the Office of the Undersecretary of Defense, the Assistant Secretary of Defense for Space Policy and others to inform them of NASA and DARPA activities and seek common technology development or application opportunities.

7. Commonality, such as reactor designs, nuclear fuels, infrastructure, and testing, among SNPP systems, and between SNPP and terrestrial nuclear systems, will greatly increase the development and advancement of SNPP programs. How are DoD and NASA working with partners to evaluate and use opportunities for commonality with other SNPP needs, terrestrial power needs, and reactor demonstration projects planned by agencies and the private sector?

Response: Due to the significant differences between SNPP and terrestrial nuclear systems, there are few areas of technology research and development that would benefit from commonality. The primary drivers for the differences are the operating temperatures, time of operation, and overall power density in the reactor (power produced per cubic volume). The same small set of US nuclear companies are involved in the several SNPP efforts; however, compared to terrestrial systems, SNPP systems are likely to be very small to meet launch mass and size requirements, which means they must operate at high temperatures (sometimes thousands of degrees hotter) to deliver the energy needed for the spacecraft. In addition to the operating time limitations, this brings about fuel form, reactor design, and material development challenges that the terrestrial reactors do not need to address. What's more, the propellants and working fluids inside of SNPP systems necessitate reactor designs and control mechanisms that are unlike terrestrial configurations.

The DoD and NASA are consulting industry and Department of Energy (DOE) partners on their respective SNPP interests to determine if the institutional knowledge for fuel form development, reactor design, materials technology and other aspects are applicable for the envisioned HALEU systems.

8. "Extensibility" is the concept that technologies developed in the near-term will be useful for future exploration as well. Extensibility prevents the development of "dead-end" capabilities. How is NASA ensuring that its investments in space nuclear propulsion are extensible?

Response: The current direction of the NASA Space Nuclear Propulsion (SNP) project is aimed at the development of a fully integrated, testable, subscale, prototype NTP engine by the end of 2026. The demonstration engine will be half the thrust of the vision NTP flight engine that is intended for crew and/or cargo missions to Mars in the late 2030's. One of the project guidelines is that the subscale engine design must be extensible to the larger engine such that the development of the larger engine only requires minor upgrades and up-sizing of assemblies and parts in lieu of a completely new reactor design and engine cycle. Details on the extensible aspects of the SNP project, its program planning and investment strategies is best addressed by NASA.

9. When will NASA need space nuclear propulsion capabilities? What architecture and strategic planning informs that schedule?

Response: This would best be answered by NASA as there are many facets to cover in the response that only NASA can answer.

10. How should the government synergize nuclear surface power generation and space nuclear propulsion development?

Response: Because of the different operational characteristics between nuclear thermal propulsion and nuclear power production such as for NEP systems or surface use, finding common areas and opportunities to synergize technology research and development poses many challenges. Factors critical to each application such as fuel form, working fluid, operating temperatures and run time lead to significant differences in reactor design, control approaches, materials considerations and performance expectations. In addition, nuclear electric power and propulsion systems are accompanied by and wholly dependent upon other subsystems such as power conversion/generation, heat rejection, cooling and pumping, and a variety of others that need to be independently matured and are not present for NTP engines. As fission surface power projects and NTP efforts continue to mature, opportunities to leverage common technology development paths may arise where government investment would benefit both applications.

11. How is NASA coordinating current investments in cryogenic propellant storage and transfer so that it could be applicable for space nuclear propulsion?

Response: NASA has been a leader in cryogenic fluid management (CFM) research which is considered a key technology for outer planet science and exploration missions utilizing NTP. CFM capability for long-term storage and transfer of liquid hydrogen is critical to NTP missions as well as for storing oxygen and other cryogenic liquids needed for crew sustainability and supplemental propulsion. NASA has recently stood up a CFM project aimed at technology maturation for key applications in conjunction with their Space Nuclear Propulsion (SNP) project focused on NTP. Specifics on the CFM project plan and investment coordination are best answered by NASA.

12. What kind of propellants do nuclear electric propulsion systems use and what are the costs and benefits? Are there any rare or exotic fuels under consideration that could entail supply risks?

Response: NTP engines utilize a single propellant while NEP systems utilize a "working fluid" inside the reactor core that enables power production as well as a propellent dedicated to the electric thrusters. In either case, the options for the fluids must be carefully traded based on performance needs. The fuel form and reactor must also be designed specifically for the chosen fluid since the fluid itself affects the nuclear fission process inside the core. The fluids mentioned here are generally abundant, affordable and have appreciable levels of research to justify their consideration.

- Nuclear thermal propulsion (NTP) engines utilize liquid hydrogen as propellant. NTP engines operate by pumping the hydrogen from a storage tank into the engine's reactor core where it gets heated, then expelled from the engine through a rocket nozzle to produce thrust. Of all the NTP propellants that have been examined, hydrogen delivers the highest efficiency, is the best coolant, can be heated to extreme temperatures without dissociating and is non-corrosive. Other propellants such as ammonia and water will work inside of an NTP engine, but their lower efficiencies reduce the attractiveness of NTP concepts for certain missions.
- Nuclear electric systems operate by circulating a working fluid in a closed loop arrangement that includes the reactor core, some form of mechanical power generation assembly, a means to cool the fluid and pump system. Typical working fluids are liquid combinations of sodium and potassium (NaK) or could be gaseous such as supercritical carbon dioxide (sCO2) or a helium-xenon mix (He-Xe). Other gases (steam) and liquids (ex. ammonia, mercury, lithium) have been explored, but offer unfavorable launch and safety considerations, among other detractors. As for the propellants for the electric thrusters themselves, xenon gas has extensive flight heritage and predictable performance, but argon has also been used.

13. The development of next generation nuclear propulsion involves advancing technologies associated with thrusters, power generation, power management, and cooling. What are the biggest challenges to scaling up the power or capacity of those subsystems?

Response: Before the challenge of scaling these systems up can be addressed, getting them to work together in an integrated system is paramount. Since each of these critical subsystems is dependent on each other and their designs are influenced by the nuclear reactor fuel, configuration and working fluid, the entire system must be tailor-made for its mission. There are many options for each of the subsystems mentioned and some are backed by copious amounts of literature, studies and experimental research, but there are currently no focused technology maturation efforts due to the absence of a definitive mission for fission-based systems.

Even if a mission were conceived to establish definitive requirements, the complete NEP system would first need to be developed, integrated and tested, perhaps at a subscale level, to validate design models, characterize performance, and explore integration sensitivities. Scaling these components to then handle the full mission demands would have to consider auxiliary components or capabilities, packaging into the launch vehicle, flight loads, reliable on-orbit deployment and assembly, and autonomous operation.

It is important to recognize the Dynamic Radioisotope Power System (RPS) lunar demonstration project at NASA Glenn Research Center (GRC). Dynamic RPS is where a nuclear decay-based heat source (as also used in an RTG) is coupled to thermo-mechanical power conversion systems. Future fission-based nuclear electric configurations may utilize similar systems. One aspect of the project is to provide a demonstrated capability for dynamic (likely Stirling cycle) nuclear power production in an in-space application, with opportunities to scale up the conversion system to meet larger power demands in other applications.

14. How far along are other countries in advanced in-space propulsion? Are there any key technology areas in which the US does not lead?

Response: Advanced in-space propulsion covers a broad range of technologies including small, micro thrusters for cubesats, large upper stage engines, exotic concepts like fusion systems and alternatives like solar sails and tethers. Aside from what is published at open-source, technical conferences that accept international submittals and audiences, this is a difficult question to address at the unclassified level.

15. Highly enriched uranium (HEU) raises proliferation concerns and restricts the number of private sector organizations that could contribute to developments. Recent proposals have favored high assay low enriched uranium (HALEU) to address those concerns. But according to the Academy report, technical feasibility, performance, safety, fuel availability, cost, and schedule considerations do not favor HEU or HALEU. Should NASA make significant investments in space nuclear propulsion before conducting a comprehensive assessment of the relative merits and challenges associated with HEU and HALEU?

