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Space Nuclear Propulsion Technologies Committee

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

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Preface

NASA's Space Technology Mission Directorate requested the National Academies of Sciences, Engineering, and Medicine to convene an ad hoc committee to identify primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion technologies of interest to future exploration missions. The particular systems of interest were specified as nuclear thermal propulsion and nuclear electric propulsion systems. The committee was also tasked with determining the key milestones, a top-level development and demonstration roadmap, and other missions that could be enabled by successful development of these systems.

The Aeronautics and Space Engineering Board of the National Academies' Division on Engineering and Physical Sciences assembled a committee to carry out the assigned statement of task (see Appendix B). The committee members (see Appendix C) held 14 virtual meetings during 2020 and drafted this report based on inputs received during its public meetings, additional documents reviewed by the committee, and the expertise of the members. A list of all of the findings and recommendations that appear in the main body of the report appears in Appendix A.

Robert D. Braun, *Co-Chair*
Roger M. Myers, *Co-Chair*
Space Nuclear Propulsion Technologies Committee

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their review of this report:

Douglas M. Allen, Schafer Corporation (retired),
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Susan S. Voss, Global Nuclear Network Analysis, LLC, and
Edward L. (Ned) Wright, NAS, University of California, Los Angeles.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by William Kastenberg, NAE, University of California, Berkeley (retired), and Lester Lyles, NAE, Independent Consultant. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Executive Summary

In 2020, the National Academies of Sciences, Engineering, and Medicine convened the ad hoc Space Nuclear Propulsion Technologies Committee to identify primary technical and programmatic challenges, merits, and risks for maturing space nuclear propulsion technologies of interest to a future human Mars exploration mission. Through interactions with experts from across the space propulsion community, the committee assessed the present state of the art, potential development path, and key risks for (1) a nuclear thermal propulsion (NTP) system designed to produce a specific impulse[1] of at least 900 s and (2) a nuclear electric propulsion (NEP) system with at least 1 megawatt of electric (MWe) power and a mass-to-power ratio that is substantially lower than the current state of the art. As requested by NASA, each system was assessed with regard to its ability to support a particular baseline mission—an opposition-class human exploration mission to Mars with a 2039 launch date.[2,3] For both NEP and NTP systems, efforts to mature the requisite technology and mitigate key technical risks were integrated into a top-level development and demonstration roadmap. Infusion of technology results, expertise, and synergy with other government programs and missions was also examined.

In the near-term, NASA and the Department of Energy (DOE), with inputs from other key stakeholders, including commercial industry and academia, should conduct a comprehensive assessment of the relative merits and challenges of highly enriched uranium (HEU) and high-assay, low-enriched uranium (HALEU) fuels for NTP and NEP systems as applied to the baseline mission.

For NEP systems, the fundamental challenge is to scale up the operating power of each NEP subsystem and to develop an integrated NEP system suitable for the baseline mission. This requires, for example, scaling power and thermal management systems to power levels orders of magnitude higher than have been achieved to date. While no integrated system testing has ever been performed on MWe-class NEP systems, operational reliability over a period of years is required for the baseline mission. Lastly, application of a complex set of NEP subsystems to the

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[1] Specific impulse 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.

[2] Opposition-class missions to Mars have shorter mission times but require a more capable propulsion system than the alternative: conjunction-class missions.

[3] The human exploration mission in 2039 would be preceded by cargo flights beginning in 2033.

baseline mission requires parallel development of a compatible large-scale chemical propulsion system to provide the primary thrust when departing Earth orbit and when entering and departing Mars orbit. 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 in 2039.

NTP development faces four major challenges that an aggressive program could overcome to achieve the baseline mission in 2039. The fundamental challenge 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. The other three challenges are 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). Although the United States has conducted ground-based testing of NTP technologies, those tests took place nearly 50 years ago, did not fully address flight system requirements, and recapturing the ability to conduct necessary ground testing will be costly and time-consuming. Furthermore, no in-space NTP system has ever been operated.

Despite recent work in fuel development, this area remains a challenge, particularly for NTP systems. A comprehensive assessment of HALEU versus HEU for NTP and NEP systems that evaluates a full set of critical parameters as applied to the baseline Mars mission has not been performed. Similarly, a recent apples-to-apples trade study comparing NEP and NTP systems for crewed missions to Mars, in general, or the baseline mission in particular, does not exist. The committee recommends that NASA and DOE, with inputs from other key stakeholders, including commercial industry and academia, conduct a comprehensive and expeditious assessment of the relative merits and challenges of HEU and HALEU fuels for NTP and NEP systems as applied to the baseline mission.

The committee recommends that the development of operational NTP and NEP systems include extensive investments in modeling and simulation. Ground and flight qualification testing will also be required. For NTP systems, ground testing should include integrated system tests at full scale and thrust. For NEP systems, ground testing should include modular subsystem tests at full scale and power. Given the need to send multiple cargo missions to Mars prior to the flight of the first crewed mission, the committee also recommends that NASA use these cargo missions as a means of flight qualification of the space nuclear propulsion system that will be incorporated into the first crewed mission.

NEP and NTP systems show great potential to facilitate the human exploration of Mars. Using either system to execute the baseline mission by 2039, however, will require an aggressive research and development program. Such a program would need to begin with NASA making a significant set of architecture and investments decisions in the coming year. In particular, NASA should 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.

1

Introduction and Baseline Mission Requirements

INTRODUCTION

The human exploration of Mars is a daunting undertaking. Safely transporting astronauts to and from Mars will require advances in many areas to develop spacecraft that are up to the challenge. Propulsion systems are one such area. Advanced nuclear propulsion systems (alone or in combination with chemical propulsion systems) have the potential to substantially reduce trip time compared to fully non-nuclear approaches. Shorter trip time reduces risks associated with space radiation, zero gravity, launch and orbital assembly requirements, and many other aspects of long-duration space missions.

This report assesses the primary technical and programmatic challenges, merits, and risks for developing a nuclear thermal propulsion (NTP) system or a nuclear electric propulsion (NEP) system augmented with a chemical propulsion system for the human exploration of Mars. The report also includes NEP and NTP development roadmaps with key milestones.

Many NASA studies have considered the use of NTP or NEP to facilitate the human exploration of Mars.[1,2,3] Mission scenarios associated with nuclear, solar, and chemical propulsion systems and various mission parameters are shown in Table 1.1. Launch assumptions varied with the launch systems in use or under development at the time of each study. Because crewed Mars missions are significantly more challenging in terms of launch mass and trip time than all prior space missions, in-space propulsion is a critical technology. This is evident by the wide range of propulsion systems that have been considered over multiple mission studies.

Based on the relative orbits of Mars and Earth, the distance between Earth and Mars ranges from 55 to 400 million km over a synodic period of approximately 26 months. Launch (or Earth departure) requirements vary significantly over this cycle.

---

[1] Portree, David S., "Humans to Mars: 50 years of Mission Planning", Monographs in Aerospace History #21, NASA SP-2001-4521.

[2] Explore Mars, Inc., "The Humans to Mars Report 2020," https://www.exploremars.org/wp-content/uploads/2020/08/H2MR_2020_Web_v1.pdf.

[3] NASA, "Human Exploration of Mars: Design Reference Architecture 5.0", NASA SP-2009-566, 2009, https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf.

TABLE 1.1 Mission Scenarios for Crewed Mars Missions

Surface Time	• Short stay time on Mars (30 to 90 days) (Opposition class) • Long stay time on Mars (~ 500 days) (Conjunction class)
Vehicles	• All-up (no separate cargo missions) • Cargo missions precede crewed missions
Options for Mars Orbits	• Low Mars orbit (e.g., altitude of 200-400 km with an orbital period of 1-2 h), • Elliptical Mars orbit with a period of one Martian day • Areosynchronous orbit (i.e., spacecraft tracks over the same geographic position on the Mars surface) • Base of operations on Phobos
Options for In-Space Propulsion Systems	• Nuclear thermal propulsion (NTP) • Nuclear electric propulsion (NEP) • NEP with chemical augmentation • NEP-NTP bimodal • Solar electric propulsion (SEP) with chemical augmentation • SEP-NTP • Chemical • Chemical with aeroassist • NTP with aeroassist

Each 26-month cycle is not the same. Propulsion system performance requirements, in terms of the total velocity increment (ΔV) of a round trip Mars mission, vary from one launch opportunity to the next. The ΔV for a particular mission also depends on other mission constraints, particularly the stay time at Mars and the desired trip time.

There are two classes of crewed missions to Mars: conjunction class and opposition class. Conjunction-class missions have the lowest ΔV requirements. For crewed conjunction-class missions, trip times are typically 180 to 210 days each way, stay times on Mars are typically 500 days or more, and total mission time is around 900 days.[4] These are the "long stay" missions in Table 1.1.

In contrast, one leg of opposition-class missions occurs when the orbital alignment of Earth and Mars is less favorable, but they allow for short stays on the surface of Mars ("short stay" missions in Table 1.1). These missions have higher ΔV requirements and require more propellant, which increases the mass of the Mars vehicle and the number of launch vehicles necessary to lift the required mass to its assembly orbit. Opposition-class missions are characterized by much shorter stay time on Mars (30 to 90 days) and a shorter total mission time (400 to 750 days). An additional complexity of opposition-class missions is that the long leg of the mission typically passes inside Earth's orbit, generally as close to the Sun as the orbit of Venus, to mitigate the adverse planetary alignment of that leg of the mission. This results in both thermal and radiation challenges for a crewed Mars mission. Representative trajectories for each of the crewed mission scenarios are shown in Figure 1.1.[5]

[4] National Aeronautics and Space Administration, "*Human Exploration of Mars: Design Reference Architecture 5.0*, NASA- SP-2009-566-ADD, 2009.

[5] Exact trajectories would depend on many parameters such as launch date and the nature of the propulsion system.

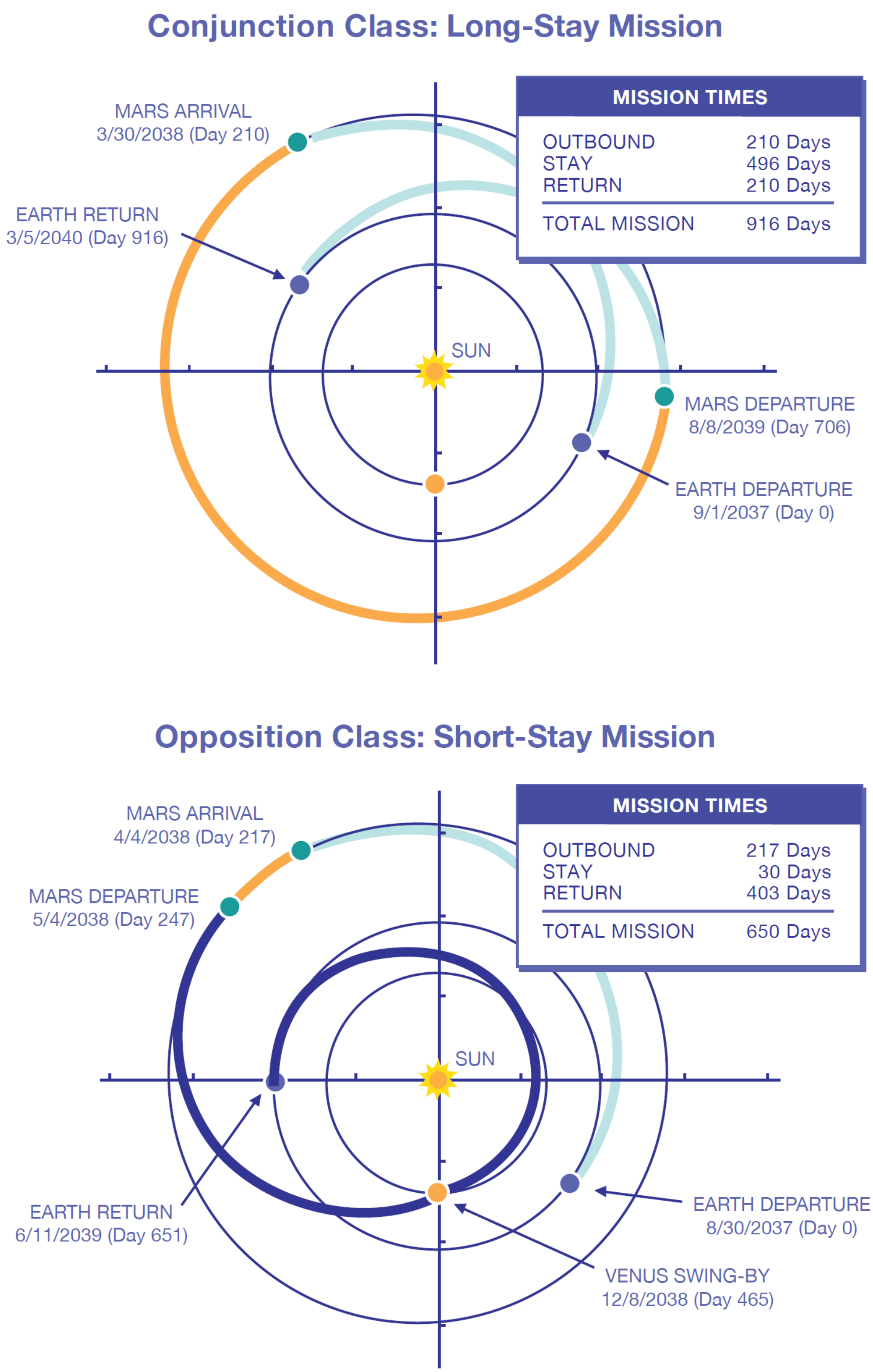

FIGURE 1.1 Trajectories for typical conjunction class (long-stay, top) and opposition class (short-stay, bottom) missions. SOURCE: NASA, Human Exploration of Mars, Design Reference Architecture 5.0, p. 48., https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf.

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BASELINE MISSION TO MARS: CREWED OPPOSITION CLASS MISSIONS

The baseline mission specified by NASA for this report is an opposition-class crewed mission to Mars launched in 2039. This mission would be preceded by cargo missions beginning in 2033 to pre-place surface infrastructure and consumables for the crew. The propulsion system needed for this mission would also be sufficient for conjunction-class missions. The baseline mission has the following parameters:

- Crew mission launch in 2039 opportunity;
- Total crew trip time ≤750 days;[6]
- Split mission with separate crew and cargo vehicles,
  - Same propulsion systems used on all vehicles,
  - Cargo vehicles arrive at Mars prior to first crew departure from Earth;
- Stay time on the Mars surface of 30 days;
- Crew of four, two of whom land on Mars; and
- Vehicle systems, cargo, and propellant launched by multiple launch vehicles to an assembly orbit, which would be either in low Earth orbit or cislunar space.

In order to meet the requirement for total trip time, with an NEP system Earth departure and Mars capture and departure would be augmented by an additional in-space liquid methane and liquid oxygen (LOX) chemical propulsion system. The NEP system provides acceleration and deceleration in interplanetary space. In contrast, the NTP system provides propulsion for all transit maneuvers. The mission segments and the propulsion system used for each phase of flight are described in Table 1.2.

As Earth and Mars revolve about the Sun, the most efficient trajectories vary, resulting in varying levels of propulsive requirements (ΔV) over a 15- to 17-year period (see Figure 1.2).

TABLE 1.2 Nuclear Propulsion Architectures for the Baseline Crewed Mars Mission

Propulsion System	TMI	Departure DSM	Mars Capture	TEI	Return DSM	Earth Return
NTP	NTP	NTP	NTP	NTP	NTP	Capsule EDL
NEP/Chemical	NEP/ Chemical	NEP [a]	NEP/ Chemical	NEP/ Chemical	NEP [a]	Capsule EDL

[a] For some launch opportunities, the total velocity increment (ΔV) requirements for deep space maneuvers will be so great that an NEP system will also need to use its chemical propulsion system to meet the desired trip time.
NOTE: DSM, deep space maneuver EDL, entry, descent, and landing; NEP, nuclear electric propulsion; NTP, nuclear thermal propulsion; TEI, trans-Earth injection; TMI, trans-Mars injection.

[6] Some hardware will have a total mission time of perhaps 4 years, assuming 2 years in an assembly orbit and round-trip flight time of 2 years.

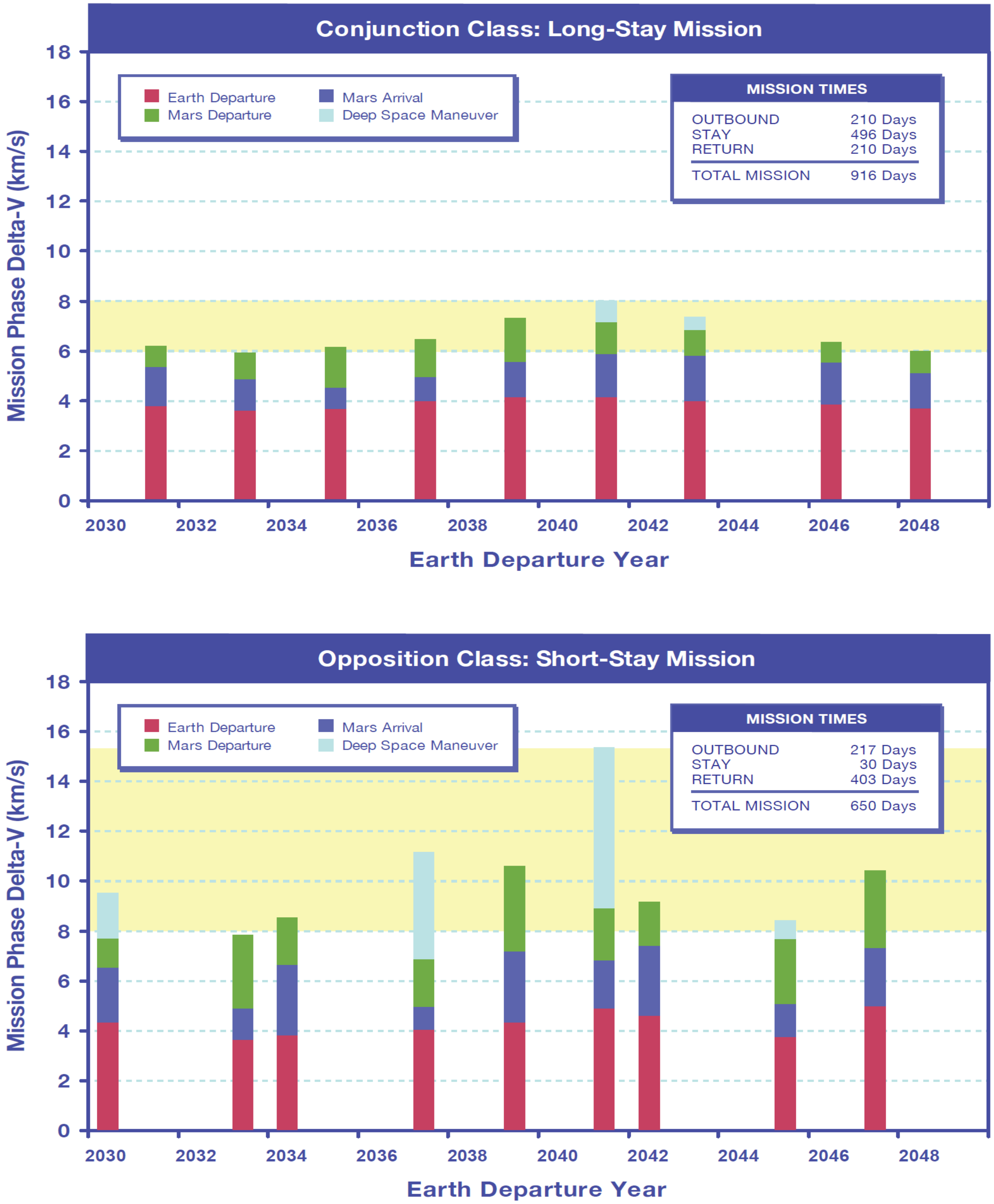

FIGURE 1.2 Total propulsive system requirements (ΔV) for conjunction-class (top) and opposition-class (bottom) missions. Mission parameters: Optimized trajectories assuming 407 km circular low Earth departure orbit, propulsive capture at Mars into a 1-sol orbit of 250 km × 33,800 km, direct entry at Earth at 13 km/s. The yellow horizontal band indicates the typical range of total ΔV requirement for each class of mission. SOURCE: NASA, Human Exploration of Mars, Design Reference Architecture 5.0 Addendum, NASA/SP–2009–566-ADD, p 57.

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A factor in mission assessment for repeated trips to Mars is the ability of propulsion systems to meet mission ΔV requirements over a series of consecutive launch opportunities without large variability in overall mission parameters, such as propellant mass, which could drive very different launch requirements for different opportunities. This variability is reduced by propulsion systems with high specific impulse (I_{sp}).[7] Previous studies have shown the impact of NTP for an opposition-class mission in different launch opportunities, although not for the current years of interest. An example of the change in vehicle (propellant) mass with launch date is shown in Figure 1.3 for an advanced chemical system with an I_{sp} of 480 s and an NTP system with an I_{sp} of 825 s. The mass variation with launch opportunity for the higher I_{sp} system is about one half of the variation of the chemical system. Similar benefits would likely be achieved with an NEP system with an I_{sp} of 2,000 s paired a conventional chemical system. This is particularly important because some launch opportunities are not feasible using purely a chemical system. Flexibility to launch date is a major architectural advantage of the use of nuclear propulsion.

PROPULSION SYSTEM REQUIREMENTS

Although NEP and NTP systems both use nuclear power, they convert this power into thrust in different ways based on different technologies (as will be discussed in Chapters 2 and 3). The performance of rocket propulsion systems is defined by multiple parameters that define how much propellant they use and how much acceleration they can generate. In the case of chemical rockets or NTP systems, the two primary parameters are the I_{sp} and thrust. For NEP systems, I_{sp} is important to determine propellant requirements, but thrust and acceleration are defined by multiple parameters: power, thrust efficiency, and specific mass. Thrust efficiency defines how much electric power is converted into thrust power, and the specific mass is defined as the mass of the entire NEP system divided by the electrical power available for the thrusters. NEP systems have a higher I_{sp} than NTP systems, but they have very low thrust. The megawatt electric (MWe)-class NEP systems proposed to execute the baseline mission therefore require chemical rockets (which have an I_{sp} that is much lower than either an NTP system or an NEP system) to meet the desired trip time.

NTP and NEP system performance requirements to execute the baseline mission are a topic of ongoing study by NASA. Table 1.3 summarizes the committee's estimate of those requirements for NTP and NEP systems based on information from multiple sources.[8]

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[7] 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.

[8] To meet the trip time specified for the baseline mission, the requirements for a pure NEP system (without an auxiliary chemical propulsion system), would include a much higher power level and a much higher I_{sp} than those specified in Table 1-3. M. McGuire et al. (2006). Use of High-Power Brayton Nuclear Electric Propulsion (NEP) for a 2033 Mars Round-Trip Mission. AIP Conference Proceedings. 813. 10.1063/1.2169198.

