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

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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By way of background, NTP systems are conceptually similar to chemical rockets, where the combustion chamber has been replaced by a compact, very high-power-density nuclear reactor.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.