Response: The enrichment of the fuel form drives key aspects of the nuclear reactor design regardless of SNPP application. While HALEU and HEU both have functional aspects that affect technical considerations on reactor design and performance, they must be carefully traded against mission requirements and desired performance as well as their availability, acquisition avenues, regulatory approvals, volume, mass, safety, transport, cost, HALEU/HEU industrial base, international non-proliferation requirements, and launch compliance measures. To illustrate this, an HEU reactor design will generally be smaller and less complex than an HALEU design that produces equivalent energy, but it will be subject to nonproliferation concerns. Similar assessments could also be made against these and other criteria. It is therefore important to ensure that thorough and objective analyses support comparisons that drive fuel selection. NASA would best to address their investment strategies and considerations for HEU and HALEU.

16. Are their non-governmental markets for space nuclear propulsion systems?

Response: Several commercial companies have expressed an interest in capturing or developing notional markets like nuclear-powered space tugs or lunar cargo transport missions that may benefit from SNPP systems. These are all conceptual and based on the presumed success that SNPP systems might demonstrate through government-funded projects. Even though some companies may be pursuing internal efforts, there is minimal information to date on private or industry investment in these ideas.

17. In May, China become the only non-U.S. country to successfully deploy a rover on the surface of Mars. Shortly afterwards, China announced that it intends to conduct crewed missions to Mars in 2033. The head of the China Academy of Launch Vehicle Technology indicated at the time that to shorten the travel time, spacecraft would have to tap energy released from nuclear reactions in the form of heat and electricity, in addition to traditional chemical propellants. What insight do we have into China's current capabilities regarding space nuclear propulsion? How much are they spending per year? Are their schedules realistic? Are they focusing on NEP or NTP? If they are focused on both, which technology is father along? Could they develop space nuclear propulsion before we do?

Response: Press reports and articles from foreign countries openly describing their ambitions, plans, and budgets in SNPP must be further examined for their validity, credibility and accuracy. These can be assessed via several sources specializing in space technology foreign intelligence and evaluation. Based on their performance in the global space sector, however, confidence exists in the assumption that China likely has the expertise and capability to mature the key technologies needed to enable their objectives. The consideration that they could quickly establish themselves as the global leader in SNPP technology must be accounted for when strategizing US government support for SNPP.

18. Dr. Meholic, what do you estimate is the technology readiness level for current U.S. capabilities in each nuclear thermal propulsion and nuclear electric propulsion? How much additional investment of resources would be needed to fully mature each capability, and how long would that take before we could leverage that into a human mission to Mars?

Response: Technology readiness level (TRL) assessment is driven by data and evidence, but also has a subjective component depending on who's doing the assessment. Both NEP and NTP systems have multiple areas of technology that must be matured into a complete system that can fulfill the application. Some of these critical areas and subsystems are at the concept level (TRL 0-2), while others may have heritage related to their applications, experimental results or other supporting data to rank them higher (perhaps TRL 5 or 6). Smaller, laboratory-scale demonstrations may be closer to becoming reality than the full mission systems and thus might have higher TRLs, which could skew the interpretation of the assessment. There have been several studies examining the TRLs for NEP and NTP, but until a definitive mission is offered where these approaches can then be traded against one another, assessments of technical and application readiness levels are likely to incorporate subjectivity and may not be a reliable influence for program plan or investment strategies.

19. Solar power is limited by available surface area and distance from the sun. In the future, missions will likely require more and more power, and U.S. government investment in developing space based nuclear electric generation would be a great step forward. How would missions with nuclear thermal propulsion produce electricity for missions where solar is not a viable option? How would you assess the benefits of using nuclear electric propulsion that could provide ample for missions as well as propulsion? How should that characteristic be weighted in architecture decisions?

Response: Solar power remains a viable option for powering modest electric loads on many human space flight missions in the inner solar system. Notable exceptions are lunar night or permanently shaded regions of the lunar south pole. NEP produces electric power that can be used for both propulsion and payloads. There are NTP concepts called bimodal systems in which the NTP engine reactor also produces a small amount of

electrical power sufficient for mission needs even when the NTP engine is not being use for propulsion. The added complexity of bimodal NTP is often traded against NEP or NTP with solar augmentation.

20. There have been exceptional advancements in high-power electric propulsion (EP) accelerated by recent investment from the private sector, such as in the NASA NextSTEP public private partnerships that led to the recent 88-hour endurance test of a VASIMR test engine. Additionally, electric propulsion innovation benefits from fusion energy development (now also accelerating with private investment) and the great advancements in power electronics for transportation and industry electrification. Yet, high-power electric propulsion development has suffered from low and intermittent investment over many decades. The National Academy of Sciences' panel recommended that the U.S. must accelerate a robust and sustained program to develop high-power electric propulsion thrusters needed to maintain and advance our leadership in space propulsion? How should NASA (and the federal government as a whole) invest in both incremental innovations, such as the Hall Effect Thruster, and disruptive innovations, such as the VASIMR engine?

Response: This question is best addressed by NASA.

21. What is the technology readiness level for current U.S. capabilities in each nuclear thermal propulsion and nuclear electric propulsion? How much additional investment of resources would be needed to fully mature each capability, and how long would that take before we could leverage that into a human mission to Mars?

Response: Technology readiness level (TRL) assessment is driven by data and evidence, but also has a subjective component depending on who's doing the assessment. Both NEP and NTP systems have multiple areas of technology that must be matured into a complete system that can fulfill the application. Some of these critical areas and subsystems are at the concept level (TRL 0-2), while others may have heritage related to their applications, experimental results other supporting data to rank them higher (perhaps TRL 5 or 6). Smaller, laboratory-scale demonstrations may be closer to becoming reality than the full mission systems and thus might have higher TRLs, which could skew the interpretation of the assessment. There have been several studies examining the TRLs for NEP and NTP, but until a definitive mission is offered where these approaches can then be traded against one another, assessments of technical and application readiness levels are likely to incorporate subjectivity and may not be a reliable influence for program plan or investment strategies.

Responses by Mr. Michael French

Committee on Science, Space, and Technology
Subcommittee on Space and Aeronautics
October 20, 2021 Hearing
"Accelerating Deep Space Travel with Space Nuclear Propulsion"
Responses to Questions for the Record
Michael French, Aerospace Industries Association
December 21, 2021

Chairman Beyer

1. Commercial actors in space nuclear propulsion include small and large businesses, new entrants, and established providers from both the aerospace and nuclear power sectors. What are some considerations for the federal government for sustaining and partnering with such a diverse array of organizations, especially for what is a relatively niche and specialized technology?

   Accelerating deep space travel with space nuclear propulsion requires a close partnership between the federal government and industry. In developing these partnerships, the federal government should consider the industry partners' (1) experience working in a nuclear regulatory environment, (2) expertise delivering complex, high-consequence nuclear and space systems, (3) ability to support the lifecycle of nuclear system design and delivery, and (4) ability to innovate on new nuclear technologies such as fuel development.

2. The focus of NASA's potential use of space nuclear propulsion technology is primarily on getting humans to Mars. What is the business case for space nuclear propulsion, and what is the market outlook?

   NASA's investment in a nuclear thermal propulsion system for a future human mission to Mars will develop key technologies relevant to the broader energy market. This includes the development of automated systems to run a reactor remotely, new nuclear fuels that are more risk tolerant, and the development of high temperature materials. Each of these technical developments is applicable to future domestic power systems. NASA's investments in surface power systems also have a direct market relevance. Reactor technologies for the surface power systems are expected to show extensibility to higher powers that would be needed for Nuclear Electric Propulsion (NEP) systems. These investments provide additional incentives for the development of nuclear fuels and power conversion technologies relevant to the future domestic power market.

3. What, in your view, are the biggest policy or regulatory hurdles for advancing space nuclear propulsion?

   The update of National Security Presidential Memorandum-20, Launch of Spacecraft Containing Space Nuclear Systems[i] and release of Space Policy Directive 6, National Strategy for Space Nuclear Propulsion and Power ("SPD-6"),[ii] are positive policy steps for advancing space nuclear propulsion. Remaining committed to both policy changes and completing the individual federal agency and interagency requirements detailed in each policy are significant steps the Executive Branch can take to advance space nuclear propulsion.