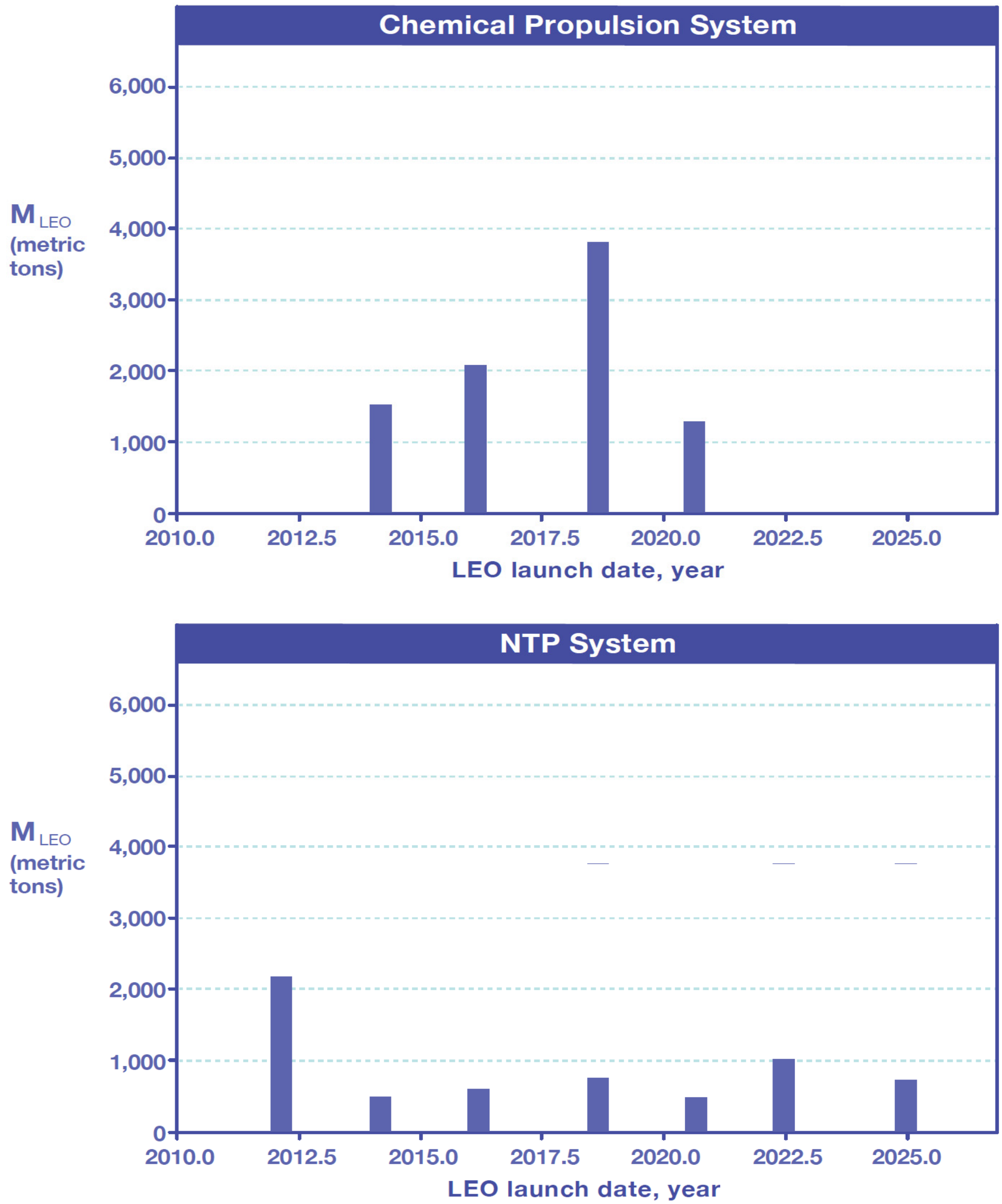

FIGURE 1.3 The impact of advanced propulsion, in this case nuclear thermal propulsion (NTP), on the total launch mass (fuel) with differing launch opportunities. NOTE: M_{LEO} = the mass that must be launched to low Earth orbit to complete a given mission. As a point of reference, the mass of the International Space Station is approximately 400 metric tons. SOURCE: Braun, R. D., and Blersch, D. J., "Propulsive Options for a Manned Mars Transportation System," J. Spacecraft, Vol. 28, NO. 1, Jan.-Feb. 1991.

TABLE 1.3 Estimated Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) System Requirements and Characteristics for the Baseline (Opposition Class) Mission

NTP		NEP	
I_{sp}	900 s	I_{sp}	≥ 2,000 s
Thrust	up to 100,000 lbf, with up to 25,000 lbf per engine[a]	Electrical power	1 to 2 MWe
		Thruster efficiency	>50%
		Specific mass[b]	
		Entire NEP system	≤20 kg/kWe
		EP subsystem	≤5 kg/kWe
System restarts	6 to 8	All other subsystems	≤15 kg/kWe
Total operational lifetime (intermittent operation)	4 h	Operational lifetime (continuous operation[c])	4 years for power generation 1 to 2 years for thrust
Reactor thermal power	~500 MWth	Reactor thermal power	~3 to 10 MWth
Temperature of propellant at reactor exit	~2700 K	Reactor coolant outlet temperature	~1200 K
System mass exclusive of propellant	indeterminate	System mass exclusive of propellant	<40 to 80 MT
Propellant		Propellant options	
LH_2	stored at 20 K ~70 to 210 MT	argon	stored as a cryogenic liquid (90 K)
		lithium	stored as a solid
		krypton	stored as high-pressure gas
		xenon	stored as high-pressure gas
		mass	indeterminate
		Supplemental chemical propulsion system	
		Fuel	Liquid methane (110 K) and liquid oxygen (90 K)
		I_{sp}	360 s
		Thrust	25,000 lbf
		Mass	indeterminate

[a] An NTP system for the baseline mission will include multiple reactors and engines.

[b] The specific mass (or "α") of an NEP system is the ratio of mass to power. The specific mass of a complete NEP system is the sum of the specific mass for each of its subsystems. Specific mass does not include propellant mass. A list of all NEP subsystems is provided in Chapter 3.

[c] NEP systems may be operated continuously even when their electrical power and propulsion is not needed to avoid having to shut down and restart the reactor.

NOTE: Lbf, pounds force; MT = metric tons.

CARGO MISSIONS

Conjunction-class missions have the lowest possible ΔV requirements because they use minimum energy, or Hohmann-like, trajectories. These trajectories are traditionally cited for cargo missions in which mass efficiency rather than trip time is a priority. Cargo missions also benefit from the higher I_{sp} of NEP and NTP systems. To ensure delivery of the requisite payloads to Mars before launch of crew, multiple cargo flights are planned as an integral aspect of this enterprise. As discussed in Chapters 2 and 3, using the crew vehicle propulsion system on one or more of the precursor cargo vehicles provides significant risk reduction and valuable flight information about propulsion system reliability, safety, and performance.

SUMMARY

NASA is presently considering multiple forms of propulsion, including NTP and NEP, in its mission architecture analyses. Opposition-class missions, while reducing crew duration on Mars and total mission time, markedly increase mission ΔV requirements. This mission class introduces a higher sensitivity in propulsion system requirements from one launch opportunity to another, which could be achieved by either an NTP or NEP system. Successful development of an NTP or NEP/chemical system at relevant scale and performance would allow NASA to develop a robust architecture with flexibility across multiple mission opportunities.

This report provides a technology assessment of the NTP and NEP development challenges that must be overcome to execute the baseline Mars mission. It is not intended to provide—nor did the committee's statement of task allow—a comprehensive assessment of all aspects or trade studies associated with how a human Mars exploration mission should be organized, funded, or executed.

2

Nuclear Thermal Propulsion

SYSTEM CONCEPT

A nuclear thermal propulsion (NTP) system is conceptually similar to a chemical propulsion system, where the combustion chamber has been replaced by a nuclear reactor to heat the propellant. Figure 2.1 depicts the basic components of an NTP system, which consists of three highly integrated subsystems: a nuclear reactor, a rocket engine, and a propellant storage and management subsystem. The reactor subsystem consists of the core, control drums and their actuators, reflector, shield, and pressure shell. The engine subsystem consists of the turbomachinery (including associated valves and pipes) and nozzle, and the liquid hydrogen (LH_2) tank and helium pressurization tanks are part of the propellant storage and management subsystem.

In both NTP and nuclear electrical propulsion (NEP) systems (and terrestrial nuclear power plants), the reactor produces heat from fission of nuclear fuel.[1] Nuclear reactors also produce high levels of radiation that require shields to reduce the exposure of people and materials in the vicinity of the reactor. For an NTP system, the LH_2 propellant from the cryogenic LH_2 tank is delivered to the reactor using one or more turbopumps and the propellant management components. The LH_2 is directly heated by the nuclear reactor and then accelerates out the nozzle to generate thrust. This is in contrast to generating heat with combustion, as is the case in a chemical rocket. The control drums, which absorb neutrons, are situated around the outer annulus of the reactor core within the reflector. The drums are used to turn the reactor "on" and "off" and to increase or decrease reactor power. The hydrogen turbopumps are used to control the mass flow rate and pressure of the hydrogen propellant.

[1] Although many isotopes of various elements can be used as nuclear fuel, uranium-235 (U-235) is the fuel of choice for all space nuclear propulsion designs under development by the United States.

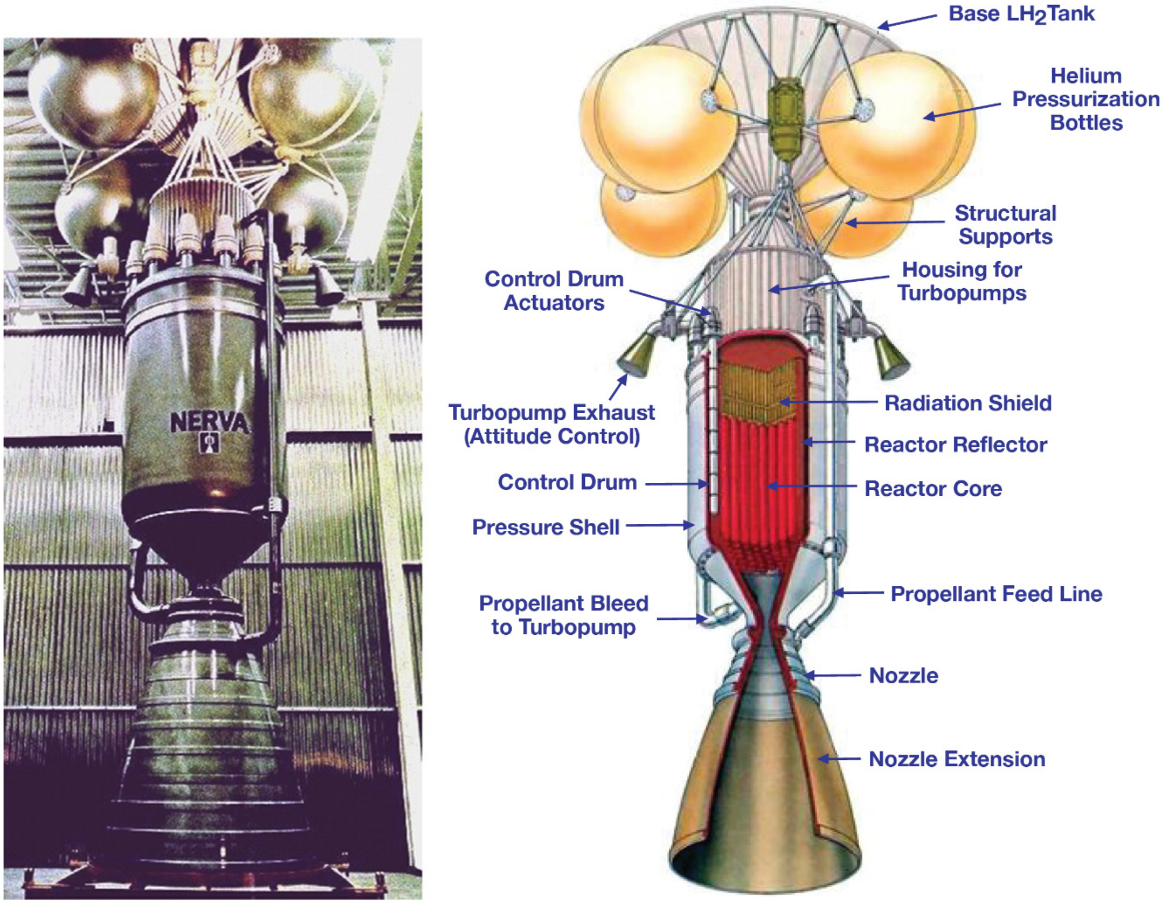

FIGURE 2.1 Photo of a nuclear thermal propulsion (NTP) system from the Rover/NERVA programs (left) and a cutaway schematic with labels (right). SOURCE: M. Houts et. al., NASA's Nuclear Thermal Propulsion Project, NASA Marshall Space Flight Center, August 2018, ntrs.nasa.gov/citations/20180006514.

Figure 2.2 shows a reactor core cross section and fuel segment cluster of the NTP nuclear reactor of a type developed by the Rover and Nuclear Engine for Rocket Vehicle Applications (NERVA) programs.[2] Figure 2.2 depicts tightly packed hexagonal (also known as prismatic) fuel elements. This particular core is surrounded by 12 control drums, which are partially covered by reflector material and which reflect neutrons emitted from the core back into the core, to help sustain nuclear fission during reactor operation. Power is controlled in the reactor by rotating the drums. There is an inner and outer pressure vessel and reflector materials surrounding the control drums. Within each fuel element cluster are the tie tubes. The purpose of the tie tubes for the Rover/NERVA type cores is to regulate the temperature of the outer edge of the fuel elements and to provide some structural support to the fuel elements in the core.

[2] From 1955 until 1973 the Atomic Energy Commission's Project Rover sought to develop nuclear reactors suitable for use with an NTP system. From 1961 until 1973 NASA's NERVA Program sought to develop a complete NTP system. Both programs were jointly managed by the Space Nuclear Propulsion Office.

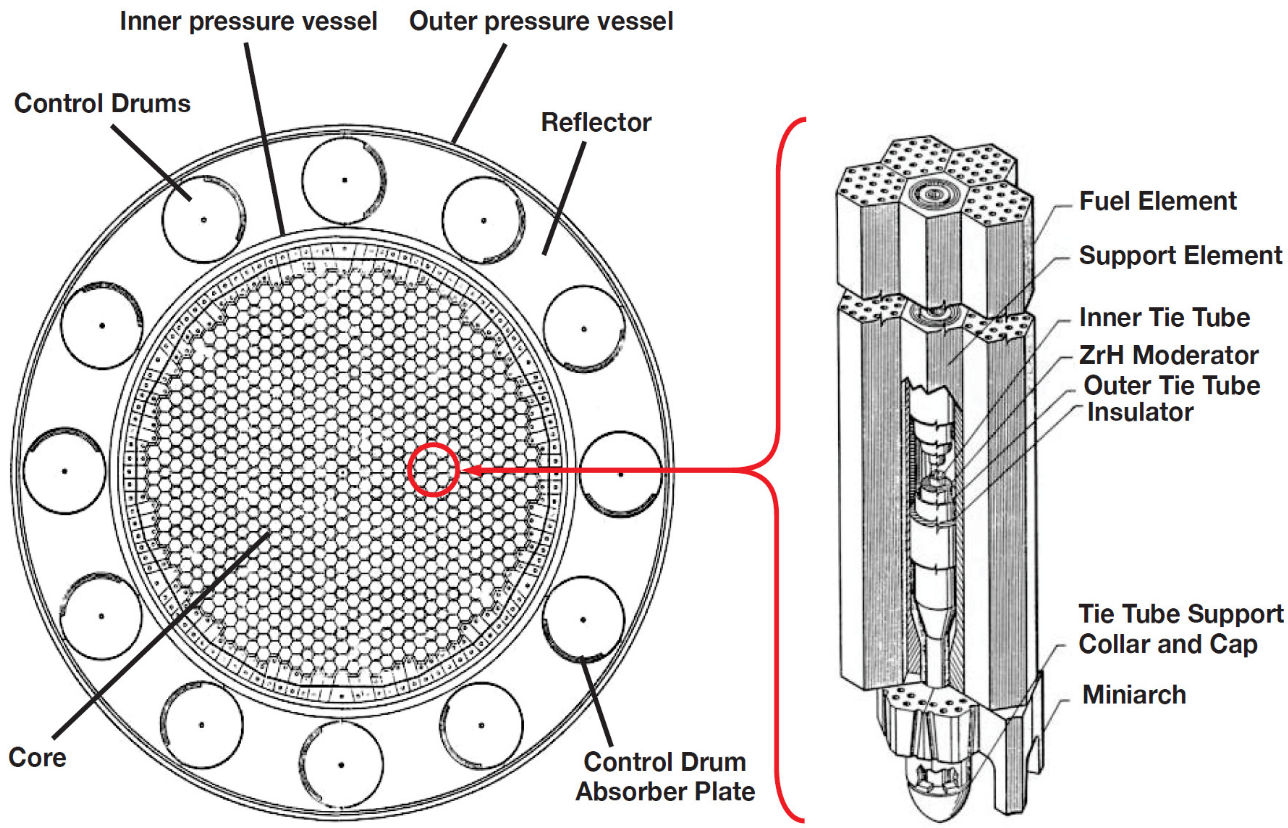

FIGURE 2.2 Rover/Nuclear Engine for Rocket Vehicle Applications (NERVA) reactor core cross section (left) and fuel segment cluster (right). SOURCE: M. Houts et al., NASA's Nuclear Thermal Propulsion Project, NASA Marshall Space Flight Center, August 2018, ntrs.nasa.gov/citations/20180006514.

HISTORICAL OVERVIEW

The Rover/NERVA reactor and NTP engine development program included a ground testing campaign that built and tested 22 reactors, using highly enriched uranium (HEU) graphite fuel with uranium dioxide (UO_2), uranium dicarbide (UC_2), and coated UC_2 particles.[3,4] In addition to demonstrating controlled reactor operation, the Rover/NERVA programs demonstrated the feasibility and challenges of the NTP engine concept. Specifically, the feasibility of using a nuclear reactor to heat the hydrogen propellant to generate predicted values for specific impulse (I_{sp}) using flow paths through solid graphite HEU fuel, tie tubes, and turbomachinery was demonstrated. The ground test campaign enabled the design of the Rover/NERVA reactors to iteratively evolve in response to issues identified during testing. For instance, the early

[3] Finseth, J. L. Overview of Rover Engine Tests. George C. Marshall Space Flight Center, 1991. https://ntrs.nasa.gov/api/citations/19920005899/downloads/19920005899.pdf.

[4] HEU refers to uranium that is enriched to the point that 20 percent or more is uranium-235, which is fissile, with remainder being uranium-238, which is not fissile. High assay low enriched uranium (HALEU) refers to uranium that contains between 5 percent and 20 percent uranium-235. Naturally occurring uranium contains less than 1 percent uranium-235.

Rover/NERVA reactors such as Kiwi B4A had structural issues caused by flow-induced vibrations that necessitated the testing and destruction of at least two entirely different reactors in order to isolate and fix the problem.[5] Lessons were also learned regarding neutron moderation.[6] Neutron moderation was primarily achieved by the graphite in the fuel elements, which operated simultaneously as a heat transfer element and as the primary neutron moderator.[7]

The Peewee reactor from the NERVA program incorporated additional, separately cooled zirconium hydride (ZrH) moderator material in its tie tubes and demonstrated a peak fuel temperature of 2750 K and a propellant temperature of 2550 K at the reactor exit, which corresponds to approximately 875 s I_{sp} in a vacuum with ideal expansion. Peewee accumulated two 20-min runs at full design power of 500 megawatt thermal (MWt), with a total of 192 min above 1 MWt. Most fuel elements used a niobium carbide (NbC) coating on graphite surfaces exposed to hot hydrogen, but a few fuel elements were coated with zirconium carbide (ZrC) instead. Pronounced cracking of the NbC graphite coating was observed; with significantly less deterioration for the ZrC coatings. The Pewee reactor also demonstrated that by adding the additional ZrH moderator material into a HEU core, the overall mass of the system could be decreased, making Pewee the smallest, highest-performing reactor in the NERVA series.[8] However, the reactor life was unclear, and the fuel used in the Peewee reactor is not being considered for current NTP systems.[9] The XE-Prime reactor from the NERVA program successfully demonstrated a record number of engine starts, shutdowns, and restarts that far exceeds the requirements of a Mars mission (i.e., 28 reactor starts, although some of the engine parts (e.g., turbopump bearings) had to be replaced).[10]

One of the keys to maximizing the I_{sp} of an operational NTP system is to shorten as much as possible the time it takes to startup and shutdown the system. I_{sp} is directly related to operating temperature, so I_{sp} is reduced during reactor startup and shutdown when hydrogen propellant is flowing through the reactor but is not being heated to full operational temperature. In particular, the start-up transient of the NTP reactor should allow the system to reach full operating temperature in 1 min or less in order to reduce the performance reduction for each individual engine firing, which would generally be under 30 min each and can be as short at 10 min. These rapid transients introduce many design challenges throughout the system.

Table 2.1 summarizes the measured and predicted values (theoretical, assuming ideal conditions, and no losses) for I_{sp} for a sampling of reactors and engines tested after the preliminary Kiwi series.

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[5] Pierce, B. L. Comparison of analytical and experimental flow induced core vibrations. No. WANL-TME-645. Westinghouse Electric Corp., Pittsburgh, Penn. Astronuclear Lab., 1964.

[6] Neutron moderation is a broad term that refers to the effect a material has on lowering the energy of a neutron, such that the neutron's energy is at an optimal level for capture by a fissionable material leading to nuclear fission. Sometimes a material is included in a reactor strictly for purposes of moderating neutrons, in effect making that material "the moderator" of the reactor. In the case of NERVA, the graphite in the fuel was not meant solely for the purpose of moderating neutrons (even though it had moderating effects); even so, graphite can be used by itself as a moderator in some reactor designs.

[7] Taub, J. M. Review of fuel element development for nuclear rocket engines. No. LA--5931. Los Alamos Scientific Lab., 1975.

[8] Moderators would likewise reduce the size of NTP reactors fueled by HALEU.

[9] Ibid, Finseth.

[10] Koenig, Daniel R. Experience Gained from the Space Nuclear Rocket Program (Rover). Los Alamos National Laboratory, 1986. https://fas.org/nuke/space/la-10062.pdf.

TABLE 2.1 A Sampling of Data from Reactor and Engine Tests that Occurred in the Later Stages of the Rover/NERVA Programs

Reactor	Fuel temperature at reactor exit (K)	Propellant temperature at reactor exit (K)	I_{sp}, (vacuum, ideal) (sec)	Power (MWth)	Thrust (lbf)
Phoebus series (1A, 1B, and 2A)	2300 to 2450	2100 to 2250	820 to 850	4000	200,000
Pewee 1	2750	2550	875	500	25,000
NRX A series (A2, A3, A5, A6)	2250 to 2550	2100 to 2400	810 to 870	1100	55,000
NRX/EST	>2400	2300	>840	1100	
XE-Prime	>2400	2250	>710	1100	55,000

NOTE: In these tests, reactor fuels were exposed to the integrated effects of startup, operation, and shutdown through ground-testing of a complete NTP engine configuration. The Pewee reactor demonstrated the hottest measured fuel and propellant exit temperature of the Rover/NERVA series. The NRX Engine System Test and XE-Prime reactors were both tested engine hardware which was the closest to being "flight-like." All of these tests were conducted between 1964 and 1969, inclusive.
SOURCE: Adapted from Finseth (1991) and Koenig (1986).