As detailed in my written testimony to the Committee, Congress can further accelerate the development of space nuclear propulsion by:

- *Finalizing FY22 funding for nuclear thermal propulsion with flight demonstration direction;*
- *Adopting the NASA infrastructure investments included in pending infrastructure legislation;*
- *Continuing to consistently fund nuclear thermal propulsion development and a flight demonstration in FY23 and beyond; and*
- *Passing a NASA reauthorization that includes language authorizing nuclear thermal propulsion activities, establishes a 2026 nuclear thermal propulsion flight demonstration date, and endorses accelerated partnership and coordination between NASA and the national security agencies on nuclear thermal propulsion flight demonstrations, common fuels, and operational systems production.*

4. During the question-and-answer portion of the hearing, Dr. Myers stated that the National Academies committee determined that "you really need to test full scale, fully integrated systems for nuclear thermal [propulsion]" on the ground before going to space. Do you agree with this statement? Why or why not?

   While the concept of nuclear propulsion was explored in the past, technological advancements now make it far more practical. One of those developments is modern analytics that allow for detailed digital analysis and design with less extensive ground testing than historically required. DARPA's Demonstration Rocket for Agile Cislunar Operations (DRACO) program is partnering with industry to advance methods for modeling and simulation and enable a flight demonstration. Aligned with recent Congressional funding and direction, NASA studies have determined a near term in-space flight demonstration of nuclear propulsion technology would accelerate the development of this technology.

Mr. Babin

1. How are the uranium fuel forms being developed to enable a range of terrestrial as well as space applications, including future commercial applications, and maximizing private-sector engagement and cost savings?

   NASA's investment in a nuclear thermal propulsion system for a future human mission to Mars will develop key technologies relevant to the broader energy market. This includes the development of automated systems to run a reactor remotely, new nuclear fuels that are more risk tolerant, and the development of high temperature materials. Each of these technical developments is applicable to future domestic power systems. NASA's investments in surface power systems also have a direct market relevance. Reactor technologies for the surface power systems are expected to show extensibility to higher powers that would be needed for Nuclear Electric Propulsion (NEP) systems These investments provide additional incentives for the development of nuclear fuels and power conversion technologies relevant to the future domestic power market.

2. In August 2019, the National Security Policy Memorandum 20 (NSPM-20) was updated to establish safety guidelines and safety analysis and review processes for Federal Government launches of

spacecraft containing space nuclear systems, including SNPP systems, and for launches for which the Department of Transportation has statutory authority to license as commercial space launch activities (commercial launches). How have these new guidelines improved the development of SNPP systems?

The update of National Security Presidential Memorandum-20, Launch of Spacecraft Containing Space Nuclear Systems[iii] is an important policy development for accelerating advanced nuclear propulsion. Under the updated system, a nuclear propulsion flight demonstration would likely be considered a Tier II mission under the policy given technology heritage and the expected use of low enriched uranium. The Executive Branch has additional tasks to complete under the updated policy, but the overall approach will better align with the future approval of low enriched uranium SNPP systems under development.

3. Which uranium fuel forms are needed to meet the nearest-term mission needs? How are they utilizing the same or similar materials, processes, designs, or infrastructure — across these fuel forms?

   NASA invested in highly enriched uranium (HEU) technologies in its legacy Nuclear Engine for Rocket Vehicle Applications (NERVA) and Space Nuclear Thermal Propulsion (SNTP) programs. These investments provide a foundation of research for the development of next generation systems, including the development of high assay low enriched uranium (HALEU) systems currently being explored by NASA, the Department of Energy, and industry.[iv] AIA supports NASA's continued partnership with industry on nuclear propulsion fuels development but is not expert on the technical development of uranium fuel forms. AIA recommends NASA's space nuclear technologies portfolio office provide further information.

4. Are the uranium fuel forms to meet near-term mission requirements maximizing private-sector engagement? Will these fuel forms be developed to enable a range of terrestrial as well as space applications, including future commercial applications?

   The development of low enriched uranium supported by NASA's nuclear thermal propulsion investments are relevant to the broader energy market. This includes the development of automated systems to run a reactor remotely, new nuclear fuels that are more risk tolerant, and the development of high temperature materials. Each of these technical developments is applicable to future domestic power systems. NASA's investments in surface power systems also have a direct market relevance. Reactor technologies for the surface power systems are expected to show extensibility to higher powers that would be needed for Nuclear Electric Propulsion (NEP) systems. These investments provide additional incentives for the development of nuclear fuels and power conversion technologies relevant to the future domestic power market.

5. How are departments and agencies collaborating on SNPP systems? Are they conducting regular technical exchanges among SNPP programs?

   Nuclear expertise and investments reside across the federal government and AIA supports enhanced federal collaboration on SNPP systems outlined in Space Policy Directive 6. Currently, AIA is aware of

and supports the active coordination taking place between DARPA's DRACO program and NASA's Marshall Space Flight Center, with support from NASA Headquarters and other national security agencies, to establish joint working groups to achieve common goals in their respective nuclear thermal propulsion activities.

6. Commonality, such as reactor designs, nuclear fuels, infrastructure, and testing, among SNPP systems, and between SNPP and terrestrial nuclear systems, will greatly increase the development and advancement of SNPP programs. How are DoD and NASA working with partners to evaluate and use opportunities for commonality with other SNPP needs, terrestrial power needs, and reactor demonstration projects planned by agencies and the private sector.

   NASA's nuclear thermal propulsion program and DARPA's DRACO program are complementary efforts to advance nuclear thermal propulsion technologies leading to a flight demonstration. DARPA and NASA are working collaboratively with industry partners across both programs. DARPA and NASA's Marshall Space Flight Center, with support from NASA Headquarters and other national security agencies, are also collaborating within the federal government to establish joint working groups to achieve common goals in their respective nuclear thermal propulsion activities.

7. "Extensibility" is the concept that technologies developed in the near-term will be useful for future exploration as well. Extensibility prevents the development of "dead-end" capabilities. How is NASA ensuring that its investments in space nuclear propulsion are extensible?

   NASA's investments and partnerships with industry on nuclear thermal propulsion and nuclear surface power system technologies are directly applicable to NASA's deep space exploration plans. NASA includes nuclear propulsion and nuclear surface power as two of the "6 Technologies NASA is Advancing to Send Humans to Mars."[v]

8. When will NASA need space nuclear propulsion capabilities? What architecture and strategic planning informs that schedule?

   NASA's 2015 Technology Roadmaps determined the need to develop nuclear thermal propulsion technology in the first half of the 2020s for a technology need date of 2027[vi] *and nuclear thermal propulsion remains an enabling technology in NASA's updated 2020 technology taxonomy.*[vii] *These timelines align with Congressional funding and direction for nuclear thermal propulsion development and an in-space flight demonstration.*

9. How should the government synergize nuclear surface power generation and space nuclear propulsion development?

   The federal government can take two steps to help synergize nuclear surface power generation and space nuclear propulsion development. First, the federal government should continue and enhance interagency collaboration on SNPP programs as outlined in SPD-6. Second, the government should continue to partner with industry in the development of both technologies. The combination of cross-government and industry-government insight will best ensure investments maximize industry capabilities and further overall development across both areas.

10. How is NASA coordinating current investments in cryogenic propellant storage and transfer so that it could be applicable for space nuclear propulsion?
AIA does not have insight into NASA's coordination in this area and recommends NASA's Space Technology Mission Directorate provide further information regarding this question.

11. What kind of propellants do nuclear electric propulsion systems use and what are the costs and benefits? Are there any rare or exotic fuels under consideration that could entail supply risks?

The thrusters being proposed for NASA's nuclear electric propulsion systems use xenon or krypton propellants and there are numerous production facilities located within the US.

12. The development of next generation nuclear propulsion involves advancing technologies associated with thrusters, power generation, power management, and cooling. What are the biggest challenges to scaling up the power or capacity of those subsystems?

AIA suggests a briefing from individual member company experts in this area for further information regarding this question and can arrange a briefing at your convenience.

13. How far along are other countries in advanced in-space propulsion? Are there any key technology areas in which the US does not lead?