The NTP performance requirements for the baseline mission require a maximum fuel temperature high enough to heat propellant to a temperature of approximately 2700 K at the reactor outlet (see Table 1.3).

Table 2.2 provides additional information on the maximum operating temperature of fuel forms used in historic NTP materials programs. The nonnuclear prototypic testing designation typically refers to furnace temperature testing that was prototypic or exceeded the fuel's designed operating temperature. Nuclear testing typically denotes testing in a research reactor facility. Full-core testing signifies that the fuel was used as the primary or sole fuel source in a fully functioning nuclear core. As shown, several advanced fuel forms with greater than 2700 K performance have been produced and undergone environmental testing in high temperature furnaces, in radiation fields, and in a combination of temperature and hydrogen exposure. Although the fuel forms listed in Table 2.2 have not been demonstrated under the integrated effects of an NTP engine operation, for the most part, they were able to withstand the maximum operating temperatures shown without exhibiting significant degradation.

TABLE 2.2 Maximum Operating Temperature of Fuel Forms Tested in Historic Nuclear Thermal Propulsion (NTP) Materials Programs

	Historical Nuclear Thermal Propulsion Materials Programs						
	NERVA/Rover Program Fuel Forms			Ceramic-metal (cermet) Fuel Forms (General Electric and Argonne National Lab, ANL)		Space Nuclear Thermal Propulsion (Particle Bed Reactor)	Former Soviet Union
	Graphite Composite	Monolithic Carbide	Graphite Composite	Refractory Metal Composite	ANL Refractory Metal Composite	Monolithic Carbide Solid Solution	
Fuel Compound	UC_2	(U, Zr)C	(U, Zr)C	UO_2 UN	UO_2	(U, Zr)C (U, Nb)C	(U, Zr,Nb)C (U, Zr,Ta)C
Matrix Material	Graphite	N/A	Graphite	Tungsten	Tungsten	N/A	N/A
Geometry	Solid block w/coolant channels	Solid block w/coolant channels	Solid block w/coolant channels	Solid block w/coolant channels	Solid block w/coolant channels	Particle Bed	Twisted Ribbon
Fuel Exit Temperature Tested (K)	2750	2450	2450	2900	2850	2800	3500 3300
Testing Completed	Full core	Nonnuclear prototypic Full core	Full core	Nonnuclear prototypic	Nonnuclear prototypic Nuclear	Nonnuclear prototypic Nuclear	Nonnuclear prototypic Nuclear Full core
I_{sp} (vacuum ideal) (sec) [a]	890	830	830	945	930	915	
Sources	1-3	1-4	1-4	1, 2, 5	1, 2, 6	1, 2, 7	1, 2, 7

[a] I_{sp} does not account for the temperature difference between the reactor fuel and hydrogen propellant, which can be as high as 200 K. Accounting for this difference would reduce the projected I_{sp}. The values of I_{sp} shown above would likely still be at least 900 sec as long as the fuel exit temperature is approximately 2900 K or more.

NOTE: Acronyms are defined in Appendix D.

SOURCES:

[1] S. K. Bhattacharyya, “An Assessment of Fuels for Nuclear Thermal Propulsion,” Argonne National Laboratory, IL, ANL/TD/TM01-22, 2002, https://www.osti.gov/servlets/purl/822135.

[2] J. L. Finseth, “Rover Nuclear Rocket Engine Program: Overview of Rover Engine Tests. Final Report,” Sverdrup Technology, Inc., Huntsville, AL, , 1991, https://ntrs.nasa.gov/citations/19920005899.

[3] Bhattacharyya, S.K., “An Assessment of Fuels for Nuclear Thermal Propulsion,” ANL/TD/TM01-22, Argonne National Laboratory, IL, 2001.

[4] Lyon, L.L., “Performance of (U, Zr)C-Graphite (Composite) and of (U,Zr)C (Carbide) Fuel Elements in the Nuclear Furnace 1 Test Reactor,” Los Alamos Scientific Laboratory, NM, , https://www.osti.gov/servlets/purl/4419566.

[5] A. Andrews, “GEMP-600, 710 High-Temperature Gas Reactor Program Summary Report,” United States Atomic Energy Commission Contract AT (40-1)-2847, Contractor: General Electric, Cincinnati, OH, 1982.

[6] J. Marchaterre, “Nuclear Rocket Program Terminal Report,” ANL-7236, Argonne National Laboratory, Argonne, IL, 1968.

[7] A. Lanin, Nuclear Rocket Engine Reactor, Springer Series in Materials Science, Volume 170, Springer-Verlag Berlin Heidelberg, 2013.

While most of the Rover/NERVA research reactors did not use flight-configured engine hardware, there were a few reactors tested with NTP engine hardware components, with the XE-Prime being the system closest to the envisioned operational system.[11] This experimental engine test incorporated pump and hardware arranged as designed for flight (i.e., close-coupled propellant feed system similar to the reactor and engine hardware arrangement seen in Figure 2.1), although it was only tested to 710 s I_{sp}. Additionally, the NRX/EST was an engine system test that used a breadboard that connected relevant flight hardware to the reactor while mounted to a train car.

Although the Rover/NERVA programs demonstrated proof of concept for an NTP system, the program was cancelled before program goals were achieved due to a shift in funding priorities. Consequently, no complete NTP system has been assembled and tested in its flight configuration or flown in space. Other NTP programs have been carried out since Rover/NERVA, but none have built any additional reactors or engines. The Argonne National Laboratory (ANL) and General Electric GE-710 programs developed concepts for fast-spectrum[12] ceramic-metal (cermet) fuels for nuclear-powered aircraft and NTP concepts that utilized HEU.[13] Cermet fuels, such as tungsten uranium dioxide (WUO_2) were manufactured and tested. The Space Nuclear Thermal Propulsion (SNTP) program was primarily a fuel development effort for the particle bed reactor that tested the use of coated HEU particles for NTP, and it identified many challenges. The SNTP program also conducted moderator block experiments using polyethylene moderator material,[14] and it produced hardware for non-nuclear component engine testing. Ground testing of complete SNTP reactors was planned, but not implemented, before program termination. The Soviet Union had NTP development efforts as well (such as the RD-410) which purportedly used a unique (twisted ribbon) carbide HEU fuel and a ZrH moderator.[15,16]

STATE OF THE ART

This section discusses the state of the art of the subsystem technologies that make up an NTP system as well as associated modeling and simulation (M&S) capabilities.

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[11] Sikorski, David, and Richard T. Wood. "Nuclear Thermal Rocket Control." Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting Richland, WA, February 25 – February 28, 2019, available online at http://anstd.ans.org/.

[12] A fast spectrum reactor is designed to rely predominately on fast (unmoderated) neutrons, whereas a thermal-spectrum reactor relies predominantly on moderated (thermal neutrons). Fast-spectrum reactors, which require a more intense radiation field, can be designed to use HALEU, but they are more compatible with HEU because it has a higher concentration of fissionable uranium (i.e., U-235) relative to HALEU. Thermal-spectrum reactors can be designed to use either HEU or HALEU.

[13] Bhattacharyya, S. K. An assessment of fuels for nuclear thermal propulsion. No. ANL/TD/TM01-22. Argonne National Lab., IL (US), 2001.

[14] Haslett, R. A. Space Nuclear Thermal Propulsion Program. Grumman Aerospace Corp Bethpage NY, 1995.

[15] Vadim, Zakirov, and Pavshook Vladimir. "Russian nuclear rocket engine design for Mars exploration." Tsinghua Science and Technology 12.3 (2007): 256-260.

[16] Lanin, Anatoly. Nuclear rocket engine reactor. Vol. 170. Springer Science & Business Media, 2012. Doi 10.1007/978-3-642-32430-7.

Reactor Subsystem

The only data available in the United States that can be used to validate NTP reactor models are from HEU reactor-engine subsystems in the 1960s and 1970s; there are no experimental data on high-assay, low-enriched uranium (HALEU) NTP subsystems.

The current state of the art for the reactor subsystem is limited to the M&S capabilities used to analyze a reactor virtually. Existing hardware manufacturing capabilities are insufficient to build an NTP reactor at the scale required for cargo or crewed missions associated with the baseline mission. Current M&S capabilities can generate steady-state neutronic designs of NTP reactors to simulate the nuclear core sustaining a chain reaction.[17,18] Reactor core models can be coupled with thermal-hydraulic, fluid models for simplified one-dimensional core-wide approximations and higher fidelity simulations for subscale analyses (i.e., using computational fluid dynamics simulations).[19,20] Numerous M&S design studies derive new concepts based on prior NERVA-type experiments. However, the coupled neutronic, thermal-hydraulic and engine balance of plant M&S tools are limited in their ability to reliably model NTP systems for which there are no experimental data for model validation, particularly for transients. Additionally, state-of-the-art M&S tools lack the ability to conduct coupled, high-fidelity analyses to assess system lifetime and potential failure mechanisms. Modeling the dynamic nature of the nuclear reactor, coupled with the flow of propellant and change of temperature, has not been completed for NTP, and significant uncertainty remains in the materials interactions between the hydrogen propellant and the reactor fuel. Simulations of dynamic reactor behavior exist, such as the dynamic modeling capability of Los Alamos National Laboratory that was used for the Kilopower Program's subscale power system test.[21] Such tools will need to be adapted and benchmarked against test data, for NTP dynamic modeling, which use different materials under different conditions, different scales, and different working fluids. State-of-the-art M&S tools lack the capability for mechanical and structural simulation of reactors needed to assess the potential for flow-induced vibration issues, such as those faced by Kiwi B4A. This is also due to a lack of materials data that is needed for M&S inputs, such as for block monolithic ZrH at elevated temperatures.

Fuels

Several ceramic composite fuel forms (ceramic fuel particles in a graphite matrix with a protective NbC or ZrC coating) were demonstrated in the NERVA program to exhibit acceptable behavior in flowing hydrogen, mostly up to propellant temperatures of about 2550 K during reactor testing, with the Pewee fuel setting a record at 2750 K at its peak. Cermet fuels were not reactor-tested in the NERVA program, but thermal cycling tests demonstrated a mass loss of less than 1 percent for WUO_2 cermets up to 2800 to 3000 K in flowing hydrogen for 70 to 193

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[17] Monte-Carlo N Particle Transport Code, https://mcnp.lanl.gov/.
[18] MOOSE, https://www.mooseframework.org/.
[19] STAR CCM+, https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html.
[20] Ansys Fluent, https://www.ansys.com/products/fluids/ansys-fluent.
[21] McClure, Patrick R., et al. "KRUSTY Experiment: Reactivity Insertion Accident Analysis." Nuclear Technology 206.sup1 (2020): 43-55.

thermal cycles.[22] NASA, the Department of Energy (DOE), and other research organizations, including those in industry and academia, have attempted to build solid HEU-based fuel rods. These efforts have included fuel rods comprised of graphite (i.e., Rover/NERVA derived), cermets (i.e., ANL/GE-710 derived), and other refractory blends.[23,24,25,26,27] The fuel types are largely derivative of a variety of historic HEU reactor core concepts. These solid fuel elements have been created using hot isostatic pressing, spark plasma sintering, and other methods, and have undergone testing in facilities such as the Compact Fuel Element Environment Simulator and the Nuclear Thermal Rocket Element Environment Simulator, which can achieve isothermal, steady-state temperatures in excess of 2500 K in the presence of flowing hydrogen.

A driving characteristic for the design of NTP systems is the high operating temperatures in the reactor core; an I_{sp} of 900 s corresponds to a hydrogen propellant reactor exit temperature of approximately 2700 K.[28,29]

NASA is currently involved in testing uranium nitride (UN) cermet and ceramic-ceramic (cercer) fuel forms, including high-temperature hydrogen testing of uncoated fuels, and is planning further nonnuclear and nuclear testing. Upcoming non-nuclear prototypic testing will include flowing hot-hydrogen furnace testing at temperatures greater than or equal to 2850 K of the following: tungsten-coated UN particles, ZrC-coated UN particles, tungsten/molybdenum alloy-UN cermet composite fuel, and ZrC-UN cercer composite fuel, as well as full length cermet and cercer fuel elements.

NASA has also indicated an interest in solid-solution carbide fuel technology with coated carbide particles.[30] Although the United States has not successfully demonstrated NTP solid-solution quaternary carbide fuel forms, there is some limited documentation on the Russian RD-410 NTP fuel technology.[31] Because the melting temperatures of UC_2 and uranium carbide (UC) particles are 2730 K and 2780 K, respectively,[32] it is difficult for an NTP system to achieve a

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[22] M.E.M. Stewart, B.G. Schnitzler, A Comparison of Materials Issues for Cermet and Graphite-Based NTP Fuels, in: 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, American Institute of Aeronautics and Astronautics, 2013.

[23] O'Brien, R., et al. "Recent Research Activities at the Center for Space Nuclear Research in Support of the Development of Nuclear Thermal Rocket Propulsion." Nuclear and Emerging Technologies for Space, Paper 3060 (2012).

[24] Barnes, Marvin W., et al. "NTP CERMET Fuel Development Status." (2017).

[25] Barnes, Marvin W., Dennis S. Tucker, and Kelsa M. Benensky. "Demonstration of Subscale Cermet Fuel Specimen Fabrication Approach Using Spark Plasma Sintering and Diffusion Bonding." (2018).

[26] Jolly, B., Trammell, M., and Qualls, A. L. "Coating Development on Graphite-Based Composite Fuel for Nuclear Thermal Propulsion" 51st AIAA/SAE/ASEE Joint Propulsion Conference (2015) doi:10.2514/6.2015-3777.

[27] Raj, S., Nesbitt, J., and Stewart M. "Development of Advanced Coatings for NERVA-Type Fuel Elements" 2015 Nuclear and Emerging Technologies for Space Conference (2015) http://anstd.ans.org/wp-content/uploads/2015/07/3006.pdf.

[28] Joyner, C. R. et al, Presentation to Space Nuclear Propulsion Technologies Committee from Aerojet, NTP & NEP Design Attributes for Mars Missions, Slide 8 "Readiness of Liquid Rocket Hardware for NTP", June 29, 2020.

[29] Burns, Douglas, Idaho National Laboratory, presentation to the NASEM Space Nuclear Propulsion Technologies Committee, "DOE Role in Nuclear Thermal Propulsion Technology Development," June 22, 2020, virtual meeting.

[30] Houts, M. Nuclear Thermal Propulsion, Presentation to National Academy of Sciences Panel, June 8, 2020.

[31] Ibid, Vadim.

[32] D. Manara, F. De Bruycker, K. Boboridis, O. Tougait, R. Eloirdi, M. Malki, High temperature radiance spectroscopy measurements of solid and liquid uranium and plutonium carbides, J. Nucl. Mater., 426 (2012) 126-138.

propellant reactor exit temperature of approximately 2700 K with uncoated carbide particles, unless they are mixed in a solid solution with refractory carbides such, as ZrC.

Moderators and Non-Fuel Materials

Limited HEU reactor subsystem data exists on the successful performance of ZrH moderators in the single-pass tie tubes of the Pewee HEU reactor. Issues such as power oscillations,[33] hydrogen migration and hydrogen dissociation, and loss at temperatures above 700 K remain as potential challenges for the incorporation of ZrH into an NTP reactor. ZrH moderator blocks were demonstrated in Soviet Thermionic Operating Reactor Active Zone (TOPAZ) space reactors. Two TOPAZ I reactors were launched as flight demonstrations, and in the early 1990s the United States purchased a developmental TOPAZ II reactor for non-nuclear test and evaluation.[34,35,36] In addition, DOE is currently manufacturing and testing ZrH. The United States, however, has no flight experience with moderator block technology.

Beryllium (Be) is often proposed for use in NTP designs as a reflector and as a moderator. Beryllium can be used in forms such as beryllium oxide (BeO) or in pure form (Be). It is most suitable for components with an operating temperature of less than 1000 K; reactors and cooling approaches are designed to ensure this temperature is not exceeded. Beryllium was used for the reflector and in the control drums for the NERVA reactors and in a general capacity for a variety of other nuclear power reactors.[37]

Engine Subsystem

Engine hardware, such as turbomachinery and valves, has evolved independent of NTP reactor hardware for use on chemical propulsion systems. Existing chemical propulsion engine components can be scaled, modeled, and integrated for NTP use. For instance, the RL-10 and similar turbopumps have been modeled for decades for a variety of NTP design studies while having undergone maturation and hardware testing for a variety of chemical propulsion uses, including in space.[38,39]

M&S capabilities applicable to the non-nuclear (i.e., chemical) engine subsystem elements are well developed for both static and dynamic engine flow conditions. Some of these models[40,41]

[33] Stafford, D. S. “Multidimensional simulations of hydrides during fuel rod lifecycle.” Journal of Nuclear Materials 466 (2015): 362-372.

[34] Buden, D. “Summary of Space Nuclear Reactor Power Systems (1983-1992),” Idaho National Engineering Laboratory, 1993.

[35] El-Genk, Mohamed S. “Deployment history and design considerations for space reactor power systems.” Acta Astronautica 64.9-10 (2009): 833-849.

[36] Adrianov, V.N. et al, “Topaz-2 NPP Reactor Unit Mechanical Tests Summary Report Vol. 1,” CDBMB through INERKTEK Technical Report, Moscow, Russia.

[37] Ibid, Finseth.

[38] Joyner, C. R. et al, “LEU NTP Engine System Trades and Mission Options” Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting Richland, WA, February 25 – February 28, 2019, available online at http://anstd.ans.org/.

[39] Joyner, C. R. et al, Presentation to Space Nuclear Propulsion Technologies Committee from Aerojet, NTP & NEP Design Attributes for Mars Missions, Slide 8 “Readiness of Liquid Rocket Hardware for NTP”, June 29, 2020.

[40] Numerical Propulsion System Simulator, https://software.nasa.gov/software/LEW-17051-1.

[41] Rocket Engine Transient Simulation Software, https://software.nasa.gov/software/MFS-31858-1.

are also applicable to NTP engine subsystems and have been used to model both HEU and high-assay, low-enriched uranium (HALEU)-type engines.

Propellant Storage and Management Subsystem

Long-term storage and active cryogenic technologies for liquid hydrogen has similarly evolved independently of NTP, but significant challenges must still be overcome to meet a storage time of perhaps 4 years for the baseline mission (2 years in an assembly plus 2 years for the roundtrip to Mars). Ongoing research technology development by NASA will lead to several missions beginning in 2021 to demonstrate advanced technologies for the storage and transfer of cryogenic fluids in space.

TECHNOLOGY REQUIREMENTS, RISKS, AND OPTIONS

NTP system performance is strongly driven by the heat transfer efficiency of a given design. This is a function of the temperature profile during operations, time at the maximum operating temperature, the number of planned operating cycles (with safety margins for additional potential cycles), and rates of change for temperatures across the system. The primary NTP system-level risks are driven by the following:

- The high operating power density and temperature of the reactor necessary to heat the propellant to approximately 2700 K at the reactor exit for the duration of each burn. This is necessary to meet the 900 s I_{sp} mission requirement.
- The need for long-term storage and management of cryogenic LH_2 propellant.
- The much shorter NTP reactor startup times (as little as 60 s from zero to full power) relative to other space or terrestrial power reactors (sometimes as long as several hours).
- The longer startup and shutdown transients of an NTP system relative to chemical engines. This drives design of the engine turbopumps and thermal management of the reactor subsystem.

Reactor Subsystem

An NTP system with a propellant reactor exit temperature of approximately 2700 K represents an extreme environment in terms of temperature and hydrogen corrosion for the materials in the reactor core. This reactor operating temperature implies that there are few viable fuel architectures. The fuel element, which includes the fuel and cladding, the fuel assemblies, moderator, support structures, and the reactor pressure vessel must maintain physical integrity while cycled through the thermomechanical stress induced during repeated cycles of reactor startup, operation at power, shutdown, and restart.

At least three new NTP fuel architectures are under consideration by NASA, including the following:

1. Cercer-coated fuel particles in a refractory ceramic matrix,
2. Cercer solid solutions of mixed (U, Zr, Nb)C carbide fuel with multiple potential particles (UN, UC, UCZr, etc.), and
3. Cermet-coated fuel particles in a refractory metal matrix.

Multiple fuel particle packing densities (15 to 70 volume percent) and varying fuel particle architectures are under consideration for some of these fuel options. An overview of these NTP fuel options is provided in Figure 2.3. Both HEU and HALEU fuel enrichments are possible. Currently, the reference cermet fuel architecture uses uranium nitride (UN) particle fuel at 40 to 70 volume percent packing density, with fuel particle architecture to be finalized, and a molybdenum (Mo)-30%W[42] metal matrix. The metal matrix composition involves a compromise between limiting parasitic thermal neutron absorption (i.e., by reducing tungsten content) and maximizing the alloy melting temperature (i.e., by increasing tungsten content). Cercer fuels with coated fuel particles offer the potential for increased safety margins with respect to fuel matrix melting compared to cermet systems, but cercer fuels are at a lower level of technological and fabrication maturity. Cercer solid solution fuels similarly offer the potential for higher performance and safety (fuel melting) margins but are at a similar lower level of technological maturity. Graphite matrix fuel systems have demonstrated excellent high temperature capability (greater than 3000 K), but would require a robust, defect-free high temperature coating such as ZrC for all surfaces exposed to hot hydrogen due to the fundamental high temperature incompatibility of graphite and hydrogen. Pronounced cracking was observed in ZrC coatings on graphite composite fuel coolant channel surfaces even at temperatures as low as about 1500 K in the NERVA program, although more recent research has made advances in this area.[43]

NASA and DOE will need to determine if current or planned HEU or HALEU fuel feedstock production capabilities will be sufficient to meet the needs of the NTP baseline mission. Key issues include identification of a suitable fuel architecture. Trade studies to address these issues will be needed in advance of mission formulation and initial design efforts.

Testing of candidate core materials may consider the applications of core fabrication for both conventional and advanced manufacturing methods. Advanced methods, such as additive manufacturing, are showing promise in both aerospace and nuclear manufacturing industries. These techniques are most likely to be suitable for NTP components outside the highest temperature environments of the reactor core. New manufacturing techniques, however, lack a substantive body of relevant performance testing in either nuclear or in-space high-radiation environments. As a result, new manufacturing techniques will require performance testing and analysis, even if these techniques are used to fabricate nuclear-qualified materials previously made using conventional techniques.

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[42] That is, an alloy of molybdenum with 30 percent by weight of tungsten.

[43] Raj, S. V., and Nesbitt, J. A., "Development of Advanced Coatings for NERVA-type Fuel Elements," NETS2015-5072, Nuclear and Emerging Technologies for Space (NETS) 2015, Albuquerque, NM, February 2015.

Permission pending

FIGURE 2.3 Fuel assemblies under consideration for NASA's NTP reactor designs. SOURCE: J.K. Witter, BWXT Technologies, Presentation to Space Nuclear Propulsion Technologies Committee, July 13, 2020.

While the NTP propulsion concept has been studied for more than six decades, insufficient technical maturity for fuel forms, fuel assemblies, moderator materials, and high-temperature structural materials, in particular for the three new core concepts noted above (cermet, cercer, and cercer/carbide), is a significant risk to overall program success. Without substantial up-front investment in the development of these specific areas of technical risk, many of the integrated system designs and associated integrated risks cannot be adequately managed or mitigated.