China and Russia have made public claims of pursuing space nuclear propulsion, with Russia announcing it will fly a nuclear propulsion system in 2030.[viii] *If accomplished, this would represent a significant technological advancement.*

14. Highly enriched uranium (HEU) raises proliferation concerns and restricts the number of private sector organizations that could contribute to developments. Recent proposals have favored high assay low enriched uranium (HALEU) to address those concerns. But according to the Academy report, technical feasibility, performance, safety, fuel availability, cost, and schedule considerations do not favor HEU or HALEU. Should NASA make significant investments in space nuclear propulsion before conducting a comprehensive assessment of the relative merits and challenges associated with HEU and HALEU?

NASA invested in highly enriched uranium (HEU) technologies in its legacy Nuclear Engine for Rocket Vehicle Applications (NERVA) and Space Nuclear Thermal Propulsion (SNTP) programs. These investments provide a foundation of research for the development of next generation systems, including the development of high assay low enriched uranium (HALEU) systems currently being explored by NASA, the Department of Energy, and industry.[ix] *AIA supports NASA's continued partnership with industry on nuclear propulsion fuels development.*

15. Are their non-governmental markets for space nuclear propulsion systems?

NASA's investment in a nuclear thermal propulsion system for a future human mission to Mars will develop key technologies relevant to the broader energy market. This includes the development of automated systems to run a reactor remotely, new nuclear fuels that are more risk tolerant, and the development of high temperature materials. Each of these technical developments is applicable to future domestic power systems. NASA's investments in surface power systems also have a direct market relevance. Reactor technologies for the surface power systems are expected to show extensibility to higher powers that would be needed for Nuclear Electric Propulsion (NEP) systems. These investments provide additional incentives for the development of nuclear fuels and power conversion technologies relevant to the future domestic power market.

16. In May, China become the only non-U.S. country to successfully deploy a rover on the surface of Mars. Shortly afterwards, China announced that it intends to conduct crewed missions to Mars in 2033. The head of the China Academy of Launch Vehicle Technology indicated at the time that to shorten the travel time, spacecraft would have to tap energy released from nuclear reactions in the form of heat and electricity, in addition to traditional chemical propellants. What insight do we have into China's current capabilities regarding space nuclear propulsion? How much are they spending per year? Are their schedules realistic? Are they focusing on NTP or NTP? If they are focused on both, which technology is father along? Could they develop space nuclear propulsion before we do?

China has shown accelerated progress of its space capabilities and Congressional investments across the civil and national security space enterprise are critical given China's focus in this area. In the near term, this includes the extension of the International Space Station to maintain U.S. global space leadership in low Earth orbit. AIA is aware of public statements regarding Chinese interest in developing nuclear propulsion systems but does not have further insight into China's nuclear propulsion activities.

17. Mr. French, Congress has Appropriated hundreds of millions of dollars towards nuclear thermal propulsion over the last several years, and your testimony calls for greater investment in nuclear thermal propulsion. Why the emphasis on this technology? Given the synergies between nuclear surface power and nuclear electric propulsion, does AIA support investment in nuclear electric propulsion as well?

AIA supports continued NASA, DOE, and DOD investment and partnership with industry to advance nuclear thermal propulsion and nuclear surface power technologies. AIA supports continued investment in nuclear propulsion aligned with NASA's technology roadmaps and the findings of the National Academies' Nuclear Propulsion study. NASA's 2015 Technology Roadmaps determined the need to develop nuclear thermal propulsion technology in the first half of the 2020s for a technology need date of 2027[x] and nuclear thermal propulsion remains an enabling technology in NASA's updated 2020 technology taxonomy.[xi] The National Academies of Sciences, Engineering, and Medicine's Space Nuclear Propulsion for Human Mars Exploration study found an "aggressive program" could achieve a nuclear thermal propulsion baseline mission in 2039.[xii] AIA further supports NASA and DOE's efforts to advance nuclear surface power as an enabling technology for sustainable exploration. AIA supports investment in technologies relevant to nuclear electric propulsion, including NASA's surface power efforts and the development of nuclear fuels.

18. Solar power is limited by available surface area and distance from the sun. In the future, missions will likely require more and more power, and U.S. government investment in developing space based nuclear electric generation would be a great step forward. How would missions with nuclear thermal propulsion produce electricity for missions where solar is not a viable option? How would you assess the benefits of using nuclear electric propulsion that could provide ample for missions as well as propulsion? How should that characteristic be weighted in architecture decisions?

    AIA suggests a briefing from individual member company experts in this area for further information regarding this question and can arrange a briefing at your convenience.

19. There have been exceptional advancements in high-power electric propulsion (EP) accelerated by recent investment from the private sector, such as in the NASA NextSTEP public private partnerships that led to the recent 88 hour endurance test of a VASIMR test engine. Additionally, electric propulsion innovation benefits from fusion energy development (now also accelerating with private investment) and the great advancements in power electronics for transportation and industry electrification. Yet, high-power electric propulsion development has suffered from low and intermittent investment over many decades. The National Academy of Sciences' panel recommended that the U.S. must accelerate a robust and sustained program to develop high-power electric propulsion thrusters needed to maintain and advance our leadership in space propulsion? How should NASA (and the federal government as a whole) invest in both incremental innovations, such as the Hall Effect Thruster, and disruptive innovations, such as the VASIMR engine?

    AIA recommends NASA's Space Technology Mission Directorate provide further information regarding this question.

20. What is the technology readiness level for current U.S. capabilities in each nuclear thermal propulsion and nuclear electric propulsion? How much additional investment of resources would be needed to fully mature each capability, and how long would that take before we could leverage that into a human mission to Mars?

    The National Academies of Sciences, Engineering, and Medicine's Space Nuclear Propulsion for Human Mars Exploration study found an "aggressive program" could achieve a nuclear thermal propulsion baseline mission in 2039.[xiii]

21. Mr. French, AIA is endorsing greater investment in nuclear thermal propulsion. Why the emphasis on this technology? Does AIA support investment in nuclear electric propulsion as well?

    AIA supports continued NASA, DOE, and DOD investment and partnership with industry to advance nuclear thermal propulsion and nuclear surface power technologies. AIA supports continued investment in nuclear propulsion aligned with NASA's technology roadmaps and the findings of the National Academies' Nuclear Propulsion study. NASA's 2015 Technology Roadmaps determined the need to develop nuclear thermal propulsion technology in the first half of the 2020s for a technology

need date of 2027[xiv] *and nuclear thermal propulsion remains an enabling technology in NASA's updated 2020 technology taxonomy.*[xv] *The National Academies of Sciences, Engineering, and Medicine's Space Nuclear Propulsion for Human Mars Exploration study found an "aggressive program" could achieve a nuclear thermal propulsion baseline mission in 2039.*[xvi] *AIA further supports NASA and DOE's efforts to advance nuclear surface power as an enabling technology for sustainable exploration. AIA supports investment in technologies relevant to nuclear electric propulsion, including NASA's surface power efforts and the development of nuclear fuels.*

Mr. Crist

1. The Aerospace Industries Association (AIA) is endorsing greater investment in nuclear thermal propulsion.
    a. Why the emphasis on this technology?

AIA supports continued NASA, DOE, and DOD investment and partnership with industry to advance nuclear thermal propulsion and nuclear surface power technologies. AIA supports continued investment in nuclear propulsion aligned with NASA's technology roadmaps and the findings of the National Academies' Nuclear Propulsion study. NASA's 2015 Technology Roadmaps determined the need to develop nuclear thermal propulsion technology in the first half of the 2020s for a technology need date of 2027[xvii] *and nuclear thermal propulsion remains an enabling technology in NASA's updated 2020 technology taxonomy.*[xviii] *The National Academies of Sciences, Engineering, and Medicine's Space Nuclear Propulsion for Human Mars Exploration study found an "aggressive program" could achieve a nuclear thermal propulsion baseline mission in 2039.*[xix] *AIA further supports NASA and DOE's efforts to advance nuclear surface power as an enabling technology for sustainable exploration.*

    b. Does AIA support investment in nuclear electric propulsion as well?

AIA supports investment in technologies relevant to nuclear electric propulsion, including NASA's surface power efforts and the development of nuclear fuels.

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[i] National Security Presidential Memorandum-20, Launch of Spacecraft Containing Space Nuclear Systems, 2019, available at https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-launch-spacecraft-containing-space-nuclear-systems/ (visited 10/15/21)

[ii] Space Policy Directive 6 available at https://www.federalregister.gov/documents/2020/12/23/2020-28457/posting-of-the-presidential-policy-directive-6-space-policy-national-strategy-for-space-nuclear (visited 10/15/21)

[iii] National Security Presidential Memorandum-20, Launch of Spacecraft Containing Space Nuclear Systems, 2019, available at https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-launch-spacecraft-containing-space-nuclear-systems/ (visited 10/15/21)

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[v] "6 Technologies NASA is Advancing to Send Humans to Mars," NASA, available at https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars (visited 12/13/21)

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[xiv] July 2015 NASA Technology Roadmaps, TA 2: In-Space Propulsion Technologies, NASA, available at https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf (visited 10/15/21)
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Responses by Dr. Franklin Chang-Diaz

Responses (for the record) to Questions from Members of Congress

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April 14, 2022



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I. Submitted by Chairman Beyer

1. You are leading the development of an early-stage technology. What are the biggest challenges you have experienced in leading such a program in the private sector, and what, in your view, are important factors to consider in effective government partnerships with early-stage private sector technology development?

   Answer: In the case of Moon and Mars, early-stage technology implies high risk without a near-term addressable market (presently there is no business case for going to the Moon, let alone Mars). Both these conditions will inhibit early private investment. Therefore, the most important factors for the government to consider are: 1) buy the risk and 2) generate an early market for the technology.

   A good example of an effective government-sponsored partnership in space that stimulated a new commercial market was NASA's Commercial Orbital Transportation System (COTS) Program that helped Space X and Orbital Sciences Corp. develop the Dragon and Cygnus commercial ISS resupply vehicles respectively and the follow on NASA contracts to those companies to provide those services.

II. Submitted by Mr. Babin

1. How are the uranium fuel forms being developed to enable a range of terrestrial as well as space applications, including future commercial applications, and maximizing private-sector engagement and cost savings?

   Answer: The uranium level of enrichment always evokes nuclear proliferation concerns. For terrestrial, non-military applications, low enrichment is preferred as the size and weight of the reactor are not as critical and access to the materials is more difficult to control. However, for high-power, nuclear-electric space propulsion, highly enriched uranium (HEU) would be my preference, as it would tend to make the reactor, and many of its associated systems, compact and lightweight. Access to HEU is also easier to control in space.

   On the private-sector engagement, from its inception, the nuclear industry has operated as a public-private relationship. I do not see any reason to change this arrangement for space.

2. What is the power range for the current demonstration of a fission power system on the surface of the Moon? How is that program aligned with mission needs for, and potential future government and commercial applications of, in-space power, NEP, and terrestrial nuclear power?

   Answer: The power range of present fission surface power systems being considered for the Moon is far too low (1-10 kW) to be relevant or aligned with high-power NEP human missions to Mars. Consider some approximate numbers: The power range of a typical

terrestrial nuclear power plant is in the 1000s of MW; a typical nuclear submarine is ~100 MW; the PELE portable reactor being developed for the US ARMY is 1-5 MW. For space, the power of an NTP rocket is ~200 MW. A compelling and relevant fission NEP system for space should be at least tens of MW.

3. In August 2019, the National Security Policy Memorandum 20 (NSPM-20) was updated to establish safety guidelines and safety analysis and review processes for Federal Government launches of spacecraft containing space nuclear systems, including SNPP systems, and for launches for which the Department of Transportation has statutory authority to license as commercial space launch activities (commercial launches). How have these new guidelines improved the development of SNPP systems?

   Answer: From a quick read of NSPM-20, my sense is that, when applied, the effect of the guidelines would be minor, albeit beneficial. For SNPP[1] operations near the Earth, the safety of the population is the most important factor and hence it makes sense that the level of authority for approving the launch of nuclear material increase with the risk. However, commercially, the utility of SNPP systems is not as compelling near the Earth or even the Moon. For missions far from Earth (Moon, Mars and beyond) where SNPP shines, the risk to the population goes down quickly.

4. Which uranium fuel forms are needed to meet the nearest-term mission needs? How are they utilizing the same or similar materials, processes, designs, or infrastructure — across these fuel forms?

   Answer: From my answer to question 3 above, the true value of SNPP is for applications far from Earth, including fast human missions to Mars and beyond (where population and proliferation risks are low). For these applications, I would favor the use of highly enriched uranium (HEU).

5. Are the uranium fuel forms to meet near-term mission requirements maximizing private-sector engagement? Will these fuel forms be developed to enable a range of terrestrial as well as space applications, including future commercial applications?

   Answer: As discussed above, from its inception, the nuclear industry has operated quite well as a public-private relationship. Terrestrial operations, both civilian and military, are quite mature. I do not see a reason to change this arrangement for space.

6. How are departments and agencies collaborating on SNPP systems? Are they conducting regular technical exchanges among SNPP programs?

   Answer: Speaking of NASA and the DoE, from what I have been able to observe, the collaboration and cross-pollination are slowly improving, though not fast enough to fully explore the value proposition of SNPP. There is a growing bias towards nuclear-thermal

[1] Space Nuclear Power and Propulsion (SNPP)

propulsion (NTP) versus nuclear-electric propulsion (NEP), which is tending to stifle the maturation of the latter, an option that actually provides the best long-term payoff.

7. Commonality, such as reactor designs, nuclear fuels, infrastructure, and testing, among SNPP systems, and between SNPP and terrestrial nuclear systems, will greatly increase the development and advancement of SNPP programs. How are DoD and NASA working with partners to evaluate and use opportunities for commonality with other SNPP needs, terrestrial power needs, and reactor demonstration projects planned by agencies and the private sector?

   Answer: This commonality is most evident in NEP applications; however, as I discuss in my answer to question 2, the present power level being considered is far too low to make a compelling extrapolation to fast NEP human transportation to Mars and beyond. I would recommend that DoE/DoD and NASA work together on a much higher power NEP option, such as a space derivative of the PELE portable terrestrial (1-5 MW) reactor being developed for the US ARMY.

8. "Extensibility" is the concept that technologies developed in the near-term will be useful for future exploration as well. Extensibility prevents the development of "dead-end" capabilities. How is NASA ensuring that its investments in space nuclear propulsion are extensible?

   Answer: While others will surely disagree, it is hard for me to imagine NTP providing an "extensible" long-term nuclear propulsion option for fast human missions to Mars and beyond. The maximum specific impulse of these systems is not likely to exceed ~1000 sec, which, while twice as good as the best chemical rocket, does not compare to the 10 to 20 times better performance of a high-power NEP system. Also, NEP systems based on high density magnetized plasmas are natural precursors (extensible) to future fusion rockets.

9. When will NASA need space nuclear propulsion capabilities? What architecture and strategic planning informs that schedule?

   Answer: The need is now, but mission studies of high-power (50-100 MWe) NEP are lacking. The work on NTP started in the 1950s and was terminated in the 1970s. The work on high-power NEP was stifled by minimal efforts and a thin portfolio of electric thrusters that could handle such high power levels. Times have changed. Advances in high-temperature superconductors, radiofrequency plasma technology (driven by the DoE fusion program) and miniaturized power electronics are enabling high-power thrusters that can meet the high-power NEP challenge. NASA should conduct a high power (50-100 MW) NEP mission study that fully explores the value proposition of that technology.

10. How should the government synergize nuclear surface power generation and space nuclear propulsion development?

Answer: A relationship between institutions like Idaho National Laboratory (INL) and NASA needs to be nurtured and strengthened, along with a strong parallel effort in high power electric propulsion and nuclear-to-electric power conversion. For example, an end-to-end test of a high-power electric thruster could be conducted at INL with electric power from the PELE reactor, which will soon come into operation. Such a test could provide useful information to develop a near-term demonstrator to be tested in space.

11. How is NASA coordinating current investments in cryogenic propellant storage and transfer so that it could be applicable for space nuclear propulsion?