Thermodynamically stable high-performance neutron moderators are an important aspect of a thermal-spectrum NTP reactor core design. Potential moderator materials include ZrH, YH, Be, BeO, and Be_2C. For the hydrides and pure beryllium, maximum use temperatures are expected to be about 700-1500 K due to hydrogen dissociation and beryllium melting concerns. Upper operating temperature limits based on dissociation need to be accurately determined so that candidate moderator materials can be assessed and cooling channels designed. The effects of hydrogen embrittlement and infiltration into the moderator material and the related dissociation characteristics are also important considerations. These characteristics will need to accommodate temperature and thermo-mechanical excursions experienced during startup and shutdown transients of the NTP reactor system. In particular, hydrogen flow will need to continue after reactor shutdown to provide cooling, which will impose some performance penalty on the NTP system.

The reactor structure serves as the primary interface to the LH_2 propellant at the upper plenum inlet as well as the interface to the nozzle. While there has been some progress in the development of reactor structural materials and the initial design of these systems, key aspects of the reactor structure will need to be matured to accommodate optimization for mass, propellant flow, propellant pressure drop through the length of the structure, flow rates and stability, and stress analysis. Shielding, for both gamma and neutron radiation, will also need to be considered as part of the overall reactor system design. Shielding design, composition, and placement will need to account for the location of instrumentation and control electronics, radiation susceptible turbomachinery, the cryotank for LH_2 storage, and the crew vessel.

Reactivity control (i.e., thermal neutron absorber) materials are also needed for operational control, launch safety considerations, and multiple reactor startups and shutdowns. Many of the existing and current designs employ reactivity control drums located radially within a reflector assembly. Control drums are primarily constructed of a neutron reflector material with a section of a thermal neutron absorber, such as B_4C, that can be rotated to face the core (to shut down the reactor) or rotated away from the core (for reactor startup and operation). The control mechanism for the control drums will need to manage the flow rates for LH_2 and gaseous H_2 through the moderator, outer reactor structure, nozzle, and reactor core. For the initial flight of an NTP system, additional sensors for temperature, pressure, coolant flow rate, and neutron flux will likely be necessary to provide additional characterization of the flight system.

FINDING. ***NTP Fuel Characterization*.** A significant amount of characterization of reactor core materials, including fuels, remains to be done before NASA and DOE will have sufficient information for a reactor core design.

RECOMMENDATION. ***NTP Fuel Architecture*. If NASA plans to apply nuclear thermal propulsion (NTP) technology to a 2039 launch of the baseline mission, NASA should expeditiously select and validate a fuel architecture for an NTP system that is capable of achieving a propellant reactor exit temperature of approximately 2700 K or higher (which is the temperature that corresponds to the required specific impulse (I_{sp}) of 900 s) without significant fuel deterioration during the mission lifetime. The selection process should consider whether the appropriate fuel feedstock production capabilities will be sufficient.**

Engine Subsystem

The engine subsystem has significant heritage from chemical rocket engines, including the use of gaseous H_2 and LH_2 as a fuel. Additional testing for the engine subsystem will be necessary to demonstrate integrated operability, lifetime, and reliability. However, assuring the performance of the engine subsystem is a relatively low-risk element of developing an NTP system for the baseline mission.

Propellant Storage and Management Subsystem

The development of multiyear cryogenic storage capabilities for LH_2 remains a significant challenge. Storage of metric tons of LH_2 at cryogenic temperatures as low as 20 K, with minimal losses, is needed because of the long duration of the baseline mission, including time for in-space vehicle assembly and the round trip to Mars. The current expectation for the baseline mission is that at least six NTP system starts will be needed, with a total LH_2 propellant requirement that ranges from 7 to 21 10,000-kg tanks of LH_2 depending on which launch vehicles are used and the mission departure year. Minimizing the boiloff of LH_2 from the storage tanks is necessary to reduce the amount of LH_2 that must be launched and the number of storage tanks that must be integrated into the Mars exploration spacecraft.[44]

Although development of refrigeration technology is proceeding, existing cryocooling systems cannot reliably meet propellant tank requirements over a mission of this duration. Additionally, propellant mass must be accurately measured before and after each firing of the propulsion system to appropriately balance flow rate to the reactor start up and reactivity control operations. Cryocooling systems will require electrical power throughout the mission, which would be provided by small solar arrays that are dedicated to this purpose.

FINDING. *NTP Storage of LH_2.* NTP systems for the baseline mission will require long-duration storage of LH_2 at 20 K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission.

RECOMMENDATION. *NTP Storage of LH_2.* If NASA plans to apply nuclear thermal propulsion (NTP) technology to the baseline mission, it should develop high-capacity tank systems capable of storing liquid hydrogen (LH_2) at 20 K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission.

TESTING, MODELING, AND SIMULATION

As described above, the components of the engine subsystem and the propellant storage and management subsystem have been demonstrated on chemical rockets to a high technology readiness level (with the exception of long-term storage of LH_2 in space with minimal boiloff). Therefore, the largest return on testing, and on M&S efforts, would accrue through a focus on the reactor subsystem, wherein lies the dominant system risks.

Testing is conducted to verify material characteristics, operational performance, and functionality (e.g., operability, controllability, and thermal management) of components, subsystems, and integrated systems over the intended operational lifetime of the system, including transients and margins of safety. All previous rocket engines have undergone extensive, multi-engine full-scale ground testing as part of their certification programs. For example, 10 or more space shuttle main engines as well as J-2 and RL-10 upper-stage engines were all ground-tested for more than their full mission durations prior to certification.[45] These tests also support retirement of potential concerns related to safety and reliability of both nuclear and non-nuclear elements of the NTP system, and acquired test data provide a means to validate models used to support computational design and simulation of system operation during both steady-state and transient conditions to ensure a sufficient level of confidence regarding design margins and uncertainty under all operational conditions.

A traditional progression of tests includes separate effects testing to characterize materials properties and behaviors; component, subassembly, and assembly testing; scaled system testing; and integrated system tests. For the reactor subsystem, this could entail testing of components in

[44] Joyner, C. R. et al, Presentation to Space Nuclear Propulsion Technologies Committee from Aerojet, NTP & NEP Design Attributes for Mars Missions, Slide 8 "Readiness of Liquid Rocket Hardware for NTP", June 29, 2020.

[45] Richards, Steve, "Liquid Rocket Engine Flight Certification," Space Transportation Technology Symposium, Pennsylvania State University, 1991.

environment chambers or test reactors, subcritical tests, and critical tests (at zero-power and full power conditions).

An NTP reactor core and associated systems presents unique challenges relative to terrestrial nuclear technology employed for power production. NTP systems operate at much higher power density levels, temperatures, and coolant (propellant) flow rates than standard reactor technologies. They therefore use materials for which there is a very limited database that can be used for model validation. Additionally, in contrast to terrestrial power reactors, NTP reactors are open cycle: the reactor coolant is expelled through the nozzle rather than being contained in a closed cycle. Prior to establishing a test plan, the existing database of materials properties, under both steady state and dynamic conditions, would be assessed, and a review of data available from previous test programs on related technologies (e.g., Rover/NERVA) would be conducted, including their compatibility with flowing H_2 at operational temperatures. If similar materials and operating parameters are selected, using available data to benchmark modern modeling and simulation tools may narrow the remaining areas of uncertainty, allowing developers to reduce the overall number and types of tests necessary to retire risk. In addition, testing of reactivity control for NTP systems has only been conducted for HEU systems, and no full engine tests have been completed. Testing is needed to characterize reactivity control of a moderated HALEU-fueled NTP system.

For an NTP reactor, the reactor is ramped to full power over a period of approximately 60 s while hydrogen propellant is introduced to the outer reactor containment vessel, and subsequently the core, for temperature control (i.e., cooling using LH_2). During the initial few seconds, thermal-mechanical stresses expand the reactor core, having a reactivity impact. Introduction of H_2 also has a reactivity impact. That is, multiple feedback effects occur concurrently and locally, such that the power increase may be nonlinear and scale dependent, making it difficult to predict and control unless these behaviors are well understood and represented in the corresponding dynamic simulation of the reactor startup. These interplaying conditions must be managed at high temporal fidelity to offset transient excursions in the reactivity profile. Passage of the H_2 propellant through the core may also introduce substantial core pressure variations, both axial and radial temperature variations, flow instabilities, and engine vibration, all of which are scale dependent. Finally, the pressure differential at the nozzle throat may also induce loads or pressure gradients that impact engine performance and safety. This last effect may be less important to characterize via ground test and may instead be characterized during initial cargo missions. Beyond these nuclear and thermal-hydraulic challenges, numerous thermomechanical verification challenges exist for these engines that will operate near the limits of temperature and material property and joining technology capabilities. It is critical to recognize that most of the complex interactions described above are nonlinear and scale-dependent, meaning that the risks they represent cannot be retired by subscale testing.

Ground tests of integrated NTP reactor and engine subsystems would reduce technical risk. Such testing has been used for all previous liquid rocket engines for flight.[46] While it may be possible to characterize integrated system performance using a non-nuclear, electrically heated environment, the accuracy of such testing may be a challenge for NTP systems, which have tightly coupled neutronic-thermal-hydraulic response characteristics. In addition, heating elements used to emulate nuclear heat in these tests would need to be designed to accurately

[46] Richards, Steve, "Liquid Rocket Engine Flight Certification," Space Transportation Technology Symposium, Pennsylvania State University, 1991.

reflect core temperature profiles (both radially and axially) and heat-up/cool-down rates to adequately reflect both steady-state and dynamic operation.[47]

A series of separate effects testing for materials, components, and subassemblies is necessary prior to selection of options and system-level testing. Specific tests to characterize properties and behaviors, both pre- and post-irradiation, would be determined based on materials selections and the existing databases associated with the selected materials. Scaled testing of subsystems, designed at a scale that provides performance results that support characterization of integrated effects (employing nondimensional parameters) and identification of potential failure mechanisms may also be performed to further develop an understanding of system-level performance parameters.

Following the separate effects, component, and subassembly ground testing, system-level nuclear ground testing phases would take place. These tests could include those described below, which would be performed sequentially. Key considerations for testing in all three phases include potential requirements for safety and environmental reviews and approvals, especially for testing that requires the construction of new facilities or modification of existing facilities.

- **Phase 1. Zero-Power Critical (ZPC) and Low-Power Tests.** ZPC tests are neutronic tests that verify various operational characteristics of a fission reactor. The ZPC test series is conducted in such a way that it leaves the reactor and components essentially nonradioactive. This method of testing would verify the operability of the reactivity control system but would not ramp the reactor through the full transient conditions to achieve full power. Hence, the ZPC approach would not demonstrate the thermomechanical stability of the reactor system, nor would it demonstrate the effects of the LH_2 propellant on reactivity control, system performance, and safety. All reactor designs would be subjected to ZPC testing, and possibly low-power testing, prior to developing a flight system, regardless of the decision to include other integrated system ground testing. A ZPC test would also be conducted for the flight unit prior to launch of an NTP for either a cargo or crewed mission.
- **Phase 2. Reactor Operational Tests (Rover/NERVA-Like Testing).** Operational testing of a complete nuclear reactor subsystem would entail nuclear testing of the complete, prototypic reactor system with heat generated by fission. LH_2 would be pumped through the reactor structure and core during startup, operation, and shutdown, as a demonstration of the engine system and thermal management system for the reactor through all phases of operation. Such an approach would demonstrate reactor operability, performance, reliability and, most importantly, controllability through transient startup, operation, and shutdown conditions, and it would demonstrate performance after multiple restarts. Properly instrumented, these operational tests would provide the validation data necessary to benchmark and demonstrate the efficacy of M&S tools in predicting reactor performance, lifetime, and reliability and characterizing hydrogen effects on the reactor materials, thermal management, and reactivity controls. These tests would also allow detailed post-test inspections to determine material effects and degradation and identify incipient failure mechanisms to allow for reactor-to-reactor manufacturing variability. While such tests would not incorporate the engine subsystem, they would require a test support system to manage the hydrogen effluent as it exits the reactor core. Facilities at

[47] Bragg-Sitton et al., STAIF, 2008; and Bragg-Sitton et al., STAIF, 2007.

the Nevada Test Site could be evaluated for their ability to support operational tests, but the need to capture and/or recirculate the H_2 coolant/propellant may make it difficult to use existing facilities without extensive modifications. Safety and environmental approvals will also be required.[48]

- **Phase 3. Integrated System Tests.** These tests would add the engine and propellant management subsystems to the reactor test configuration described in Phase 2.[49] The integrated system tests could be completed on the ground, but they would require extensive investments in infrastructure and environmental approvals. Facilities to support these tests do not currently exist.

The ZPC tests described in Phase 1 can likely be conducted at existing facilities, including the launch site, although facility modifications will be needed.[50] These tests can be used as a part of the design process and, when conducted on the flight unit, can verify neutronic status and control drum operability prior to system launch. Phase 1 testing would have the most modest schedule impact and cost relative to the other test phases, but ZPC testing would not retire many of the risks associated with dynamic performance of the system, particularly during startup to full power or during the shutdown transient.

The ground testing approach described in Phase 2 emulates that which was adopted for Rover/NERVA. Facilities used to support those historical tests are no longer available, but existing facilities could be modified to support the testing needs, given sufficient time and funding. Testing with this approach is necessary to fully understand the dynamic system performance, lifetime limitations, reliability, interfaces, and manufacturing margins, thus reducing uncertainty and risk to program success. To have the greatest impact on risk reduction, multiple test units would be needed to determine the repeatability of the measured system characteristics to properly assess design margins. This test series would only be initiated after (1) a thorough review of historical data to benchmark M&S codes against prior tests to characterize the most significant areas of uncertainty and potential failure modes and (2) a detailed subsystem testing campaign.

Legacy fuels, materials, and structural design approaches (e.g., from the Rover/NERVA program) could be used to mitigate some schedule and technical risk associated with an NTP system fueled with HEU if the technology can be fully recaptured and sufficient data are available to identify failure modes and benchmark modern M&S codes used to design the NTP system.[51,52] Additional full-scale testing would be required with whatever final fuel is selected that can meet the propellant temperature requirements. Selection of cermet and/or cercer fuel and/or a moderator block design and/or materials would increase technical risk, development time, and, consequentially, cost.

[48] Borowski, S. K., et al, “Affordable Development and Demonstration of a Small Nuclear Thermal Rocket (NTR) and Stage: How Small is Big Enough?” NASA/TM- 2016-219402, AIAA-2015-4524, December 2016.

[49] The integrated system tests would validate the complete NTP system with the exception of the ability for long-term storage of LH_2; those technologies can be tested separately.

[50] C. Reese, D. Burns, and J. Werner, Cost and Schedule Estimates for Establishing a Zero Power Critical Testing Capability at Idaho National Laboratory to Support NASA Nuclear Thermal Propulsion Design Development, INL/EXT-19-53988, May 2019.

[51] Legacy systems were fueled with HEU, and the utility of legacy research and development would be of diminished for an NTP system fueled with HALEU.

[52] Borowski, S. K., et al, “Affordable Development and Demonstration of a Small Nuclear Thermal Rocket (NTR) and Stage: How Small is Big Enough?” NASA/TM- 2016-219402, AIAA-2015-4524, December 2016.

Phase 3 testing of integrated reactor and engine subsystems would entail significant investment of time and funding to construct a facility that can acquire the necessary performance data, manage the hydrogen effluent, and maintain safety under all planned test conditions and potential accident scenarios. As noted for Phase 2, testing of a number of NTP units would be necessary to fully retire risk and ensure repeatability of system fabrication and operation. This approach would minimize technical risk, but there would be cost and schedule risk associated with definition and construction of new facilities and obtaining environmental approvals. If only component, subassembly, and Phase 1 and Phase 2 system tests are performed along with extensive M&S validation, then a sequence of extensively instrumented flight tests, at full scale, could replace Phase 3. These flight tests could incorporate the cargo missions planned before first flight of crew. These missions would need to be carefully defined and instrumented to fully characterize system performance, including engine operation for the total throughput of LH_2 required for the baseline mission (i.e., a round-trip crewed mission). Additionally, one or more cargo missions would need to precede the planned crewed missions by a significant timeframe to allow for potential modification of the NTP system design based on data collected during the flight tests.

Without significant ground- based testing, benchmarking of M&S tools would be limited to component/subsystem hardware testing and legacy data on steady-state and dynamic performance, coolant flow, thermo-mechanical, and reactivity behavior from the Rover/NERVA ground testing as well as in-space testing during the cargo missions prior to the first crewed mission. A detailed review and evaluation will be required to determine the relevance of the M&S validation using Rover/NERVA test data for any new reactor design(s) and materials.

M&S predictive capabilities have advanced significantly since previous NTP development programs. The status of these capabilities to address and adequately predict coupled multi-physics simulation for NTP (to ensure startup controllability and concurrent coolability) is required before deciding on the testing path going forward. In this case, flight testing, which could be incorporated into the initial cargo missions, would become the key tool for system-level validation of successful performance, operability, controllability, coolability, reliability, lifetime, and safety. To enable this approach, the decision to freeze the flight hardware design would have to be made earlier in the development schedule, and the cargo missions would have to be launched significantly earlier than the planned 2039 crewed mission. Any technical issues identified with the first flight system would require attention, perhaps involving redesign, retest, and subsequent flight validation.

In summary, the most robust technology development program would follow testing through Phase 3, with flight tests occurring as a stand-alone mission rather than as part of a cargo mission. The lowest cost and highest risk technology development program would be to only conduct separate effects testing coupled with ZPC (Phase 1, above) and utilize flight tests conducted as part of the initial cargo missions. In this scenario, failure of the NTP on the initial cargo mission would result in significant mission delays and cost increases to support redesign and retest. There exists a spectrum of options between these two extremes. For example, ground testing through the described Phase 2 offers a lower, intermediate technical risk path, but with schedule and cost risks primarily associated with the construction of new facilities, modifications to existing facilities, safety and environmental approvals, and the completion of the testing. The schedule and cost risks associated with facilities are particularly acute for the larger facilities required for full-scale tests, especially for those that involve containment, storage, and disposal of radioactive gasses, liquids, and equipment. Environmental standards, for example, are much more stringent and the environmental approval process takes much longer to complete than when full-scale test facilities were constructed for the Rover/NERVA programs. In any approach that uses the precursor cargo missions as the means for relevant-scale spaceflight demonstration, sufficient time between the first flight and the crewed missions is required to make and validate design updates.

FINDING. ***NTP Modeling and Simulation, Ground Testing, and Flight Testing.*** Subscale in-space flight testing of NTP systems cannot address many of the risks and potential failure modes associated with the baseline mission NTP system and therefore cannot replace full-scale ground testing. With sufficient M&S and ground testing of integrated systems, including tests at full scale and thrust, flight qualification requirements can be met by the cargo missions that will precede the first crewed mission to Mars.

RECOMMENDATION. ***NTP Modeling and Simulation, Ground Testing, and Flight Testing*****. To develop a nuclear thermal propulsion (NTP) system capable of executing the baseline mission, NASA should rely on (1) extensive investments in 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.**

DEVELOPMENT AND DEMONSTRATION ROADMAP

The roadmap in Figure 2.4 shows key milestones and when they would need to be achieved to execute the baseline mission: launching a crewed mission to Mars in 2039 preceded by an initial cargo mission in 2033.

The development of an NTP system for the cargo and crewed elements of the baseline mission will require several program phases. As shown in the roadmap (Figure 2.4), there is no time for delay. These phases include the following:

- Development of technology and M&S capabilities for the NTP system and its subsystems and components,
- Ground testing of subsystems and components,
- Facility development and integrated testing of the NTP system,
- Development and launch of cargo missions, and
- Development and launch of the baseline mission for human exploration of Mars.

To meet the necessary prototype demonstration schedule, several activities would need to run concurrently, including fuel architecture technology development, reactor core design, cryogenic fluid management, integrated propulsion system design, and engine component technology development and testing. Candidate fuel architectures must be evaluated to enable selection of an architecture that can meet mission requirements. The first major milestone (by the end of 2021) will be a decision to use either HEU or HALEU fuel. NASA and DOE can then initiate a fuel technology development effort to include fuel chemistry determination (UN, UCO, UO_2, etc.) and the fuel architecture technology maturation (cercer, cermet, ceramic, etc.). As shown in Figure 2.3, the successful demonstration of fuel performance will necessarily take place prior to the initiation of the prototype final design review as this fuel architecture outcome will drive final design decisions, including the choice of moderator block configuration and reactor core materials.

Technology development for reactor core structural and moderator materials are scheduled to commence in 2022 to support preliminary design efforts as facilities within industry, NASA, and DOE are available to test and validate nuclear and non-nuclear component performance and material characterization. NASA will also need to demonstrate long-term storage technologies with near-zero boil-off for LH_2 propellant tanks in the 2025 timeframe.

Engine performance considerations and the resulting reactor core operational and safety margins associated with hydrogen flow through the system will be characterized during prototype development to support the eventual demonstration of the propulsion system. It is projected that a successful prototype demonstration could be completed in the 2027 to 2029 timeframe. This will be a critical milestone in the development of Mars flight system, the design of which must begin in 2029 or 2030 to maintain the timeline for a crewed mission in 2039.

The recommended testing regime will require new and upgraded facilities. These could become schedule-limiting without early action to develop necessary testing capabilities. Ground tests could continue into the cargo mission design phase.

Multiple cargo precursor missions are planned to deliver supplies to Mars prior to the first crewed mission, and these cargo missions could satisfy flight qualification requirements of the integrated NTP engine system. The first of these missions will need to be launched no later than 2033 to provide enough time to address any emergent issues before the 2039 crewed mission. An NTP system or the crewed mission would likely consist of multiple, largely independent, engine modules. The cargo missions may use a single NTP engine module and a lower total propellant load than is needed for the human exploration mission, but it would demonstrate the maximum propellant throughput for a single engine, and it would include enough of the performance capabilities to demonstrate adequate engine performance, lifetime, and reliability for the crewed mission.

FINDING. ***NTP Prospects for Program Success.*** An aggressive program could develop an NTP system capable of executing the baseline mission in 2039.