    Answer: I do not know how NASA is addressing this. My take is that long-term cryogenic propellant storage is an issue for NTP because the system lacks sufficient electrical power to refrigerate the propellant. This is not the case for NEP due to its abundant supply of electricity which would be used to support active refrigeration of the propellant virtually indefinitely.

12. What kind of propellants do nuclear electric propulsion systems use and what are the costs and benefits? Are there any rare or exotic fuels under consideration that could entail supply risks?

    Answer: For NTP the propellant is hydrogen (abundant and cheap). For low-power NEP, Xenon is the traditional propellant, which falls under the "exotic" category and would pose a problem in high power NEP applications as the gas is rare and expensive (~$1000/kg of Xenon as compared with ~$300/kg of Krypton and ~$5/kg of Argon). For high-power NEP, the propellant could be hydrogen, argon, krypton, ammonia, and several other options depending on the mission. All these propellants are abundant and cheap.

13. The development of next generation nuclear propulsion involves advancing technologies associated with thrusters, power generation, power management, and cooling. What are the biggest challenges to scaling up the power or capacity of those subsystems?

    Answer: funding, funding, funding...We have the know-how, but need the funds.

14. How far along are other countries in advanced in-space propulsion? Are there any key technology areas in which the US does not lead?

    Answer: Other nations have matured their low-power electric propulsion portfolio, so the playing field, on that front, is fairly even with the US.

    On high-power electric propulsion, the picture is not as clear. We at Ad Astra Rocket Company believe we have the record for the longest high-power endurance test (88 hours at 80 kW) of an electric rocket approaching TRL-5, the VASIMR® VX-200SS. There have been sketchy reports of other high-power electric thrusters operating for many hours in Russia, but these are not verified and are likely not at TRL-5 (all their critical components

in the vacuum environment). Clearly, we need to keep up the pace to stay ahead. The competition will only get more intense.

On the nuclear front, with proper funding, all the nuclear-capable nations (there are quite a few now) have what it takes to transition a reactor and nuclear-to-electric power conversion to space operations. I suspect that China and Russia are already working on this.

15. Highly enriched uranium (HEU) raises proliferation concerns and restricts the number of private sector organizations that could contribute to developments. Recent proposals have favored high assay low enriched uranium (HALEU) to address those concerns. But according to the Academy report, technical feasibility, performance, safety, fuel availability, cost, and schedule considerations do not favor HEU or HALEU. Should NASA make significant investments in space nuclear propulsion before conducting a comprehensive assessment of the relative merits and challenges associated with HEU and HALEU?

    Answer: As noted in question 4, I favor the use of HEU. Controversial as it is, HALEU is an unnecessary constraint that hinders the full potential of high-power NEP for human transportation applications. Recent conversations with nuclear experts from Idaho National Laboratory support this.

16. Are there non-governmental markets for space nuclear propulsion systems?

    Answer: None are addressable at the moment. However, I would envision that future energy-intensive space mining operations on asteroids and the Moon could favor power-rich nuclear electric architectures for power and propulsion.

17. In May, China became the only non-U.S. country to successfully deploy a rover on the surface of Mars. Shortly afterwards, China announced that it intends to conduct crewed missions to Mars in 2033. The head of the China Academy of Launch Vehicle Technology indicated at the time that to shorten the travel time, spacecraft would have to tap energy released from nuclear reactions in the form of heat and electricity, in addition to traditional chemical propellants. What insight do we have into China's current capabilities regarding space nuclear propulsion? How much are they spending per year? Are their schedules realistic? Are they focusing on NTP or NTP? If they are focused on both, which technology is father along? Could they develop space nuclear propulsion before we do?

    Answer: The little that I have observed leads me to believe they are serious about space nuclear power. Presently, we have very little insight on their programs, schedules, and level of spending and/or progress. They are probably looking at both NTP and NEP. My sense is that they are about as advanced as we are and, yes, if we do not pick up the pace on high-power NEP, they could develop it before we do.

18. Solar power is limited by available surface area and distance from the sun. In the future, missions will likely require more and more power, and U.S. government investment in developing space based nuclear electric generation would be a great step forward. How would missions with nuclear thermal propulsion produce electricity for missions where solar is not a viable option? How would you assess the benefits of using nuclear electric propulsion that could provide ample for missions as well as propulsion? How should that characteristic be weighted in architecture decisions?

    Answer: As you point out in your question, in this respect, the advantages of using high-power NEP over NTP are clear and indisputable. The high levels of electrical power produced in NEP systems could be easily switched to other energy-intensive uses, such as mining, H_2 and O_2 production through water electrolysis, waste recycling, materials processing, manufacturing, among others. From the start, NEP enables a power-rich architecture, insuring human survival and ultimately sustainable habitation.

19. There have been exceptional advancements in high-power electric propulsion (EP) accelerated by recent investment from the private sector, such as in the NASA NextSTEP public private partnerships that led to the recent 88 hour endurance test of a VASIMR test engine. Additionally, electric propulsion innovation benefits from fusion energy development (now also accelerating with private investment) and the great advancements in power electronics for transportation and industry electrification. Yet, high-power electric propulsion development has suffered from low and intermittent investment over many decades. The National Academy of Sciences' panel recommended that the U.S. must accelerate a robust and sustained program to develop high-power electric propulsion thrusters needed to maintain and advance our leadership in space propulsion? How should NASA (and the federal government as a whole) invest in both incremental innovations, such as the Hall Effect Thruster, and disruptive innovations, such as the VASIMR engine?

    Answer: The Hall Effect Thruster is a low-power electric propulsion technology, of Russian origin, imported to the US in the mid 1980s and incrementally improved with hundreds of millions of dollars in R&D invested by the federal government. The power level of these thrusters remains low.

    The VASIMR® engine is a disruptive high-power electric propulsion American technology, initially conceived and studied at MIT in the early 1980s, then at NASA and, since 2005, matured with primarily private funding, by the Ad Astra Rocket Company. The investment from the federal government over more than 40 years has been minimal. In a recent NASA competition, the VASIMR® engine achieved a (power x endurance) performance two orders of magnitude greater than that of a competing Hall Effect Thruster.

NASA High-power Electric Propulsion Endurance Test Results		
Technology	Endurance	Power

Hall Effect Thruster	0.8 hrs	67 kW
VASIMR®	88.0 hrs	80 kW

20. What is the technology readiness level for current U.S. capabilities in each nuclear thermal propulsion and nuclear electric propulsion? How much additional investment of resources would be needed to fully mature each capability, and how long would that take before we could leverage that into a human mission to Mars?

    Answer: Overall, from simple arguments[2], both NTP and NEP are at comparable TRL. In both cases, increasing the TRL will initially depend solely on funding. Down-selecting at this point is premature. Instead, a balanced funding at the $1-2 billion per year over 3-4 years for both technologies is the way to go to fully mature them to the point of testing them in space (TRL~7). At that point, it will be time to down-select. Unfortunately, today, the funding is very low and prematurely skewed in favor of NTP.

    As to how long would it take to leverage the nuclear capability into a human mission to Mars? With proper and sustained funding, the technology could be ready in ~10 years.

III. Submitted by Mr. Brooks

1. The demonstration of a nuclear propulsion system in space, based on either thermal or electric propulsion, would clearly check technology boxes VASIMR requires to be operational. Describe the other technology development VASIMR needs in addition to a nuclear propulsion demo, such as superconducting magnets and another technologies?

   Answer: Fortunately, the other technologies, such as superconducting magnets, plasma engineering, high-power radiofrequency (RF) generators, advanced materials and manufacturing have benefited from investment by the private sector and the federal government, primarily through DoE's programs in controlled thermonuclear fusion. Space qualification of these technologies is still needed, however, and presents a natural opportunity for NASA to become involved.

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[2] To make an estimate on TRL, we need to examine NTP and NEP at comparable power. For NTP operating at ~100 MW (thermal), the overall TRL is probably around 3-4. For NEP, a reactor of similar (thermal) power with nuclear-to-electric power conversion and radiator included would be at TRL~4. Four ~10 MW (TRL~3) thrusters would be required to handle the ~40 MW total electrical output (assume 40% nuclear-to-electric conversion efficiency).

IV. Brief Information on VASIMR® NEP

Sustainable space exploration near and beyond our Earth-Moon environment requires more robust and cost-effective propulsion than can be provided by chemical rockets alone. Nuclear propulsion offers great promise and especially high-power (50-100 MW nuclear-electric, NEP). The case for high-power NEP has been strengthened by the compelling results of Ad Astra's VASIMR® engine high power endurance test of July 16, 2022, combined with progress in reactor technology, high temperature high-field superconducting magnets and RF ionization of high temperature flowing gases. A VASIMR® NEP system could provide high-power and high specific impulse (I_{sp}), capability as a re-usable upper stage that could disrupt space transportation in both, cislunar and in deep space. A thorough assessment of an integrated – reactor, power conversion, thruster, and heat rejection – VASIMR® NEP system is likely to reveal an attractive mass scaling at power levels beyond 1 MWe. An integrated VASIMR® NEP system study could help bring the high-power NEP architecture into clearer focus and point the way for a space demonstration.

The VASIMR® is a high-power electric plasma propulsion device that scales favorably from 100s of kW to multi-megawatts. The high power of the engine enables sufficiently fast transits, while retaining the high specific impulse (I_{sp}) characteristic of electric rockets. The VASIMR® is well suited for large in-space cargo transport, using either solar or nuclear electric power. One of its distinguishing features (as its name implies) is its capability to optimally vary thrust and I_{sp} at constant power for minimum fuel consumption during flight, or as needed to accomplish specific mission objectives, such as fast transfers requiring a bit more maneuvering muscle than what traditional electric rockets can provide.

The development of the VASIMR® engine has been ongoing for several decades, initially as a low Technology Readiness Level (TRL) project at MIT and NASA, and later as a privately funded technology maturation effort by the Ad Astra Rocket Company (Ad Astra), a small, privately held, R&D company, incorporated in the State of Delaware and domiciled in Webster, Texas, about three miles from NASA's Johnson Space Center.

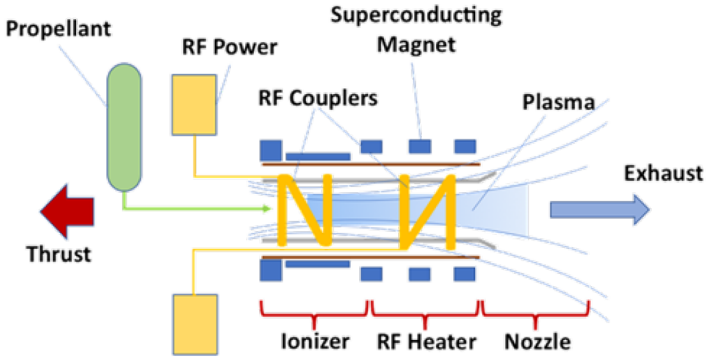
From its inception in 2005, and after an investment of >40 million dollars of, exclusively, private funds, Ad Astra matured the VASIMR® technology from a technology readiness level (TRL) of 2 to 4. Starting in late 2015, NASA and the Canadian Space Agency (CSA) contributed to Ad Astra's VASIMR® technology maturation program with contracts of 10 million and 1.5 million respectively. These funds, together with an additional 7 million in private funds from Ad Astra contributed to bringing the VASIMR® engine to TRL-5 in the summer of 2021.

The high-power scalability, small form factor, multiple propellant options, and simple power processing of the VASIMR® engine makes it attractive for space nuclear power with magnetohydrodynamic (MHD) power conversion. A point design of such an integrated nuclear-electric propulsion system has not been done and could provide valuable insight into the applicability of the VASIMR® engine to accomplish mission scenarios that may be relevant to furthering the nation's goals in space.

V. The VASIMR® engine

The VASIMR® engine works with plasma, an electrically charged fluid that can be heated to extreme temperatures by radio waves and controlled and guided by strong magnetic fields. The magnetic field also insulates nearby structures so achieving high plasma power density is possible. Electric plasma rockets enable a very high I_{sp} as compared with chemical rockets; VASIMR®, however, in addition to its high power-density, has two additional distinguishing features: 1) the ability to vary thrust and specific impulse at constant power to optimally match mission requirements (constant power throttling), and 2) the absence of physical electrodes in contact with the hot plasma. This results in greater reliability and longer life and enables a much higher power density than competing designs.

Topologically, the VASIMR® engine comprises three linked magnetic cells: 1) a plasma source, or "ionizer," 2) an "RF heater," and 3) a magnetic "nozzle." The plasma source is responsible for efficient plasma production while the RF heater acts as an amplifier further energizing the plasma to the desired conditions. The magnetic nozzle converts the plasma energy into directed motion and ultimately useful thrust.

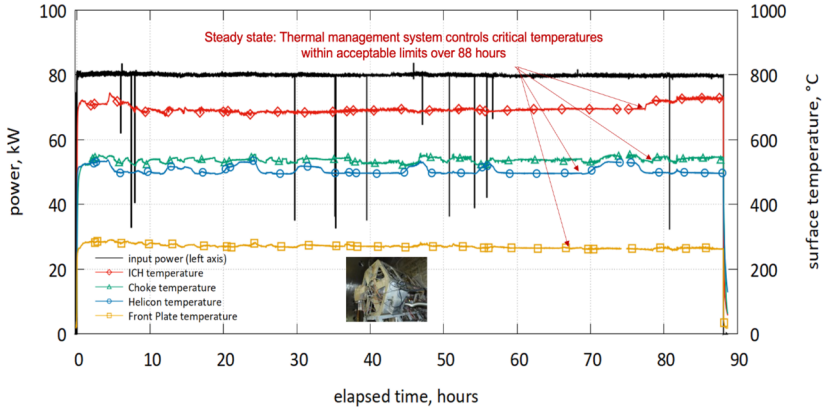


Simplified schematic of the VASIMR engine

In 2010-2013, in short duration laboratory tests, the VX-200™ VASIMR® prototype demonstrated a thruster efficiency of 72% and a specific impulse of 4900 seconds with argon propellant [(i)]. In 2015, a modified version of this thruster, called the VX-200SS™ (SS for steady-state) became one of three electric propulsion technologies selected by NASA to demonstrate steady-state operation at 100 kW of total input power [(ii)]. The VX-200SS™ design called for a new high temperature superconducting magnet to fully accommodate the new rocket core design. However, the new magnet did not become available due to NASA budgetary limitations; therefore, the VX-200SS™ operated with the original low temperature superconducting magnet of the VX-200™. The sub-optimum magnetic geometry, while not a technical "show-stoper," resulted in a more challenging thermal management problem and made meaningful erosion

measurements, a secondary objective, unreliable. Despite these limitations, however, the program produced breakthrough results with all major subsystems demonstrated at high power in thermal steady state in the vacuum environment.

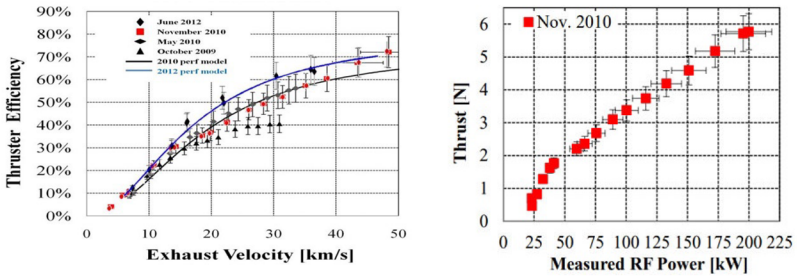
On July 12-16, 2021, a major endurance test performed on the VX-200SS VASIMR® prototype at Ad Astra's 150 m^3 high-vacuum facility, demonstrated thermal steady-state operation of the engine for 88 continuous hours at a power level of 80 kW. This test demonstrated the technological maturity of the engine, and while the TRL-5 goal has largely been achieved, additional tasks have been identified to improve the robustness of the present design and the capability of the test infrastructure. The goals of the Ad Astra team in 2022 are to demonstrate thermal steady state at 100 kW and initiate the design of a TRL-6 prototype that can be tested in space in the 2025 timeframe.