RECOMMENDATION. ***NTP Major Challenges*****. 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).**

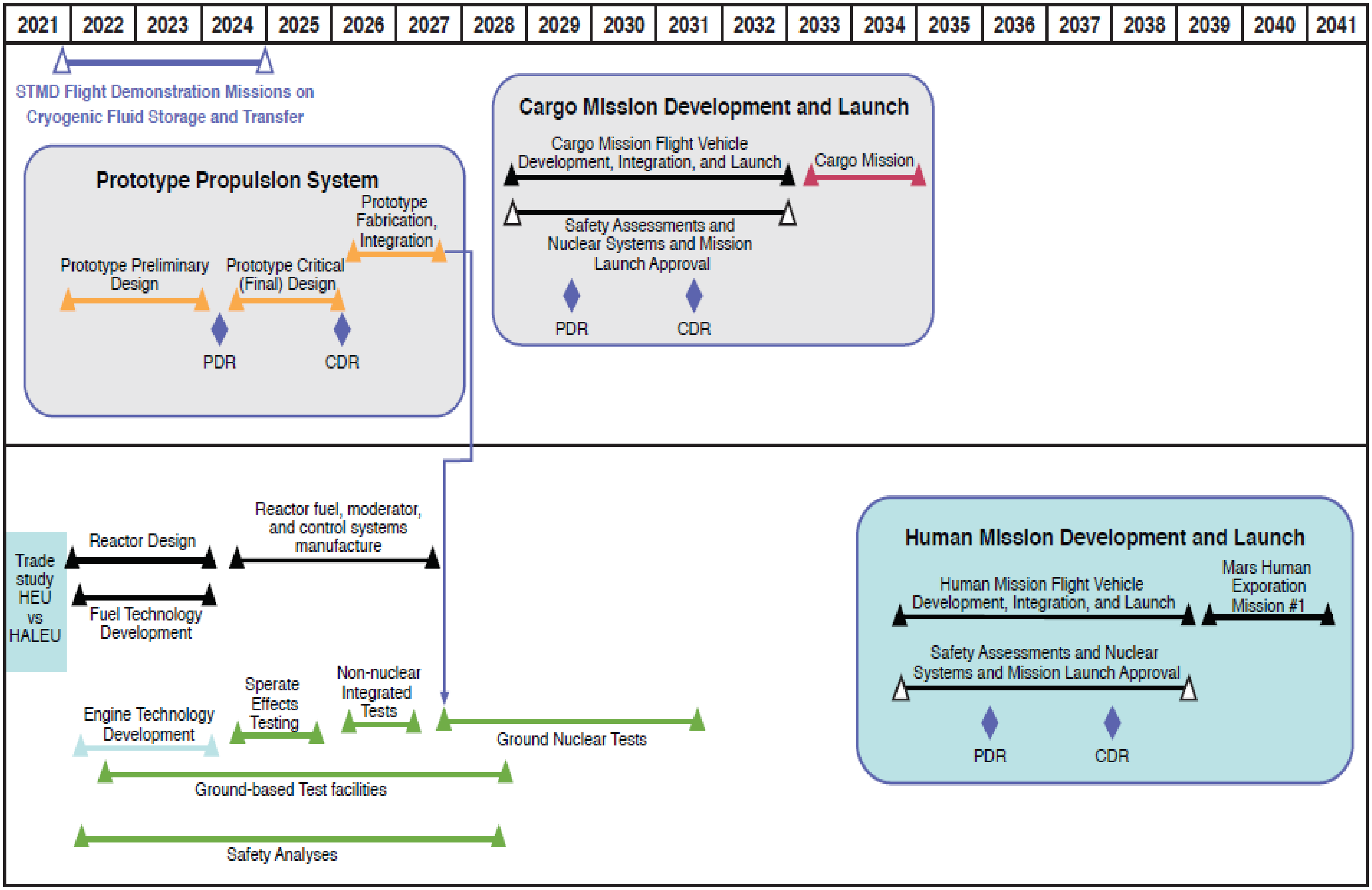

FIGURE 2.4 Nuclear electric propulsion (NEP) development roadmap for the baseline mission, with a 2039 launch of the first human mission. NOTE: Acronyms defined in Appendix D.

SUMMARY

The Rover/NERVA program demonstrated the feasibility of graphite-based HEU fuels in NTP engines by ground testing nearly two dozen reactors at full power, some integrated with NTP engine hardware. Unfortunately, much of this expertise has been lost in the intervening 50 years since the program's termination, and several design issues remain unresolved. There have been several decades of research into NTP fuels and system design since Rover/NERVA, but no NTP reactors or engines have been constructed since then, and none have ever flown. All NASA and DOE NTP programs prior to 2013 focused on HEU designs and experiments.[68,69] In addition, only limited fuel development and M&S has been devoted to HALEU designs.

NTP development faces four major challenges that, with adequate resources, can be overcome to execute the baseline mission in 2039. As noted above, these challenges are (1) heating propellant to approximately 2700 K at the reactor exit for the duration of each burn, (2) the long-term storage of liquid hydrogen in space with minimal loss, (3) the lack of adequate ground-based test facilities, and (4) rapidly bringing an NTP system to full operating temperature (preferably in 1 min or less).

There are currently no facilities in the United States that could conduct a full-power ground test of a full-scale NTP reactor comparable to the Rover/NERVA experiments. Existing facilities could be modified to support ZPC and low-power critical testing of an NTP reactor to validate control system status and operability, reactor excess reactivity, and shutdown margin prior to launch. NTP development can be conducted at increasing levels of complexity, starting with component testing and M&S development. Development may proceed to fully integrated reactor tests, such as ZPC tests, to verify criticality characteristics. Rover/NERVA-like experiments could be replicated to test the performance of fully integrated reactors during startup, extended operation at full power, shutdown, and restart.

The nonlinearity and scale dependence of many of the physics and potential failure mechanisms indicate the need for testing of the reactor and all tightly coupled subsystems at full-scale. This may be possible through ground-based testing. Subscale NTP flight testing cannot replace full-scale ground testing. Flight qualification requirements could be satisfied by leveraging the sequence of cargo missions occurring before the first crewed mission, with the first cargo mission in the 2033 timeframe. This approach would provide sufficient time for incorporation of lessons learned into subsequent NTP cargo missions and ultimately the crewed mission in 2039.

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[68] Venneri, Paolo and Kim, Yohnghee; "Physics Study of Nuclear Reactors for Space and Rocket Propulsion," Proceedings of ICAPP 2013, Paper KA148, Korea April 2013.

[69] Rosairem, Gwyne, et al. "Design of a Low-Enriched Nuclear Thermal Rocket," Center for Space Nuclear Research, August 2013.

3

Nuclear Electric Propulsion

SYSTEM CONCEPT

Nuclear electric propulsion (NEP) systems convert heat from the fission reactor to electrical power, much like nuclear power plants on Earth. This electrical power is then used to produce thrust through the acceleration of an ionized propellant.

An NEP system can be defined in terms of six subsystems, which are depicted in Figure 3.1 and briefly described below.

- *Reactor.* As with a nuclear thermal propulsion (NTP) system, the reactor subsystem produces thermal energy. In an NEP system, this thermal energy is transported from the reactor to the power conversion subsystem through a fluid loop.
- *Shield.* As with an NTP system, the shield subsystem reduces the exposure of people and materials in the vicinity of the reactor to radiation produced by the reactor.
- *Power conversion.* The power conversion subsystem converts some of the thermal energy transported from the reactor to electrical energy through either dynamic mechanical or static solid-state processes, such as flowing a heated fluid through turbines as in terrestrial power plants, or through use of semiconductor or plasma diodes to move charged particles through a material. The remaining thermal energy is rejected as waste heat.
- *Heat rejection.* Terrestrial power systems can use ambient water and air for convective cooling. The thermal energy created by NTP systems is transferred to the cryogenic propellant and exhausted into space. High-power NEP systems require heat rejection radiators with large surface areas to provide adequate cooling, and, as power levels increase, the size and mass of the heat rejection subsystem has the potential to dominate over other subsystems. Heat rejection at high temperatures reduces the radiator area since radiation increases proportionally to the fourth power of the absolute temperature of the

radiator.[1] High temperature operation thereby increases performance, but it becomes a challenge for other aspects of the system.

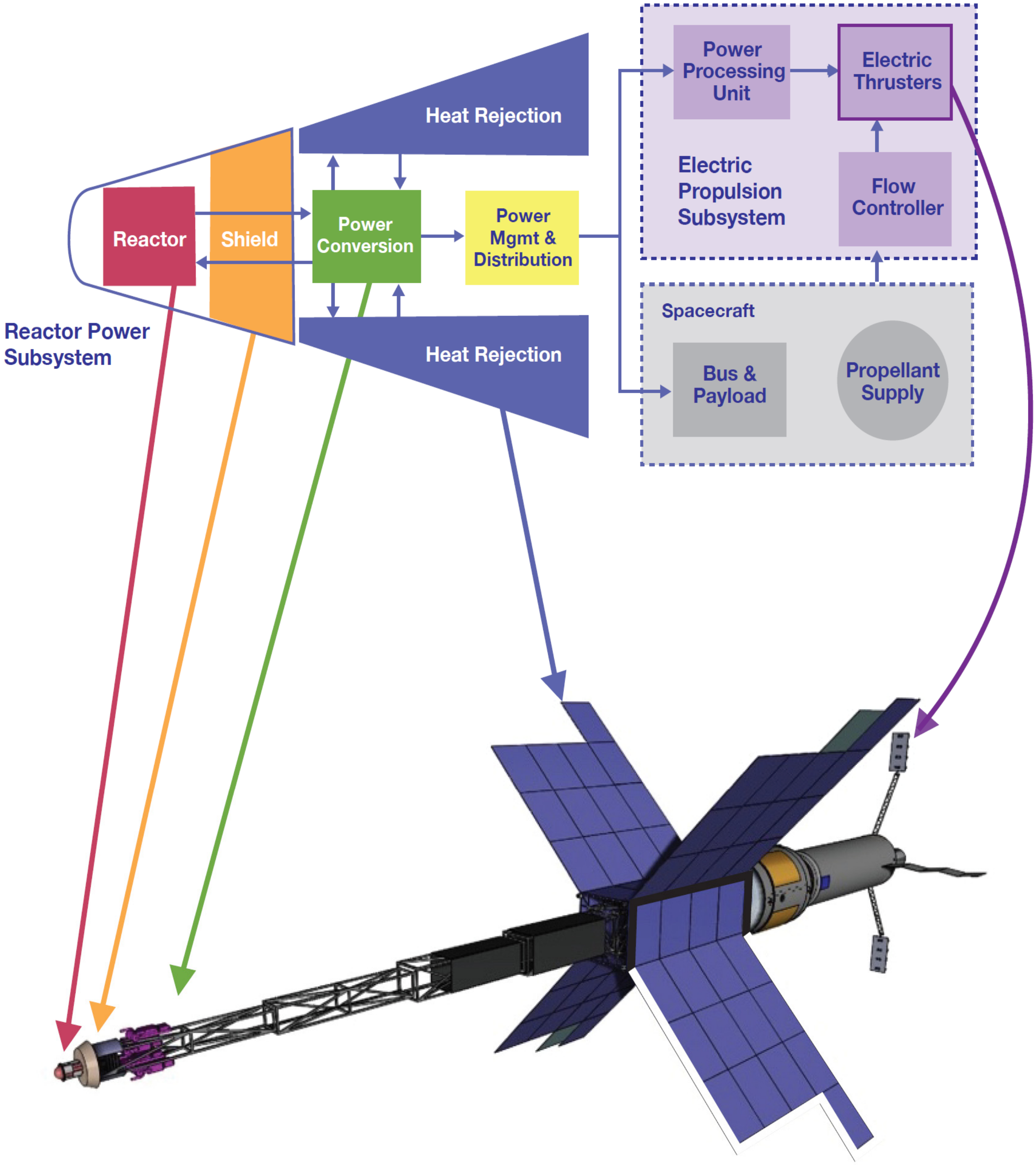

FIGURE 3.1 Nuclear electric propulsion subsystems and conceptual design. SOURCE: Mars Transportation Assessment Study briefing by Lee Mason, NASA, to the Space Nuclear Propulsion Technologies Committee, June 8, 2020.

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[1] Mission length also impacts radiator area. For longer missions larger radiators are required to account for possible damage from micrometeorites.

- *Power management and distribution (PMAD).* Electrical power from the power conversion subsystem is often generated near the reactor to avoid thermal losses; however, the power must be controlled and distributed over relatively large distances to the electric propulsion (EP) subsystems. The PMAD subsystem consists of the electronics, switching, and cabling to manage the electrical voltage, current, and frequency of the transfer efficiently.
- *EP.* The EP subsystem converts electricity from the PMAD subsystem into thrust through electrostatic or electromagnetic forces acting on an ionized propellant. The EP subsystem consists of the power processing unit (PPU), propellant management system (PMS), and thrusters. The PPU converts the power provided by the PMAD to a form that can be used to generate and accelerate a plasma. A "direct-drive" system would directly drive the EP subsystem from the PMAD subsystem with a commensurate reduction in PPU mass. Power control hardware for switching and power quality would still be required for starting, throttling, and managing transients and faults within the EP subsystem. The PMS manages the propellant flow to the thrusters.

NEP system performance is governed by the total system mass required to produce the required power level (i.e., the system specific mass, in kilograms per kilowatt-electric [kg/kWe]), the performance of the EP subsystem, and the lifetime and reliability of all subsystems. System design trades focus on maximizing the power conversion subsystem efficiency, the waste heat rejection temperature, and the efficiency and specific impulse (I_{sp}) of the EP subsystem while achieving the mission lifetime and reliability requirements.

HISTORICAL OVERVIEW

Several U.S. NEP programs have been pursued since the late 1950s, including the following:

- Systems for Nuclear Auxiliary Power (SNAP),
- SP-100 space power reactor,
- Space Exploration Initiative, and
- Jupiter Icy Moons Orbiter (JIMO)/Prometheus.

The SNAP program advanced key NEP technologies from 1958 to 1972. Systems with electrical power output from 0.5 kilowatt-electric (kWe) (SNAP-10A) to 350 kWe (SNAP-50) were developed, using various energy conversion technologies. The reactors were designed to use HEU. Over the course of the program, reactor outlet temperatures increased from 810 K to about 1350 K. The SNAP-10A nuclear reactor is the only one that the United States has launched into Earth orbit. It operated at a power level of approximately 0.5 kWe for 43 days before it was shut down because of the failure of a non-nuclear component. An equivalent reactor was ground tested for more than 10,000 h.

SP-100 was a joint program by NASA, the Department of Defense (DoD), and the Department of Energy (DOE). It was initiated in 1983 with the goal of developing a system that would generate 100 kWe using thermoelectric or thermionic power conversion, with growth potential (using dynamic energy conversion technology) to about 1 megawatt electric (MWe). The reactor was designed to use HEU and produce a reactor outlet temperature of about 1350 K. Substantial advances were achieved for the fuel elements (fuel and fuel cladding), materials (for control rods, reflectors, and shielding), and thermoelectric technologies. Solutions to other technology challenges, however, were still under development when the program was terminated in 1994 as mission and power needs within the multiple sponsoring agencies changed.

The Space Exploration Initiative, which lasted from 1991 to 1993, was intended to develop a NEP system for an opposition-class human mission to Mars with a transit time of 1 year. A reference system was defined at 10 MWe. The program supported research and analysis of 1 to 3 MWe ion and magnetoplasmadynamic (MPD) thrusters before NASA terminated this program without the completion of substantive testing or technology advancement.

The JIMO/Prometheus program, initiated by NASA and DOE in 2003, was intended to develop an NEP spacecraft to explore Jupiter and several of its moons. The NEP system was designed to produce 200 kWe.[2] Design advancements were made in dynamic energy conversion, heat rejection, and associated EP technologies. Unfortunately, no relevant-scale component, subsystem, or system testing was performed before NASA terminated the program in 2005 after reevaluating its budgetary priorities.

NASA supported research to advance thruster technologies relevant to megawatt electric power levels in parallel with the above programs, including the 200 kWe mercury ion thruster tested in 1968; fundamental research on 1 to 10 MWe pulsed MPD and pulsed inductive thrusters; 250 kWe steady state MPD thrusters; and 100 kWe Hall, radiowave-driven magnetized electrothermal (VASIMR®),[3] and field reversed configuration (FRC) thruster concepts in the recently completed Next Space Technologies for Exploration Partnerships (NextSTEP) Advanced Electric Propulsion program.[4]

The most noteworthy non-U.S. space nuclear programs were conducted by Soviet Union. As noted in Chapter 2, two TOPAZ I reactors were launched as flight demonstrations, and in the early 1990s the United States purchased a developmental TOPAZ II reactor for non-nuclear test and evaluation.[5,6,7]

STATE OF THE ART

This section discusses the state of the art of the subsystem technologies that make up an NEP system as well as associated modeling and simulation (M&S) capabilities.

Integrated MWe-Class NEP Systems

An integrated technology development program aimed specifically toward a NEP system operating at more than 1 MWe has not been undertaken. Although preliminary design studies for MWe-class NEP systems have been conducted, there have not been any significant detailed

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[2] Susan S. Voss (2020): Nuclear Security Considerations for Space Nuclear Power: A Review of Past Programs with Recommendations for Future Criteria, Nuclear Technology, doi: 10.1080/00295450.2019.1706378.

[3] VAriable Specific Impulse Magnetoplasma Rocket.

[4] Moore, C.L., Pencil, E. J., Hardy, R. L., Bollweg, K. J., Ching, M. "NASA's NextSTEP Advanced Electric Propulsion Activities," https://ntrs.nasa.gov/citations/20180007411, July 2018.

[5] Buden, D. "Summary of Space Nuclear Reactor Power Systems (1983-1992)," Idaho National Engineering Laboratory, 1993.

[6] El-Genk, Mohamed S. "Deployment history and design considerations for space reactor power systems." Acta Astronautica 64.9-10 (2009): 833-849.

[7] Adrianov, V.N. et al, "Topaz-2 NPP Reactor Unit Mechanical Tests Summary Report Vol. 1," CDBMB through INERKTEK Technical Report, Moscow, Russia.

design, hardware development, or M&S advances for the full, integrated NEP system. NEP technologies, designs, and M&S tools related to HEU fuels, power conversion, heat rejection, and thrusters have been developed for 100 to 200 kWe NEP systems; some of these technologies could be scaled to the megawatt electric power level. Developing an NEP system for the baseline mission will likely involve the use of multiple NEP modules which, in the aggregate, will provide the total propulsive power. This would increase system complexity, especially since the NEP system design includes six major subsystems (on each NEP module), and the spacecraft would also need to incorporate a chemical in-space propulsion system.

Reactor

No reactor has been developed that is representative of that needed for NEP applications. Extensive development has occurred for proposed HEU fuels and cladding for NEP reactors, including irradiations up to NEP-relevant lifetime fuel burnup levels for numerous fuel elements.[8,9] Almost no work has been done for high-assay, low-enriched uranium (HALEU) NEP fuels. HEU fuels examined include uranium nitride (UN), uranium carbide (UC), and uranium dioxide (UO_2) with cladding made of a refractory alloy, such as Nb-1%Zr,[10] molybdenum (Mo) alloys, or tantalum (Ta) alloys, that can sustain operating temperatures of approximately 1200 K. Overall, there is a sound technical basis regarding the fuel and cladding temperatures and fuel burnup levels that are needed for NEP fuel systems. However, significant technology recapture activities would be needed to reestablish robust UN or UC fuel fabrication capabilities.[11]

Likewise, past efforts developed extensive knowledge on the performance of beryllium (Be) and beryllium oxide (BeO) reflector materials, B_4C control rods, and lithium hydride/tungsten (LiH/W) radiation shield materials. Beryllium and BeO reflectors and control rods have been recently manufactured for the Kilopower program. Fabrication technologies for boron carbide (B_4C) and LiH/W would need to be recaptured due to little activity over the past 16 years. M&S tools for power reactors are well developed but require updating to include the selected materials and reactor designs for the NEP system.

As noted above, NEP reactor designs bear more similarity to terrestrial reactor designs than do NTP systems. Hence, many of the neutronic and thermal-hydraulic M&S tools used to evaluate reactor designs for standard terrestrial applications are applicable to NEP analysis. In the Prometheus program, simulation of reactor and plant interactions were used to determine overall stability of the system.[12] The modeling tools used for those simulations may be useful for development of an NEP system for the baseline mission.

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[8] J.A. Angelo, Jr., D. Buden, Space Nuclear Power, Orbit Book Company, Malabar, Florida, 1985.

[9] R.B. Matthews, R.E. Baars, H.T. Blair, D.P. Butt, R.E. Mason, W.A. Stark, E.K. Storms, T.C. Wallace, Fuels for Space Nuclear Power and Propulsion, in: M.S. El-Genk (Ed.) A Critical Review of Space Nuclear Power and Propulsion, 1984-1993, American Institute of Physics, New York, 1994, pp. 179-220.

[10] That is, an alloy of niobium with 1 percent by weight of zirconium.

[11] UO_2 manufacturing capabilities remain current because UO_2 is the predominantly used fuel in commercial nuclear power plants.

[12] Ashcroft, J. and Eshelman, C., "Summary of NR Program Prometheus Efforts," Report No. LM-05K188, February 2006.

Shielding

Space reactor shielding has been analyzed and designed for a range of power levels, and M&S tools used to evaluate radiation transport and thermal management in shielding materials are available. To minimize mass, the shield for an NEP system is designed using a “shadow shield” approach, taking the form of a conical or cylindrical barrier that attenuates radiation in a conical region extending behind the shield, within which the spacecraft and payload are located. For any spacecraft with a source of nuclear radiation, the dose rate is managed by a combination of (1) distance between the reactor (or other source) and the payload and (2) attenuation by the shield. State-of-the-art shielding materials include (1) Be, LiH, and B_4C to moderate and absorb neutrons and tungsten to attenuate gamma rays; these were tested in the SP-100 program and were planned for use in the Prometheus system as well. Shielding designs incorporated cooling of the LiH, and designs allowed passage of coolant and control lines without radiation leakage. Shield modeling performed in the Prometheus program was deemed mature enough for design, and it was used to verify that coolant and electrical paths could successfully be integrated into the shadow shield.[13]

Power Conversion

Power conversion technologies relevant to space power systems have been identified in a myriad of system studies and development programs at a range of power levels over decades. The most relevant power conversion technologies are as follows:

- Static
  - Thermoelectric converters
  - Thermionic converter[14]
- Dynamic
  - Brayton cycle engines
  - Rankine cycle engines
  - Stirling cycle engines

The level of development and the potential performance of these technologies varies widely, and none have been tested to the power levels required for a MWe-class NEP system in an appropriate operating environment, even if multiple power conversion units are used to meet total power and system reliability requirements.

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[13] Ashcroft, J. and Eshelman, C., “Summary of NR Program Prometheus Efforts,” Report No. LM-05K188, February 2006.

[14] Thermionic converters are static devices that convert heat directly into electricity. They operate at high temperatures with the potential for low specific mass. In their most elementary form, thermionic converters consist of two metal electrodes separated by a narrow gap. One of the electrodes, called the emitter, is held at a high temperature, typically 1800 to 2000 K. The other electrode, called the collector, is held at a lower temperature, typically 900 to 1000 K. The emitter emits electrons into the gap and the lower temperature collector absorbs them. The electrons absorbed by the collector produce a usable electrical current as they return to the emitter through an external circuit. (National Research Council, 2001. Thermionics Quo Vadis?: An Assessment of the DTRA’s Advanced Thermionics Research and Development Program. Washington, DC: The National Academies Press. p. 15. https://doi.org/10.17226/10254.

Thermoelectric converters have a long history in space nuclear fission systems, particularly with the SNAP program and the SP-100 program. Thermionic converters integrated with the reactor core were also used in the Soviet TOPAZ reactors. Thermoelectric and thermionic converters, however, do not scale well to megawatt electric-power levels. As noted above, the SP-100 program would have shifted from static to dynamic power conversion technology to achieve MWe-class performance.

Extensive M&S capability exists for Rankine based power conversion systems used in terrestrial reactors,[15] and Brayton cycle models are advanced for some terrestrial applications, but these would require significant upgrades for application to MWe NEP systems.

Brayton power conversion has had the greatest development effort, with NEP relevant development conducted most recently for the Prometheus and Fission Surface Power (FSP) programs, both of which use superalloys, unlike the SNAP-50 system that relied on refractory materials.[16] A design schematic for the 200 kWe Prometheus system design is shown in Figure 3.2. The Prometheus project development yielded a test of a state-of-the-art 2 kWe Brayton power conversion system directly coupled to a 2.3 kWe ion thruster to simulate NEP operation. The Brayton system was operated for 800 h.

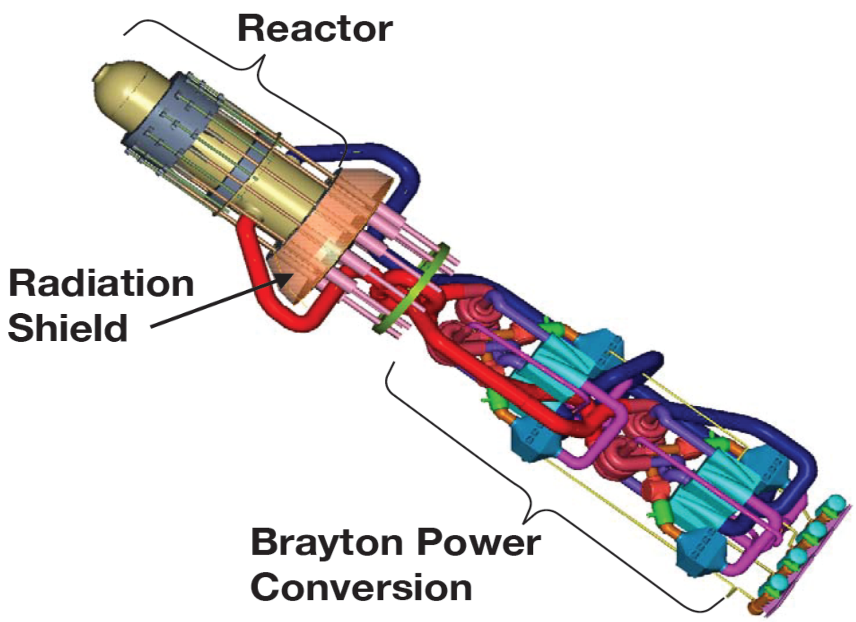

FIGURE 3.2 Prometheus/JIMO 200 kWe reactor module. SOURCE: NASA Jet Propulsion Laboratory, Prometheus Project Final Report, 2005, 982-R120461, p. 118, https://trs.jpl.nasa.gov/bitstream/handle/2014/38185/05-3441.pdf.

The Thermionic Fuel Element (TFE) Verification Program focused on life testing of single fuel elements, each with multiple thermionic converters surrounding a UO_2 fuel element in a

[15] Wright, Steven A., et al., "Closed Brayton Cycle Power Conversion Systems: Modeling, Operations and Validation," Sandia National Laboratory, Sandia Report SAND2006-2518, April 2006.

[16] A superalloy is a metal alloy with the ability to operate at temperatures up to about 1700 K. Refractory materials, which can operate at even higher temperatures, may be either metal alloys or ceramics.

relevant thermal and neutronic environment.[17] Prior to the end of the program in 1993, a single fuel element was operated up to 18 months. The TFE, however, required fuel temperatures on the order of 1800 K, which introduced additional structural material concerns for the reactor.[18]

The characteristics of the most recent power conversion technology tests relevant to space power systems are shown in Table 3.1. As shown, the demonstrated power levels for the different options vary widely, as they were not intended for use in high power, low specific mass systems. The Rankine cycle concept has been tested at 150 kWe. The other three concepts have been tested at power levels that are far below the level needed for a MWe-class NEP system. The tested values for maximum temperatures, power per converter, and the assumed materials to be used are described. The state of the art shown is for actual tested components. Much of the power conversion subsystem estimates used in projections for MWe NEP systems are based on designing existing concepts for operation at higher temperatures and scaling them to higher powers. Scaling to higher power is required, rather than simply using greater numbers of existing components to keep NEP system complexity manageable.

TABLE 3.1 Summary of NEP-Relevant Power Conversion Technology Tests

Concept	Power converter (kWe)	Reactor Exit Temperature (K)	Efficiency (%)	Materials	Program name and Date
Thermoelectric	1.5	1300	4.2	Refractory	SP-100 (1993)
Thermionic	0.7	1800	9	Refractory	TFEVP (1993)
Brayton	12	1150	20	Superalloy	Prometheus (2005)
Stirling	12	843	27	Superalloy	FSP (2015)
Rankine	150	1100	14	Refractory	SNAP-50 (1965)

NOTE: TFEVP, Thermionic Fuel Element Verification Program.

Heat Rejection

Different power conversion technologies have different waste heat rejection needs. Brayton and Stirling power conversion subsystems, which use gaseous working fluids, reject heat over a range of temperatures as the gases cool while passing through a heat exchanger. A Rankine system uses the energy released by a reactor to boil a working fluid, which is subsequently condensed at a constant temperature (the boiling point of the working fluid). Thermoelectric and thermionic converters are cooled either by (1) radiation from the cold side of the converter or (2) a coolant that transfers waste heat to a radiator. Radiator operating temperature and size is determined by various system design considerations.

[17] "Atomic Power in Space II: A History of Space Nuclear Power and Propulsion in the United States," INL/EXT-15-34409, 2015.

[18] Mason, L., "Power Technology Options for Nuclear Electric Propulsion" IECEC 2002 Paper No. 20159, 2002.

The transport of heat from the power conversion subsystem to the radiator is generally done either by (1) coolant that is pumped through an array of pipes attached to radiator panels or (2) heat pipes, which are essentially self-contained heat transfer systems that create high thermal conductivity through an internal phase change flow in each heat pipe.

Because a significant portion of the reactor power is rejected as waste heat, radiator panel area and mass can dominate an NEP system. No M&S efforts have focused on the large-scale heat rejection subsystems required for MWe-class NEP systems. In addition, the structural considerations for launch and deployment as well as the large-scale heat pipes required will present significant challenges. The state of the art for NEP-relevant heat rejection subsystems is the design for the 200 kWe JIMO/Prometheus system. This design used Ti/water heat pipes in a loop panel configuration and was designed to operate at temperatures of 500 K. Multiple heat pipes on a single representative panel were tested in vacuum in 2010.[19] The projected specific mass of the heat rejection subsystem for this 200 kWe system was 10.1 kg/kWe (about half of the total system specific mass required for the baseline mission).[20]

Power Management and Distribution

Power management and distribution (PMAD) technology is dependent on both the power source and load electronics. For high-power NEP applications, the challenge is to transfer over 1 MWe of power to the EP subsystem efficiently, both in terms of power and mass, and in a form (voltage and current) that the EP subsystem's PPU can use to operate the thrusters. While M&S tools for PMAD are highly developed, the specific requirements for MWe-class PMAD in a deep-space environment, particularly radiation, have not been assessed, and component, circuit, and subsystem models that address failure modes and power transients will be extremely complex. The state of the art for an NEP PMAD subsystem would be the design developed during the Prometheus program for the JIMO vehicle, and that PMAD subsystem did not undergo any component, subsystem, or system testing. The JIMO design assumed a direct-drive approach, where the power was delivered to thrusters at the voltage needed for thrust generation. This approach was demonstrated at a very low power with a test of a 1.6 kW Brayton system, operated in vacuum, driving a NASA Solar Technology Application Readiness (NSTAR) ion thruster. The power output of approximately 55 volts AC from the Brayton system was rectified and converted to 1100 V of direct current (DC) and transferred to the ion thruster to provide beam power to generate thrust.[21] The efficiency of this approach was 91 percent. While this was a successful demonstration of the overall direct-drive NEP concept, it was at a very low power for a very short period of time. This test did not incorporate flight-like components for the direct drive, and it did not address many aspects of fault tolerance or system transients. Subsequent

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[19] Ellis, D., Calder, J., and Siamidis, J., "Summary of the Manufacture, Testing and Model Validation of a Full-Scale Radiator for Fission Surface Power Applications," Proceedings of Nuclear and Emerging Technologies for Space 2011 Albuquerque, NM, February 7-10, 2011 Paper 3181.

[20] The Prometheus Project Final Report (Oct 1, 2005, NASA report 982-R120461).

[21] Hervol, D., Mason, L., Berchenough, A, and Pinero, L., "Experimental Investigations from the Operation of a 2 kW Brayton Power Conversion Unit and a Xenon Ion Thruster," NASA TM—2004-212960, Presented at Space Technology and Applications International Forum (STAIF–2004) sponsored by the American Institute of Physics, Albuquerque, New Mexico, February 8–12, 2004.

estimates of specific mass with direct-drive scaling for a 1 MWe NEP cargo vehicle, using 50 kWe Hall thrusters, were on the order of 1 kg/kWe for the PMAD subsystem.[22]

Electric Propulsion

Thrusters

EP systems have been used for spaceflight for decades, but to date the available power level has been limited to kilowatt-electric, not megawatt electric, and the source of power has been solar panels. Of the various thruster types that have been used, the two most likely to provide the required performance and lifetime capabilities for Mars missions at the required power levels are ion thrusters and Hall thrusters. Both of these types of thrusters have extensive flight heritage at power levels below 5 kWe.

Ion thrusters use two or more parallel grids with a voltage applied to each to extract and accelerate ions created in a discharge chamber upstream of the grids (see Figure 3.3). Because ions are extracted and accelerated through the grids, a cathode neutralizer is needed to emit electrons to prevent a charge imbalance from forming. Charge separation in the grid assembly limits the maximum thrust density of ion thrusters, meaning that 100 kWe class ion thrusters are likely quite large. Ion thruster M&S is well developed, with good predictive performance and lifetime models that will support scaling to 100 kWe class thrusters. The primary area of uncertainty in ion thruster M&S is the impact of ground test facilities on long-duration thruster life tests.

With Hall thrusters (see Figure 3.4), propellant is injected through an annular channel and ionized by electrons trapped by an applied radial magnetic field. A voltage difference is applied between the anode, which usually serves as the propellant injector at the upstream end of the channel, and a downstream hollow cathode that supplies the electrons to the channel. The mixture of electrons and ions in the acceleration zone means that the thruster does not have the thrust density limitation associated with ion thrusters, although other lifetime considerations limit the achievable thrust densities. As with ion thrusters, M&S tools for Hall thrusters are well advanced and will support scaling to 100 kWe thrusters, although ground testing of high-power Hall thrusters has revealed that interactions between the test facility, the thruster, and its conducting plasma plume can impact the performance and lifetime measurements in ways that are not fully understood as of this writing.[23,24] This introduces uncertainty into current predictions of in-space performance and lifetime for high-power Hall thrusters.

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[22] Gilland, J. H., Lapointe, M.R., Oleson, S., Mercer, C., Pencil, E., and Mason, L., "MW-Class Electric Propulsion System Designs for Mars Cargo Transport," AIAA 2011-7253, AIAA SPACE 2011 Conference & Exposition, Long Beach, California, Sept 27-29, 2011.

[23] Sekerak, M.J., et al., "Mode Transitions in Magnetically Shielded Hall Effect Thrusters ", 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, AIAA 2014-3511, July 28-30, 2014, https://doi.org/10.2514/6.2014-3511.

[24] Dale, Ethan, B. Jorns, and A. Gallimore, "Future Directions for Electric Propulsion Research." Aerospace, vol. 7, no. 9, 2020, p. 1A+. Gale Academic OneFile, https://www.mdpi.com/2226-4310/7/9/120/htm.

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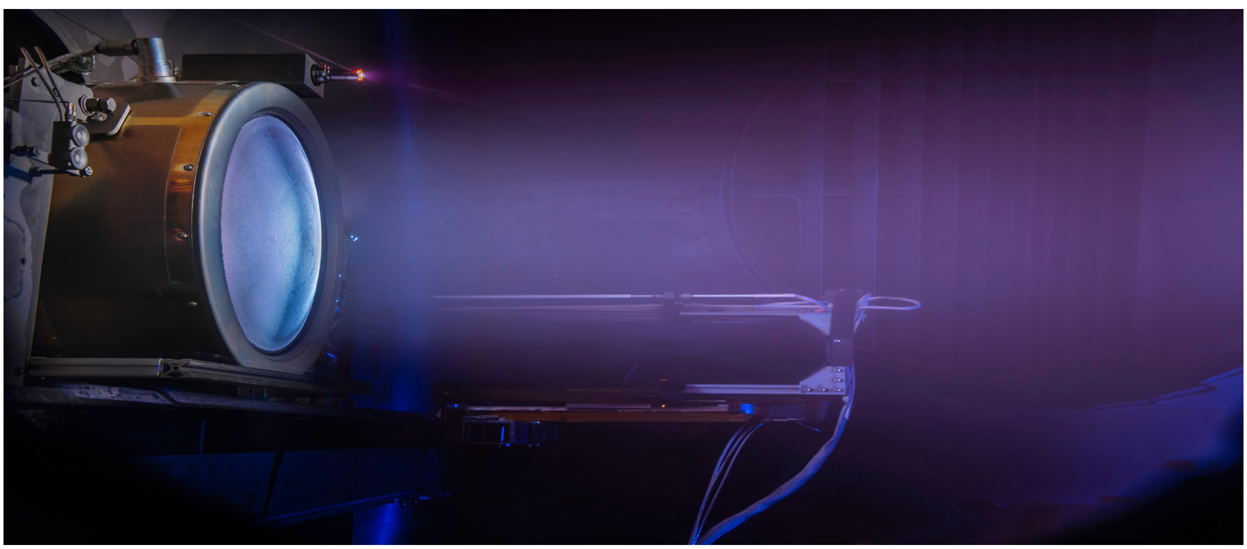

FIGURE 3.3 Ion thruster. SOURCE: Top, Edgar Y. Choueiri (Princeton University), Scientific American, February 2009, p. 62; bottom: NASA (https://www.nasa.gov/glenn/image-feature/2019/thruster-for-next-generation-spacecraft-undergoes-testing-at-glenn).

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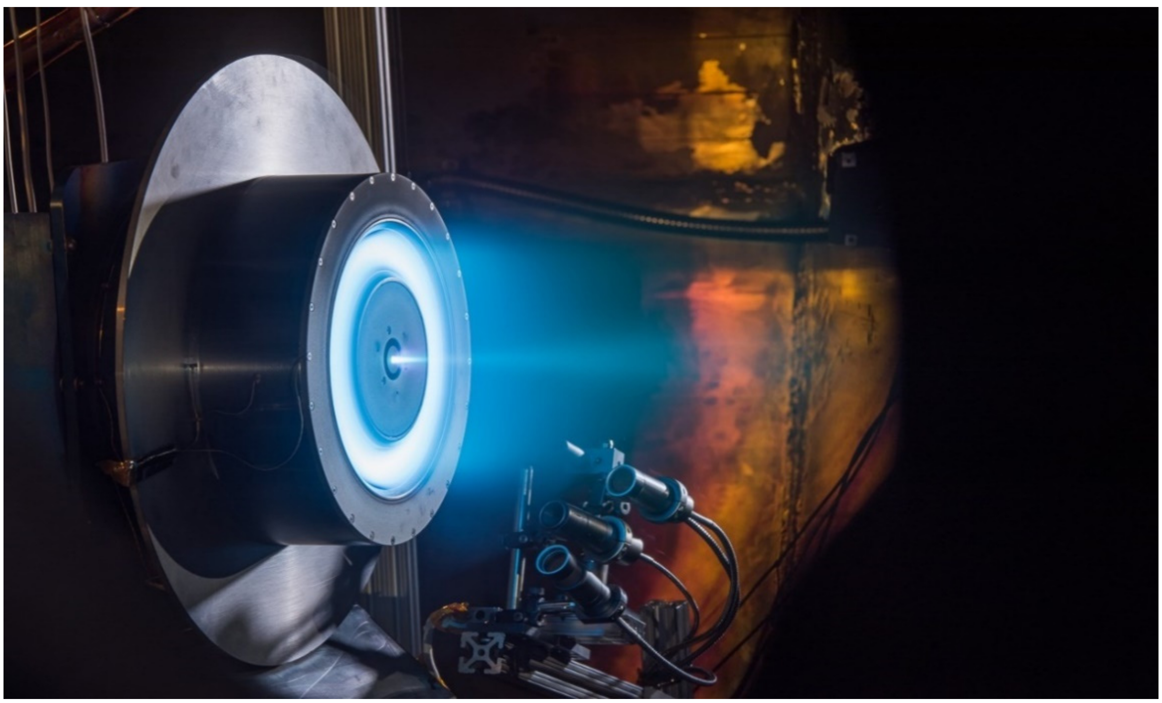

FIGURE 3.4 Hall thruster. SOURCE: Top, Edgar Y. Choueiri (Princeton University), Scientific American, February 2009, p. 63; bottom, NASA (https://www.nasa.gov/image-feature/hall-effect-rocket-with-magnetic-shielding-hermes-technology-development-unit-1).

Table 3.2 provides a list of representative state-of-the-art ion and Hall thrusters along with their operating and performance attributes. This table includes the following four flight systems:

- The Aerojet Rocketdyne XR-5 Hall thruster, which is currently in use on several DoD and commercial spacecraft and has been ground tested to over 10,000 h.
- NASA's Advanced Electric Propulsion System (AEPS) Hall thruster, which is undergoing flight development, has a projected lifetime of more than 20,000 h and is slated for NASA's Lunar Gateway Power and Propulsion Module.
- NSTAR ion thruster, which flew on Deep Space 1 (1998) and DAWN (2007), was life tested to over 30,000 h.
- NASA's Evolutionary Xenon Thruster–Commercial (NEXT-C) thruster, which was ground tested for 50,000 h and is slated for the Double Asteroid Redirection Test (DART) mission (2021).

All flight thrusters also have flight PPU and PMS subsystems, although they are designed to interface with a solar photovoltaic power system, not a nuclear power source.

TABLE 3.2 Examples of State-of-the-Art Hall and Ion Electric Propulsion Thrusters and Power Processing Units

Thruster	Thruster Type	Power (kWe)	Status	Propellant	Thruster			PPU α (kg/kWe)	References
					Isp (s)	η (%)	α (kg/kWe)		
XR-5	Hall	4.5	Flight Operations	Xenon	2020	56	2.7	2.8	AIAA-2010-6698, AIAA-2005-3682
AEPS	Hall	12.5	Flight Develop-ment	Xenon	2800	67	3.8	4.0	AIAA 2020-3626, A-R Spec Sheet
NASA-457M	Hall	50	Laboratory (inactive)	Xenon	2740	62	2.0		AIAA 2012–3940
XR-100	Hall	100	Laboratory (active)	Xenon	2570	63	2.3		IEPC-2017-228
NSTAR	Ion	2.3	Flight Operations	Xenon	3120	60	3.6	6.4	https://www1.grc.nasa.gov/space/sep/gridded-ion-thrusters-next-c/
NEXT-C	Ion	6.9	Flight Qualification Complete	Xenon	4155	70	2.0	5.1	AIAA 2020-3604
Herakles	Ion	28.5	Development (inactive)	Xenon	7000	70+	1.8	2.5	AIAA 2005-3890, AIAA 2005-3891

NOTE: α, specific mass; η, efficiency.

Current flight EP thrusters have a maximum power of 6.9 kWe, which are not practical for a MWe-class NEP system, given the large number of thrusters that would be required. Several thrusters have undergone laboratory tests for tens of hours at 50 kWe and above, including two of the Hall thrusters listed in Table 3.2 and two less-developed concepts: the MPD and

VASIMR® thrusters. The highest-power Hall thruster tested to date was the XR-100, which was operated as an integrated thruster-PPU-PMS system for several hours in an attempt to reach the goal of 100 h steady state operation set by the NASA NextSTEP Advanced Propulsion Systems program.[25]

MPD thrusters (see Figure 3.5) use the Lorentz body force that is generated by the interaction of the electrical current driven through ionized propellant with the magnetic field generated by this current. The applied magnetic field from an electromagnet may be used to enhance the acceleration process. MPD thrusters have among the highest thrust and power densities of any EP thruster. While they can operate on a number of propellants, lithium appears to be most promising for NEP applications.

The VASIMR thruster (see Figure 3.6) uses radio waves in a two-stage process to create and heat plasma that is then expanded through a magnetic nozzle for thrust production. The status of these more immature, but higher power concepts is given in Table 3.3. Neither thruster has undergone significant life testing in recent years. A Soviet-era 500 kWe lithium MPD thruster reportedly underwent a 500-h life test with promising yet uncertain results,[26] and the Ad Astra Rocket Company is working towards the goal of a 100-h test of a 100 kWe VASIMR thruster.[27] While limited M&S tools exist for both MPD and VASIMR, overall, they are more rudimentary and have not been well-validated compared to those for Hall and Ion thrusters.

Power Processing Unit and Propellant Management System

The state-of-the art PPU for Hall thrusters is arguably the one associated with the 4.5-kW XR-5 flight unit. This PPU has an input power conversion efficiency of at least 92 percent with an input voltage of 70 V DC, and it has a mass of 12.5 kg for a PPU specific mass of 2.8 kg/kWe. The XR-5 also includes a state-of-the-art PMS. The 12.5-kWe AEPS Hall thruster (along with its associated PPU and PMS), under development by Aerojet Rocketdyne for NASA's Project Artemis (launch planned in 2024),[28] is the next evolution of Hall thruster, PPU, and PMS. A laboratory PPU for the X3 Hall thruster was developed and tested during NASA's NextSTEP program and ran for tens of hours. As noted above, all of these PPUs are designed for use with photovoltaic arrays, not nuclear power sources. As with PMAD, the M&S tools for PPUs and PMS are well established, but the specific component, circuit, and fluid models appropriate for MWe-class systems have not been developed. PPU M&S development and validation will likely prove challenging due to the high power and high radiation environments for the electrical components.

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[25] "Advanced Electric Propulsion NextSTEP BAA Activity," https://techport.nasa.gov/view/33078.

[26] V.P. Ageyev, V.P. Ostrovsky, and V.A. Petrosov. "High-current stationary plasma accelerator of high power". In 23rd International Electric Propulsion Conference, July 1993. IEPC-93-117.

[27] V.P. Ageyev, V.P. Ostrovsky, and V.A. Petrosov. "High-current stationary plasma accelerator of high power". In 23rd International Electric Propulsion Conference, July 1993. IEPC-93-117.

[28] See https://www.nasa.gov/johnson/exploration/gateway.