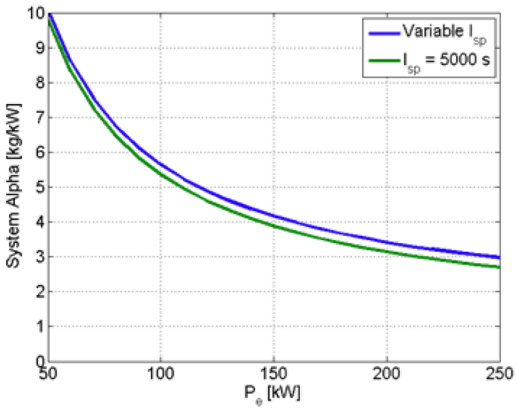
VX-200SS VASIMR® prototype 88-hr high power endurance test at 80 kW. The data shows the steady-state temperatures of critical plasma-facing components. Some variation in the steady-state temperatures is observed over the nearly four-day test, due to laboratory cooling equipment cycling on and off and occasional manual adjustments to the laboratory steady-state coolant flow

VI. Thruster Performance and Scalability

The results of the VX-200 tests with argon propellant [(i)] show good thruster efficiency at high power and high I_{sp} and the thrust to power scaling shows a linear trend with no indications of saturation at high power. In addition, a thorough mass scaling with power study was carried out by Ad Astra in 2013 [iii] that shows the power specific mass – denoted as alpha (α) – decreasing to less than 3 kg/kW as the power is increased to 250 kW. This decreasing trend is expected to continue at even higher power.



(left) Thruster efficiency as a function of exhaust velocity (I_{sp}) for various experimental campaigns of the VX-200 at 200 kW. (right) measured thrust in the VX-200 as a function of RF power, showing a nearly linear dependence for power levels greater than 50 kW.



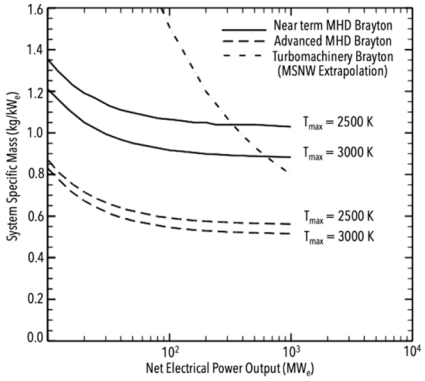
Comprehensive study of VASIMR® mass scaling with power in the range between 50 kW and 250 kW.

VII. Nuclear to Electric Power Conversion

Beyond a thruster such as VASIMR®, capable of processing large amounts of electric power in a compact and lightweight package, a high-power nuclear electric propulsion (NEP) system will need an equally lightweight and compact fission reactor with an appropriate power conversion system. Some system level studies have been carried out that show significant promise. However, these studies are approaching one to two decades from publication and need updating as technology has advanced.

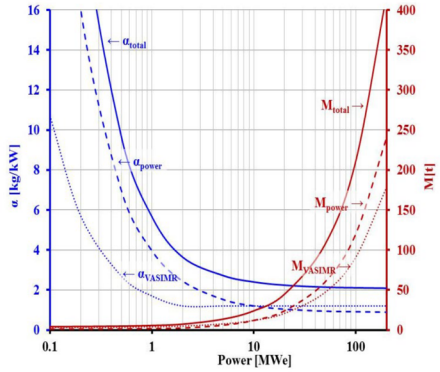
The potential for lightweight MHD power conversion was identified early by NASA's Ronald Litchford, Leo Bitteker and Jonathan Jones in their 2001 seminal study [iv]. A decade later,

Litchford and Harada proposed an MHD generator with a non-equilibrium He/Xe working plasma [v].



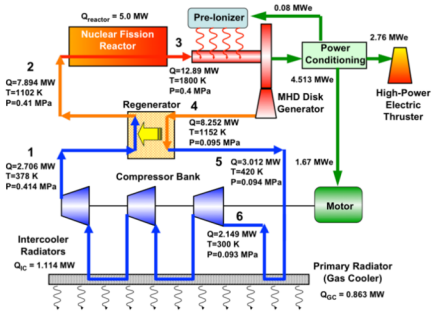
Estimates of potential advantages in specific mass scaling for MHD power conversion (from reference iv)

In 2013, an Ad Astra-led study in collaboration with researchers at NASA Marshall and Johnson Space Centers and the Nagaoka University of Technology in Japan published an integrated look at the overall system alpha (kg/kW) of an NEP system, including both, the power and propulsion elements and using the VASIMR® as the chosen propulsion technology [vi]. Once again, the results of that study point to considerable improvements in overall system alpha (power and propulsion) with MHD power conversion as the power increases beyond 1 MW.



Overall system alpha (kg/kW) and total mass of a high-power NEP with VASIMR® propulsion

The general architecture of an NEP system is shown below.



A general schematic of the nuclear power and propulsion architecture

VIII. Potential Technology Improvements in MHD Power Conversion

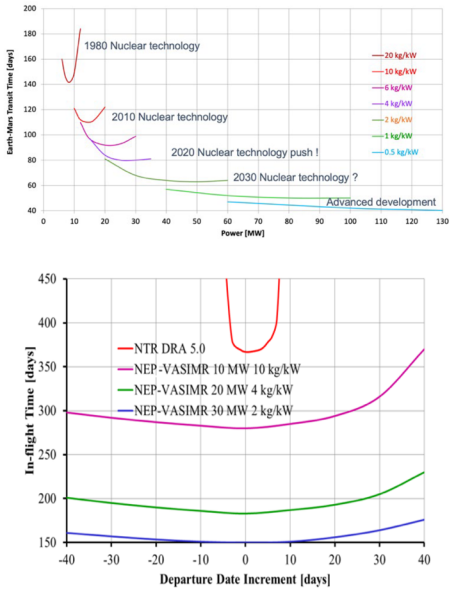
MHD power conversion technologies could benefit from two areas that have seen significant advances in recent times: 1) high temperature superconducting magnets, and 2) RF-induced ionization technology.

On the first area, superconducting magnets at field intensities of 10 Tesla are now possible with advances in Rare Earth Barium Copper Oxide (REBCO) high temperature superconductors. While the present VASIMR® superconducting magnet is a low temperature design, the engineering of these systems has advanced to magnets that do not require flowing cryogenic cooling but rather work on extremely good thermal isolation. Operating at 5 °K, and 2 Tesla, the VASIMR® VX-200SS superconductor is a conduction-cooled, cryogen-free magnet that has been reliable for more than a decade, even considering several quenches caused by unexpected power outages in the laboratory. Conceptual designs for the high-temperature version of this magnet have been initiated but have not yet been pursued to fabrication pending available funding.

On the second area, the RF system of the VASIMR® engine has matured to nearly TRL-5 and the Ad Astra team has acquired design and operational know-how on RF ionization systems. This expertise could be brought to bear in the ionization of the working fluid in the MHD generator. This is an area of study that needs to be strengthened, as the efficiency of the MHD generator is closely tied to the degree of ionization in the flowing medium. Ad Astra Rocket Company is working with the team at the MIT Plasma Science and Fusion Center (PSFC) on collaborative studies on this topic. The Ad Astra's electric propulsion laboratory in Texas has up to 250 kW of installed RF generation capacity to conduct potential ionization experiments on disk or tubular MHD configurations.

IX. The NEP Value Proposition[3]

While the 2x performance improvement generated by nuclear-thermal propulsion (NTP) over conventional chemical rockets is significant, the potential payoff of multi-megawatt nuclear-electric propulsion (NEP) is far greater and could be transformational. Much faster interplanetary transit times greatly reduce the radiation hazard and psychological stress to the crew, as well as the immense logistics burden that missions of 2+ years in deep space imply. In addition, the rapid transit afforded by multi-megawatt NEP opens the departure and return windows from days to weeks and produces much better mission abort options. These are important operational advantages in a robust and sustainable human exploration program.



One-way Mars transits with NEP vs power (left), and departure window growth (right) with advances in nuclear-electric power and propulsion technology. Ref: Ad Astra Rocket Company "Sustainable Human Exploration, Building on Commercial Capability." Briefing to Dr. Ellen Ochoa, Center Director, NASA Johnson Space Center, July 25, 2013

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