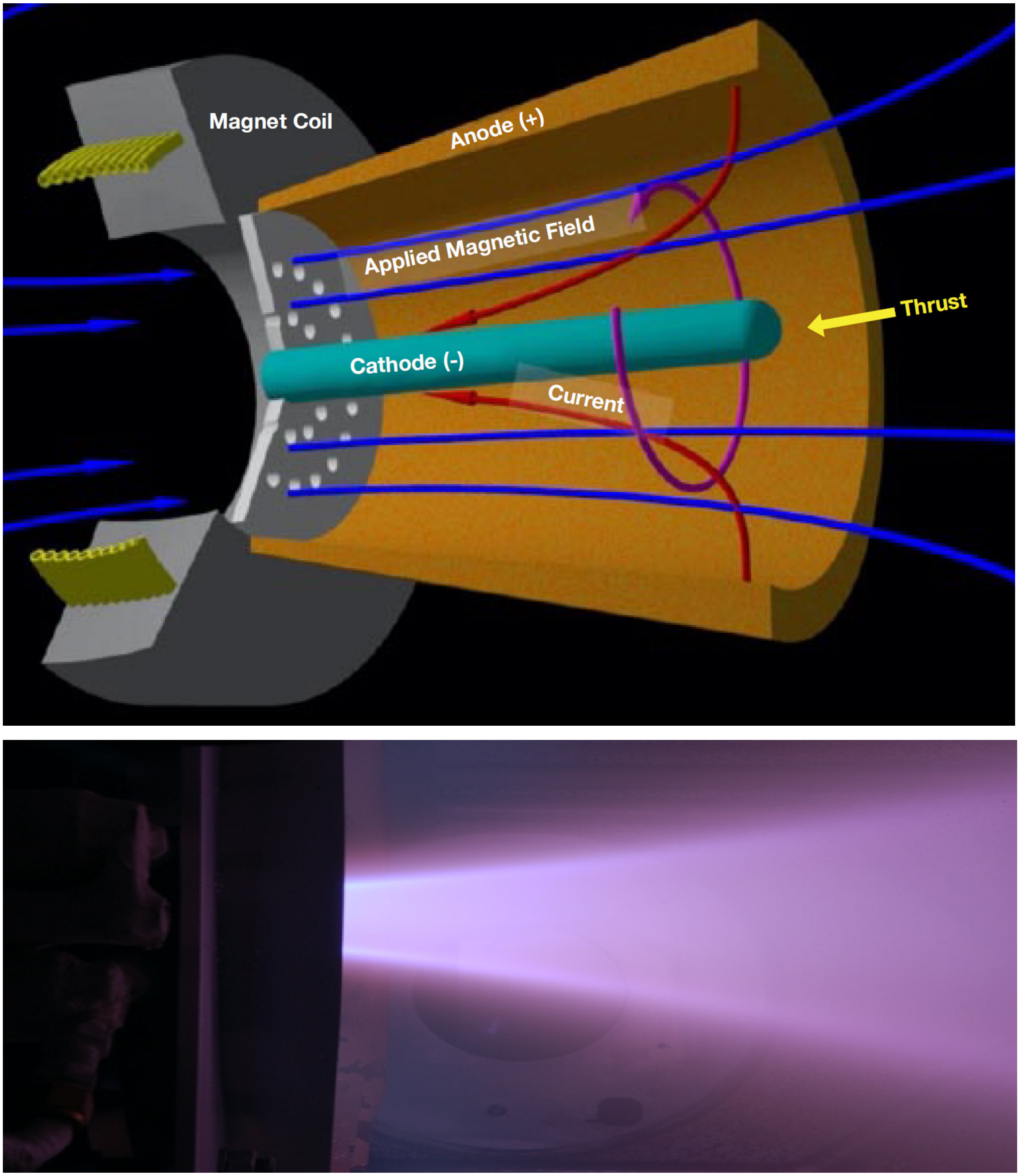

FIGURE 3.5 Magnetoplasmadynamic thruster. SOURCE: Electric Propulsion and Plasma Dynamics Laboratory, https://alfven.princeton.edu/research/lfa.

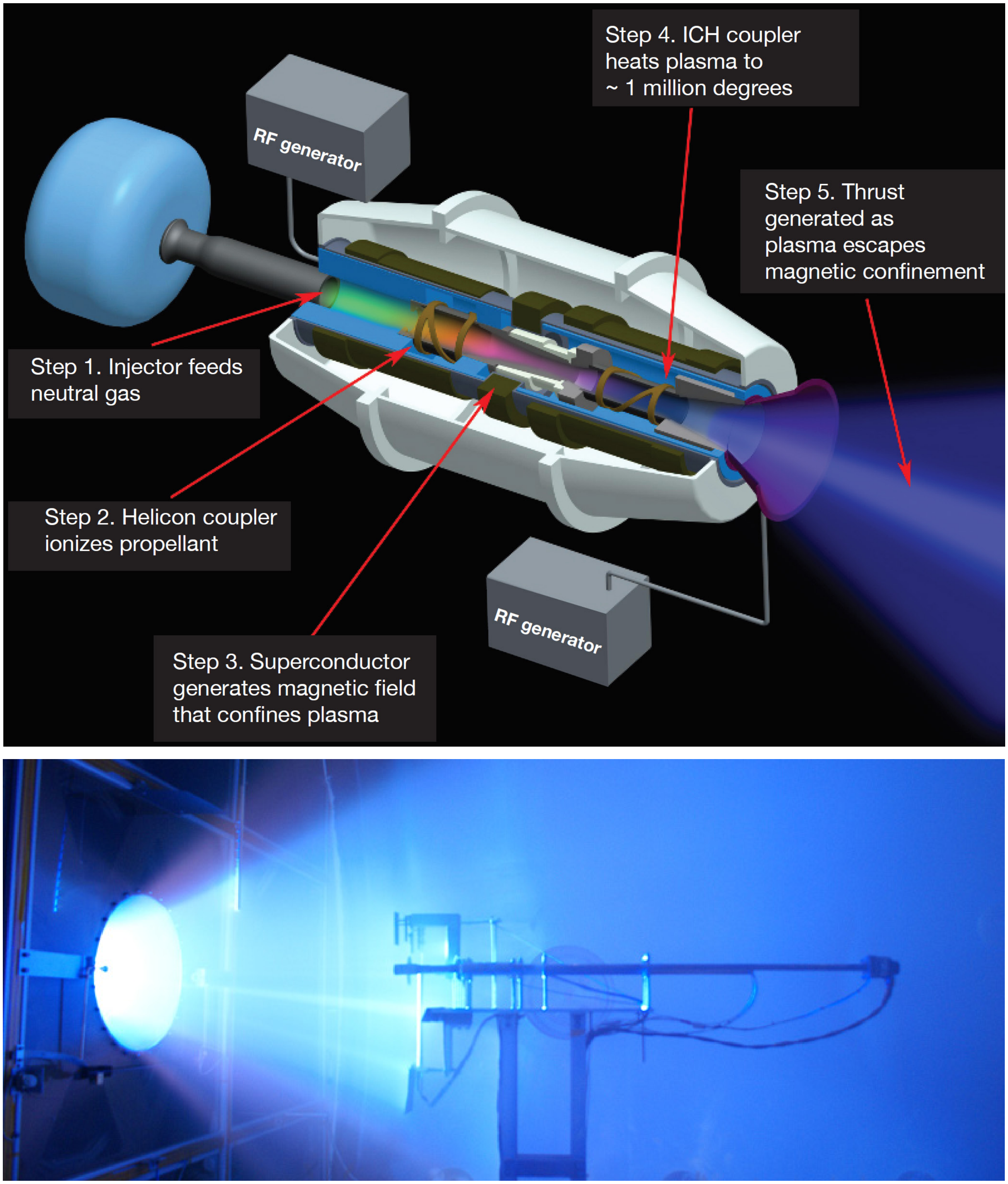

FIGURE 3.6 VASIMIR® thruster. Image used under license with Ad Astra Rocket Company.

TABLE 3.3 High-Power Research Thruster and Power Processing Unit Concepts

Thruster	Thruster Type	Power (kW)	Status	Propellant	Thruster			PPU α (kg/kWe)	References
					Isp (s)	η (%)	α (kg/kWe)		
SX3	MPD	66	Laboratory	argon	3670	~ 50			IEPC 2017-339
ALPHA2	MPD	245	Designed	lithium	6200	~ 60	0.5	1.5	AIAA 2005-3894
VASIMR	Radiowave driven magnetized plasma electro-thermal	200	Laboratory	argon	5000	~ 60	9.5	0.5	AIAA 2019-3810, AIAA 2018-4417, AIAA 2017-4630, IEPC 2019-801

NOTE: **α,** specific mass; η, efficiency.

TECHNOLOGY REQUIREMENTS, RISKS, AND OPTIONS

The baseline mission requires an NEP system whose performance far exceeds that of existing flight systems in terms of power, specific mass, and reliability, though limited subscale demonstrations of several relevant technologies have been completed. In addition, radiation-hardened power electronic systems for PMAD or PPUs at megawatt electric power levels have never been developed. Existing thruster concepts such as Hall thrusters and ion thrusters can meet I_{sp} and efficiency requirements, but thruster power levels must increase by an order of magnitude compared to current and near-term solar electric propulsion (SEP) flight systems. Higher power MPD or VASIMR thrusters are less mature. System lifetimes and reliability are poorly understood at megawatt electric power levels.

EP propellant management will essentially be a relatively straightforward scaling of current flight practice and design for systems that use propellants stored as a gas or liquid. (A feed system for MPD thrusters that use lithium propellant stored as a solid would require further development.) In either case, as discussed in Chapter 1, a 1 MWe-class NEP system capable of executing the baseline mission also requires augmentation by a chemical propulsion system using cryogenic propellants and assumes minimal boiloff using cryocooler technology. This technology will have to be matured in parallel with NEP development.

Integrated System

The NEP system is a complex system, with performance requirements for power level, specific mass, I_{sp}, efficiency, lifetime, and reliability propagating throughout the subsystems in terms of temperature and power density requirements. Achieving a specific mass of 20 kg/kWe for the entire NEP system scaled for the baseline mission is a significant challenge that drives the reactor, power conversion, and heat rejection subsystems to higher operating temperatures, and drives EP subsystems to efficient power distribution, processing, and thrust production. The multiple subsystems of an NEP system must demonstrate adequate performance and reliable operation of interconnected subsystems across all phases of mission operations as well as unexpected transients during abnormal operating conditions. The NEP system relies on a wide spectrum of physics and engineering: neutronics, thermal hydraulics, high-temperature materials, fluid mechanics, turbomachinery, power electronics, electromagnetism, and plasma physics. Detailed subsystem and system M&S tools will need to be developed to account for subsystem interactions. While this will require definitions of interfaces throughout the development of the subsystems, such a process has been successfully demonstrated for the significantly lower power levels associated with SEP robotic missions in Earth orbit and interplanetary space. NASA's most recent credible analysis of an integrated NEP system was conducted as part of Project Prometheus (2003 to 2005) at an order of magnitude lower power level. Demonstrating Prometheus-level technology at the power level and scale required for the baseline mission while meeting goals for specific mass is a considerable challenge.

FINDING. ***NEP Power Scaling.*** Developing a MWe-class NEP system for the baseline mission would require increasing power by orders of magnitude relative to NEP system flight- or ground-based technology demonstrations completed to date.

Reactor Subsystem

Chapter 1 specifies that the NEP system of interest would operate at 1 to 2 MWe, have a specific mass of no more than 5 kg/kWe for the EP system, a specific mass of no more than 15 kg/kWe for the other five subsystems combined, and a maximum fuel temperature high enough to heat reactor coolant to a temperature of approximately 1200 K at the reactor outlet. For the baseline mission, such a system would experience reactor fuel burnup of about 4 percent over a period of about 4 years. These parameters are within the envelope of irradiation tests performed on fuel systems in prior space reactor programs. Key reactor concept decisions to be finalized include fuel enrichment (HEU versus HALEU)[29] and neutron spectrum (fast versus moderated), which in turn will drive the selection of specific fuel, cladding, and structural materials for the reactor. The reference fuel system for a fast spectrum reactor of Nb-1%Zr clad UN fuel is backed up by extensive irradiation testing, although all of these tests were performed over 25 years ago. Available reactivity control materials are sufficient to produce a highly reliable reactor system. Technology recapture activities will be needed for the manufacturing of legacy materials and reactor components.

Shield Subsystem

A variety of feasible radiation shield options are available that would enable suitable shielding for the crew and sensitive electronic components at distances of about 50 to 100 m from the reactor over a 4-year life. As noted previously, shielding consists of layers of low atomic number materials (e.g., Be, LiH, and B_4C) materials to attenuate neutrons, and high atomic number materials (e.g., tungsten) to attenuate gamma rays. Most of these shields work best at temperatures between about 300 and 900 K, so cooling below the reactor operating temperature is desirable; most hydride shield materials rapidly lose hydrogen at higher temperatures.

Power Conversion Subsystem

Power conversion subsystems couple with the reactor at maximum temperatures comparable to the reactor coolant outlet temperature. For dynamic power conversion, this requires turbine

[29] See Chapter 5 for a discussion of HEU versus HALEU fuels.

material temperatures of 1100 to 1200 K, requiring at least superalloy materials or refractory metals if temperatures higher than 1150 K are necessary. For the targeted power level of 1 to 2 MWe, individual converter output power levels of 200-800 kWe would be needed, with the specific selection depending on component and system level performance, lifetime, and reliability trade studies. Power conversion subsystem lifetimes less than that required for the entire mission (2 to 4 years depending on mission assembly and operation requirements) would require duplicate components or subsystems to ensure mission success. A direct-drive approach for powering thrusters from an alternating current (AC) conversion system would require AC output at 400 to 650 V for Hall thrusters or to ~3000 V for ion thrusters, to be rectified for thruster beam power.

Operating temperatures for the power conversion subsystems tested to date are at the minimum acceptable level to meet NEP needs. Brayton energy conversion technologies are more advanced than other types, but they introduce new types of risks, and demonstrated power levels for space-qualified systems are orders of magnitude below that required for a 1 to 2 MWe system. A Rankine power conversion system, although used extensively in terrestrial systems, would pose additional risks associated with handling a two-phase flow in zero gravity. Liquid metal working fluids adopted for some power conversion options would also likely introduce the need for refractory metals in the power conversion sections. Advanced NEP systems will likely be able to convert perhaps 20 to 35 percent of the thermal energy from the reactor coolant into electrical power.[30]

Heat Rejection Subsystem

Temperatures of at least 500 K are necessary for radiators to reject heat in a mass efficient manner. At these temperatures, a total radiating area on the order of 1500 m^2 to 3000 m^2 (single sided) would be required for a 1 to 2 MWe NEP system. These radiators must also provide high thermal conductivity and operate reliably for the entire reactor and power system operating time (2 to 4 years depending on mission design). Initial studies for the NEP module used carbon composite structure and water-filled heat pipes in conjunction with a pumped sodium-potassium alloy (NaK) liquid metal loop to reach an area specific mass of about 7.7 kg/m^2, including all supporting pumps; this is similar to the approach on the Prometheus system design. A reduction in specific mass for this subsystem is possible by using higher temperature panels, but that would propagate back throughout the NEP system to higher reactor and power conversion temperatures. Another way to reduce the mass of this system is to use a constant-rejection temperature cycle such as the Rankine cycle in which the working fluid undergoes a phase change, instead of the Brayton cycle in which the working fluid decreases in temperature throughout the heat rejection portion of the cycle. This change would require additional development of the power conversion subsystem to address two-phase flow in zero gravity. A third option for reducing the mass of the heat rejection subsystem is to develop lower-mass high-temperature materials.

With such a large area, stowing, deploying, and on-orbit assembly of the heat rejection system will be significant challenges. To fit in the shroud of likely launch vehicles, the radiator panels and fluid transport systems for distributing heat to the heat pipes would need to be folded

[30] Longhurst, G. R. et al., "Multi-Megawatt Power System Analysis Report," INEEL/EXT-01-00938 Rev. 01, Prepared for the U.S. Department of Energy Assistant Secretary for Nuclear Energy Under DOE Idaho Operations Office Contract DE-AC07-99ID13727, https://inldigitallibrary.inl.gov/sites/sti/sti/2688772.pdf.

without breaching the seals for the coolant piping, and this complex assembly would need to survive launch environments. There is limited flight heritage in this area.

Power Management and Distribution (PMAD) Subsystem

Developing a PMAD subsystem for a MWe-class NEP system with a low specific mass will require either efficient, high voltage AC power transmission to a thruster PPU (see below), or direct-drive DC transmission at 400 to 800 V (assuming use of Hall thrusters) for rectification. Higher voltage transmission could result in lower mass power distribution due to the reduced current requirements. For state-of-the-art silicon components, the low (350 K) operating temperature for these electronics implies large area requirements for heat rejection. In order to meet the specific mass requirements for the baseline mission (including heat rejection), PMAD efficiencies of at least 90 to 95 percent will be needed to reduce waste heat. Additionally, as was observed in the JIMO program, radiation hardening to protect electronics against radiation damage from both the NEP system and from the space environment will be required. PMAD designs will need to address reliability in terms of switching and power regulation for the 2- to 4-year life of the baseline mission. The limited availability of highly reliable, radiation-hardened electronic components may limit the voltage and current options for the PMAD system.

Further improvement in performance might be realized with higher temperature semiconductor materials, such as SiC or GaN. These have been considered in past MWe NEP studies, but performance and life demonstration are required to determine their actual efficacy for the baseline mission. SiC can withstand higher operating temperatures of the power electronics (for the PMAD subsystem and the PPU in the EP subsystem), thereby reducing the radiator area and mass, but performance and operational life at megawatt electric power levels would have to be demonstrated for a space relevant environment.

Electric Propulsion Subsystem

Thruster performance requirements are to some extent dependent on power system specific mass and power levels. As specified in Chapter 1, the I_{sp} goal is 2,000 s or more, with thruster efficiencies greater than 50 percent in order to provide enough acceleration for the power levels, payloads, and trip times. Thruster power levels of 100 kWe or more allow for a reduction in system complexity in terms of the numbers of thrusters, PPUs, and PMSs that must be integrated. Similarly, the baseline mission imposes a total system operating time of at least 2 years, which is approximately 20,000 h. Lifetime must therefore be a minimum of 2 years, or, with the typical 50 percent margin required for space systems, 3 years or 30,000 h, or spare units will have to be included, with a commensurate mass penalty. In addition, the system must be available for the full mission life of about 4 years, which includes time for launch, in-space assembly, and the round trip to Mars.

Thrusters

Existing thrusters cannot meet all mission requirements. Flight qualified or demonstrated thrusters such as Hall and ion thrusters have operated at 4.5 and 7 kWe, respectively, with the next anticipated qualified thruster to be the AEPS Hall thruster at 12.5 kWe. All of these thrusters, however, are expected to meet the lifetime requirement of at least 20,000 h: the 4.5

kWe Hall thrusters were tested for more than 10,000 h with no life limitations identified, the 7 kW ion thruster was tested to 50,000 h, and the AEPS thruster has a design life (as yet unverified) of more than 23,000 h. Testing plasma thrusters for extended periods at power levels greater than approximately 20 kWe poses facility challenges that have limited development at these power levels (see below).

Scaling thrusters to higher power levels at the required I_{sp} represents a risk in terms of the increased power density or thruster size. In the case of ion thrusters, this represents an increase in grid area of an order of magnitude, while maintaining inter grid spacings within less than 1 mm. In the case of Hall thrusters, either channel power density must be increased, which introduces heating and lifetime issues, or channel and thruster diameter must increase for the same reason as the ion thruster. Laboratory models have been tested to address this scaling, including the use of multiple concentric channels.[31] For the ion thruster, the annular ion thruster mitigates grid spacing issues by providing a central support to the grids.[32] For the Hall thruster, multiple, nested channels have been tested to 100 kW power levels.[33] Both concepts have been tested only for short periods of time and further testing is needed.

MPD and VASIMR® thrusters, while considered to be better able to process high power, also require higher powers to operate efficiently. As a consequence, demonstrated performance and life testing are lacking. High-power thruster testing, in general, has not been prioritized because traditional spacecraft cannot provide the power levels necessary to operate them in space. Lithium MPD thruster research to date has demonstrated promising results, there is little data on performance, electrode lifetime, and thermal response at power levels above 250 kWe.[34,35] MPD thrusters are high-current, low-voltage devices, which imposes heating and switching issues for the PPU and PMAD. VASIMR is at a lower stage of development in terms of both the thruster performance and engineering. Work to date has not demonstrated the physics of the magnetic nozzle used to accelerate the plasma, the life of the device, and the implementation of superconducting magnet coils, all of which are required to meet efficiency requirements.[36]

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[31] Scott J. Hall, Benjamin A. Jorns, Alec D. Gallimore, Hani Kamhawi, Thomas W. Haag, Jonathan A. Mackey, James H. Gilland, Peter Y. Peterson, and Matthew J. Baird, "High-Power Performance of a 100-kW Class Nested Hall Thruster," IEPC-2017-228, Presented at the 35th International Electric Propulsion Conference Georgia Institute of Technology – Atlanta, Georgia – USA October 8–12, 2017.

[32] Patterson, M.J., Thomas, R., Crofton, W., Young, J., and Foster, J.E., "High Thrust-to-Power Annular Engine Technology," 51st AIAA/SAE/ASEE Joint Propulsion Conference Orlando, FL, July 27-29, 2015, https://doi.org/10.2514/6.2015-3719AIAA-2015-3719.

[33] Shark, S.W.H., Hall, S. J., Jorns, B.A., Hofer, R.R., and Goebel, D.M.," High Power Demonstration of a 100 kW Nested Hall Thruster System," AIAA 2019-3809, AIAA Propulsion and Energy Forum August 19-22, 2019, Indianapolis, IN.

[34] V.P. Ageyev, V.P. Ostrovsky, and V.A. Petrosov. "High-current stationary plasma accelerator of high power". In 23rd International Electric Propulsion Conference, July 1993. IEPC-93-117.

[35] E. Y. Choueiri, "Advanced Lithium-Fed Lorentz Force Applied Field Accelerator". Final Technical Progress Report, Princeton University, Dec. 2007.

[36] Squire, J.P., et al., "Steady-state Testing at 100 kW in the VASIMR®VX-200SS Project," AIAA 2019-3810, AIAA Propulsion and Energy 2019 Forum, Indianapolis, IN,19-22 August 2019, https://doi.org/10.2514/6.2019-3810.

Power Processing Unit

The PPU will be quite different depending whether a direct-drive or standard PPU approach is ultimately selected. If a standard PPU approach is needed, then the PPU architecture, requirements, and risks will be similar for those of other EP systems, albeit at a much higher power level. This effort would build on the recent PPU development for NASA's NextSTEP program, which demonstrated short-term operation at 100 kWe for a single thruster. For a direct-drive approach, the PPU is greatly simplified, but it still must provide power and control for cathode operation, magnet coils, thruster current control feedback to the PMS, thruster ignition and shutdown transients, thruster throttling (if required), and any thruster-to-thruster interactions that might occur in a multi-thruster system where the plasma plumes interact. Additionally, PPUs may be required to manage power during fast transients that occur normally during thruster operation and during component failures, which can induce large power transients in an integrated system and may be exacerbated for multi-thruster systems. For any PPU architecture, PPU components must operate at efficiencies over 90 percent and/or at temperatures warmer than is possible with state-of-the-art silicon components, to reduce thermal management mass in the EP subsystem.

Based on mission studies to date, overall EP subsystem specific mass will need to be less than ~4.5 kg/kWe to keep overall NEP system specific mass below 20 kg/kWe. The NextSTEP program goal for 100 kWe class EP subsystems, including the thruster, PPU, and PMS, was a specific mass less than 5 kg/kWe. While a significant challenge, a potential advantageous factor may be the use of direct-drive PMAD, in which the power from the power conversion subsystem is already configured to match thruster beam requirements. This approach could substantially reduce PPU specific mass; however, only laboratory simulations of direct drive have been performed, with laboratory power supplies supplying the other low voltage and power components needed by a thruster, and without a full assessment of control during transients. For instance, the simulated direct drive of an ion thruster by a Brayton conversion device was only for the 1100 V thruster beam power; other thruster components such as cathodes were operated using laboratory power supplies.[21] Additionally, system reliability and fault protection requirements for flight systems will increase the PPU mass.

Propellant Management System

The two most mature thruster concepts, ion and Hall thrusters, both use xenon propellant. There is extensive flight experience with the storage and distribution of xenon for orbital and interplanetary missions. Xenon is stored at high pressure as a supercritical gas, with pressure and flow regulation to the thrusters. Scaling to higher power will introduce the need for larger tanks; some of this is being addressed incrementally in the design of NASA's Power and Propulsion Element, which will incorporate a 50 kWe solar electric propulsion system and carry 2,500 kg of xenon propellant.[37,38] Of course, this is still orders of magnitude below the amount of propellant

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[37] The Power and Propulsion Element is a spacecraft is being developed as part of NASA's Project Artemis to return astronauts to the Moon.

[38] Herman, D.A., Gray, T., Johnson, I., Kerl, T., Lee, T. and Silva, T., "The Application of Advanced Electric Propulsion on the NASA Power and Propulsion Element (PPE)," IEPC-2019-651, 36th International Electric Propulsion Conference, University of Vienna, Vienna, Austria, September 15 – 20, 2019.

(which may be around 100,000 kg) that will be required for the baseline mission, and it is not clear how the propellant tank mass will scale for these very large propellant loads.

TESTING, MODELING, AND SIMULATION

An NEP system has multiple subsystems performing separate but necessary functions to convert thermal energy from the reactor to thrust. This introduces both challenges and opportunities to demonstrating the ability of the whole system to perform the desired mission. The challenge lies in the integration of the system and the demands of ground testing nuclear and non-nuclear subsystems; the opportunities lie in the fact that the system *can* be disaggregated into subsystems which can be demonstrated separately up to the point of integration. This is an approach that has been used successfully and repeatedly in SEP missions. Similarly, the planned use of EP on earlier Artemis missions offers some opportunities to advance integration and M&S capabilities for NEP.

The testing approach for NEP reflects both its level of immaturity and its separability into subsystems for some aspects of its development. Testing will be necessary at two levels. Initial testing will validate reactor fuels, materials, and selected components from each subsystem. Subsequent testing will validate subsystem-level performance and lifetime. This second phase will also establish subsystem interface requirements for the overall system. The dramatic increase in power level from today's kilowatt-electric systems to megawatt electric levels will require an assessment of test facilities for each subsystem to determine facility constraints and availability, as well as to identify any necessary modifications or construction to support the testing requirements. As discussed further below, it is essential that M&S tool development and validation proceed in parallel with testing.

The overall NEP system testing and qualification will involve multiple subassemblies, components, and subsystems developed and tested separately, with integration demonstrated after subsystem maturation.

NEP system designs allow much of the integrated system performance to be accomplished in a non-nuclear, electrically heated environment assuming that the neutronic feedback components associated with the reactor subsystem behavior are properly represented computationally and the test article is adequately instrumented to measure physical conditions that would impact core reactivity (e.g., measurement of thermal expansion with increasing temperature). Thus, an integrated ground test could involve all but the reactor subsystem, which could be emulated via simulation and electrical heating, and would not require nuclear heating or full radiator deployment. This can save both time (i.e., reduce schedule) and program cost. However, full retirement of risk for the reactor subsystem and its components would require ground testing in a representative nuclear environment.

With sufficiently rigorous M&S and ground testing, it may be feasible to conduct the first test of a fully integrated, full-scale NEP system during the first cargo mission. This would require the NEP system for that mission to include all of the instruments necessary to fully characterize system performance and to enable projecting how the system would perform during a two-way mission, as will be case during crewed missions.

Separate effects testing for materials development and characterization and subsystem performance tests would likely include the following:

- *Reactor.* Required tests range from fuel, fuel element, and core materials tests to integrated reactor tests. Development of the reactor subsystem would be conducted in concert with the modeling of neutronics and thermal hydraulics, informed by results from fundamental fuels and materials testing. This would begin as materials and fuel element testing in a test reactor facility to characterize material properties under representative temperature and irradiation conditions, assuming that data is not already available for the selected materials, followed by fuel element subassembly testing, also within a test reactor. This would be followed by testing of the full reactor subsystem under a suitable pressure and thermal environment to demonstrate power and neutronic performance, controllability, reliability, and life under both nominal and off-nominal conditions. Tests of the reactor subsystem would include ZPC, low power, and full power testing. Testing at full power will require transferring heat to the environment via use of an integrated heat exchanger or integration with the power conversion subsystem. Existing reactor facilities can likely support separate effects and materials testing. ZPC testing of a MWe-class NEP system can also likely be supported via existing facilities, with modification and investment, or in facilities currently being planned for development of terrestrial reactor technologies. The adequacy of facilities for full power testing of a MWe-class NEP system is less certain. As discussed in Chapter 5, facilities are currently under development for MWe-class power reactors that may be capable of supporting reactor subsystem tests for NEP if they are available for use within the timeframe required.
- *Shield.* Shield design and materials testing for a 1 to 2 MWe reactor (4 to 8 MWt) at temperatures suitable for NEP are relatively mature. Relevant test and modeling data from many prior space nuclear programs are available, which would allow a shield to be readily designed and tested. Component testing for shielding system designs could be supported using accelerator-driven irradiation sources that produce the necessary neutron and gamma environment to emulate the source from the reactor subsystem. In this manner, shielding performance could be validated with regard to radiation attenuation as well as demonstrating thermal management systems. However, these facilities may be limited in their ability to represent external, space-radiation sources that may also impact the thermal management in the shielding structure. Shield testing could also be conducted in concert with reactor testing.
- *Power conversion.* Power conversion subsystem tests will also range from fundamental materials tests for heat exchangers, turbines, bearings, etc., to integrated, electrically heated power conversion subsystem tests. A similar approach has been used for lower power Brayton and Stirling systems in the past. Vacuum or low-pressure operation with a thermally relevant background environment will be required. The subsystem tests would include a simulated PMAD and thruster load and would evaluate system response to all anticipated power system transients. The specific interfaces for this test will depend on whether or not a direct-drive approach is selected. Power conversion subsystems could be tested using electrical heat sources at facilities at NASA Glenn Research Center and Plum Brook Station.
- *Heat rejection.* Tests will range from heat pipe materials to multiple integrated panel tests in a suitable thermal environment. Heat rejection panels would be tested using heat supplied to the panel loop at an equivalent temperature and heat exchanger performance as designed for the NEP system, with heat rejection to a relevant sink temperature for the NEP mission. Subsystem response to planned or unplanned power system transients (e.g.,

power adjustments during startup, operation, or shutdown) would be assessed. Testing would include sufficient panels to fully evaluate any articulation or joints required by the need for on-orbit deployment. It is not clear whether sufficiently large facilities exist today for testing of the full heat rejection subsystem, although several facilities exist at NASA and DOE for testing multiple panels and confirming deployment mechanisms.

- *PMAD.* The high power involved in the NEP will likely require extensive electrical component testing to validate component performance and lifetime in relevant environments, as well as subsystem testing with simulated power conversion subsystem and EP subsystem loads. Because this system is an electric-to-electric interface, much of this testing can be accomplished with simulated input power and loads, and facilities exist for full-scale hardware testing of this type. For a direct-drive approach, the coupling of the power conversion to the EP subsystem would be demonstrated, similar to the low power test completed using Prometheus components, but designed for the selected EP system. This test series would include an evaluation of all transients during the startup, shutdown, normal operational phases, and failure scenarios to demonstrate the robustness of the entire subsystem. It will also require validation of the PMAD in a representative nuclear environment.
- *EP.* Testing involves thruster performance over the intended EP lifetime, as well as string integration tests that demonstrate the PPU, PMS and thruster interfaces during all phases of operation. Testing would be conducted such that it validates the subsystem lifetime with the expected electrical and thermal interfaces in the correct radiation environment. For a direct-drive system, the PPU will be simplified, but it will still be required as previously described. Testing would be informed by experience gained from NASA's AEPS development program and the flight operation of NASA's Power and Propulsion Element, both in terms of facility effects and thruster behavior in space. Electrical input from the PMAD (direct drive, if chosen in the design) would be simulated as input to the thrusters during the ground test to demonstrate feasibility. While many laboratory tests of 100 kWe class EP thrusters have been conducted, high-fidelity EP thruster test facilities are limited today to less than 50 kWe, and there is significant uncertainty as to the test facility requirements necessary to properly simulate the space environment. A significant effort will be required to establish EP thruster test facilities for 100 kWe thrusters capable of supporting high-fidelity long-duration life tests, and even more so to support multi-thruster tests to evaluate thruster interactions in a multi-thruster array.

As the subsystem elements mature, integrated system ground testing would occur at laboratory, engineering, and flight model stages of the development program. Potential tests could include, for example, a single electrically heated power conversion unit and heat rejection panel in a vacuum facility with relevant sink temperature, connected by a PMAD system to a thruster operating in another vacuum chamber. This would likely require several large vacuum chambers, as the heat and plasma loads of 50 to 100 kWe power conversion and thruster units would likely overload a single existing facility. Testing would include all phases of operation and potential failure mechanisms to ensure a full understanding of the NEP system dynamic response. It will also be necessary to evaluate multi-thruster interactions to ensure that no unexpected behaviors occur due to the presence of multiple plasma plumes during ignition, operation, and shutdown.

NEP testing will require extensive modeling and simulation, both to design the subsystems and to define the interfaces between subsystems to simulate flight conditions. Testing will provide the necessary data to validate the physics models embedded within the broader system and subsystem M&S software. Modeling of the steady state and dynamic operation of terrestrial nuclear systems is relatively mature, but for materials and designs of interest to NEP, the coupled neutronics and thermal hydraulics models must be informed by initial fuel and material testing. While some materials under consideration for the reactor subsystem have an established database characterizing their fundamental properties (pre- and post-irradiation), it is likely that the database even for "known" materials does not encompass the full range of operating conditions anticipated in an NEP system. EP operation on the ground relative to that observed in space is still being used to assess and update models, both in terms of performance and thruster life. EP models for performance and lifetime will be augmented using flight data from future missions. Additional instrumentation of NASA's Power and Propulsion Element flight system to evaluate thruster plumes, as well as results from ongoing and planned life tests of the AEPS thrusters, will provide data to further improve and validate current models for use in scaling thrusters to higher powers.

System-level modeling that dynamically couples the performance and transients across all subsystems will also be vital to the feasibility of NEP development. While this is something that is done routinely for terrestrial power systems up to the load, an NEP system will introduce additional challenges. At each interface, thermal, flow, electrical, and neutronic inputs (and outputs) will be required, and an overall system model, benchmarked and validated by system and subsystem tests, will be required.

Subscale in-space testing will not be sufficient to eliminate the need for full-scale ground testing. Extrapolating high power density nuclear power systems over one or two orders of magnitude from early, lower power feasibility flights introduces uncertainty of controllability, thermal hydraulic and electrical interactions, and the potential for schedule slippage. The long-life demonstration requirement (2 to 4 years) for all subsystems precludes repeated life testing either on the ground or in space in order to meet the required flight schedule.

FINDING. ***NEP Modeling and Simulation, Ground Testing, and Flight Testing.*** Subscale in-space flight testing of NEP systems cannot address many of the risks and potential failure modes associated with the baseline mission NEP system. With sufficient M&S 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. Fully integrated ground testing may not be required.

RECOMMENDATION. ***NEP Modeling and Simulation, Ground Testing, and Flight Testing*. To develop a nuclear electric propulsion (NEP) system capable of executing the baseline mission, NASA should 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 of the NEP system that will be incorporated into the first crewed mission.**

DEVELOPMENT AND DEMONSTRATION ROADMAP

The roadmap in Figure 3.7 shows key milestones and when they would need to be achieved to execute the baseline mission: launching a crewed mission to Mars in 2039 preceded by an initial cargo mission in 2033.

Executing the baseline mission to deliver humans to Mars in 2039, as well the precursor cargo missions, requires some very near-term design and a dedicated development, testing, and demonstration program. The lack of support for NEP technology development over the past decade has resulted in large uncertainty surrounding the appropriate design choices and development plan. The first design selection is the determination of the preferred level of fuel enrichment (HEU or HALEU) and neutron spectrum (fast or moderated). All past technology and system studies of NEP have assumed HEU fuels; the selection of HALEU would introduce additional uncertainties that will have to be addressed. Second, a limited set of integrated mission, system, and vehicle architectures must be defined to allow selection of a small number of NEP system requirements upon which to base development and testing. It is essential that this development effort focus on the key design selections required to define the final NEP flight system. NASA mission studies to date have indicated that an NEP system specific mass of 20 kg/kWe, achievable with a 1200 K reactor, 1150 K power conversion temperatures, and reactor fuel burnup of 4 percent over 4 years, and Hall effect thrusters using direct-drive PMAD, are sufficient; but requirements and capabilities, as well as their sensitivity to potential component and subsystem development outcomes, have yet to be confirmed.

As of the end of 2020, there are no NEP component, subsystem, or system development efforts under way. Developing and producing crew-ready flight NEP systems by 2039 would therefore require a significant and rapid ramp-up of component level development and testing, as shown in Figure 3.7. The program structure combines initial technology development of reactor fuels, materials, and designs for each of the subsystems discussed previously and assumes concurrent modeling and simulation, ranging from the physics to system levels, to address the system complexity. The roadmap also includes time for lifetime demonstration and validation testing for all NEP subsystems. Additionally, the proposed roadmap uses an early Mars cargo mission, to be launched in 2033, as the first flight of the NEP system, rather than conducting a subscale flight test.

An NEP ground testing program requires the adaptation or development of test facilities to adequately develop and qualify the full range of NEP subsystem and integration tests. This will require a full survey and assessment of relevant facility capabilities. Testing will be supported by the development and validation of M&S tools.[39] M&S capabilities for current and planned efforts in terrestrial power may be useful. Thruster life and relationships between ground test data and in-space operation may be augmented by experience with solar electric propulsion systems. However, due to the orders of magnitude difference in power levels between current systems and a MWe-class NEP system, some ground testing challenges will remain.

Operation of steady state Hall thrusters for thousands of hours at 12.5 kWe has been demonstrated and is ongoing.[40] This level of testing is in support of the planned flight of the NASA Power and Propulsion Element in 2024, which will provide extensive data on the

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[39] James E. Polk and John R. Brophy, "Life Qualification of Hall Thrusters by Analysis and Test," Paper 00547, Presented at Space Propulsion 2018 Conference Seville, Spain, May 14–18, 2018.

[40] Frieman, Jason & Kamhawi, Hani & Peterson, Peter & Herman, Daniel & Gilland, James & Hofer, Richard. (2019). Completion of the Long Duration Wear Test of the NASA HERMeS Hall Thruster. 10.2514/6.2019-3895.

correlation of ground testing to space operation of Hall thrusters. Additionally, 100 kWe Hall thrusters have been tested for dozens of hours; but they have not been flight qualified, and there is significant uncertainty as to how these test results would translate to in-space operation in terms of performance and lifetime. Testing at these levels has predominantly been performed at NASA Glenn Research Center.[41] Therefore, a parallel effort to upgrade facilities enabling EP thruster testing to 100 kWe in an adequate environment, as well as the development of improved M&S tools and advanced diagnostics would be needed to support development of Hall thrusters for a MWe-class NEP system.

A chemical stage fueled by LOX and liquid methane would be developed concurrently with the development of the NEP system. This stage would be developed in concert with the currently planned Artemis Mars Ascent engine, which is also expected to use a LOX/liquid methane propulsion system.

FINDING. ***NEP Prospects for Program Success.*** 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 in 2039.

RECOMMENDATION. ***NEP Major Challenges.*** **NASA should invigorate technology development associated with the fundamental nuclear electric propulsion (NEP) challenge, which is to scale up the operating power of each NEP subsystem and to develop an integrated NEP system suitable for the baseline mission. In addition, NASA should put in place plans for (1) demonstrating the operational reliability of an integrated NEP system over its multiyear lifetime and (2) developing a large-scale chemical propulsion system that is compatible with NEP.**

[41] Possible reference: Dankanich, J. W., Walker, M., Swiatek, M. W., and Yim, J. T., "Recommended Practice for Pressure Measurement and Calculation of Effective Pumping Speed in Electric Propulsion Testing," Journal of Propulsion and Power, 2017, Vol. 33, No. 3, pp. 668–680. doi: 10.2514/1.B35478.

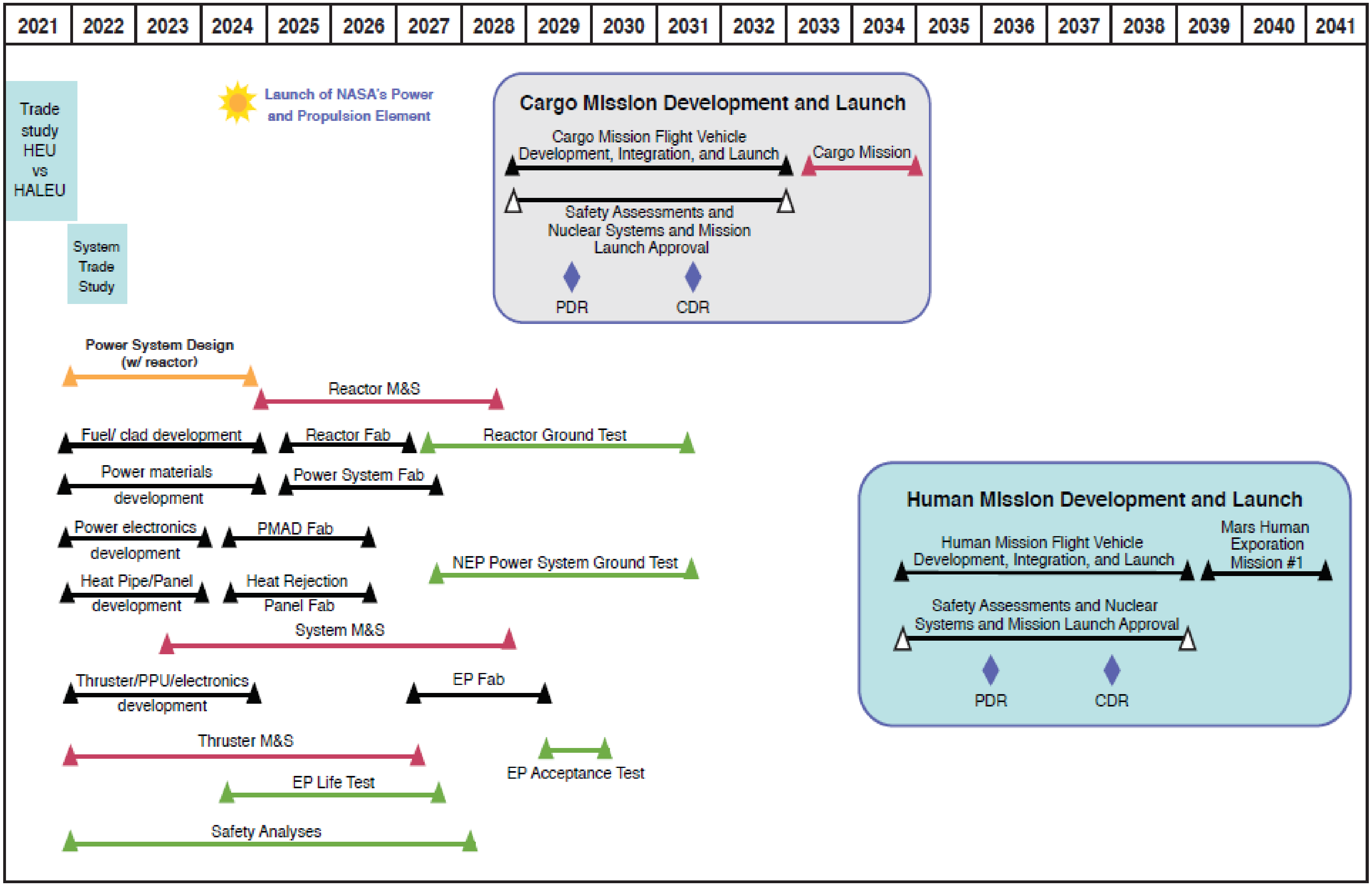

FIGURE 3.7 Nuclear electric propulsion development roadmap for the baseline mission, with a 2039 launch of the first human mission. NOTE: Acronyms defined in Appendix D.

SUMMARY

At a concept modeling and analysis level, NEP shows promise for the baseline mission. However, intermittent funding has resulted in very limited, if any, advance in its technology readiness since 2005, and that work focused on 200 kWe NEP systems, not the MWe-class system required for this application. The need to extrapolate from those results to a 1 to 2 MWe system required for the baseline mission without increasing specific mass results in considerable uncertainty in feasibility of this path on a timeline consistent with the baseline mission. In particular, uncertainty in fuel system architecture and the significant scaling of thruster requirements and thermal and power management are considerable challenges. The reliability and lifetime requirements of such a system merit careful attention and the lack of any substantive integrated system test remains a challenge.

The present state of NEP technology and limited subsystem ground test facilities for reactors and high-power EP thrusters require near-term assessment. Advanced reactor test facilities are currently under development for terrestrial programs, but the extent to which those facilities would be able to contribute to the development of MWe-class NEP systems remains to be determined.

EP has benefited from gradual increases in power level for solar powered spacecraft. There are currently hundreds of kilowatt-electric-class spacecraft flying operationally and a 40 kWe SEP system, using multiple 13 kWe thrusters, is projected to launch in 2024. However, testing thrusters at power levels above 50 kWe, particularly for in-space performance and lifetime, will challenge existing vacuum facility capabilities.

RECOMMENDATION. *NEP Pace of Technology Development*. 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.

4

System and Programmatic Issues

NTP AND NEP ARE DIFFERENT TECHNOLOGIES

Both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) systems show great potential to facilitate the human exploration of Mars with significant advantages relative to chemical propulsion. The two systems, however, have very different heritages. The development of high-power NTP systems benefits from the robust ground-based testing of many NTP reactors during the Rover/NERVA programs, but NTP systems require reactor operating temperatures about 1500°C higher than NEP systems. NASA, the Department of Energy (DOE), and the Department of Defense (DoD) are currently supporting substantive NTP research and development programs. Even so, an NTP system has never flown in space. In contrast, advanced electric propulsion (EP) technologies are deployed routinely in operational spacecraft. Such systems have demonstrated long life and high reliability, but only at power levels far below those needed for a megawatt electric (MWe)-class system, and only in a solar-powered mode. Over the past decade, there has been very little advancement in NEP technology at the scale and power-level required for the baseline mission. Given this imbalance in technology maturity, system trades are difficult to make.

NTP systems and NEP systems (which include a chemical propulsion system) are composed of many technologies, including the following:

- NTP and NEP
  - Nuclear reactors
  - Shields
  - Cryogenic fluid management
- NTP specific
  - Turbomachinery, valves, and pipes
  - Nozzles
  - Long term storage of liquid hydrogen (LH_2)

- NEP specific
  - Power conversion
  - Heat rejection
  - Power management and distribution
  - Electric propulsion
  - Chemical propulsion (for application to crewed Mars exploration missions)
  - Long-term liquid oxygen (LOX)/liquid methane storage

For those technologies that are used in both NEP and NTP systems, the engineering challenges are very different because of different operating temperatures, operational lifetimes, startup regimens, and requirements for integration with other system elements. For example, while both concepts use a nuclear reactor, as shown in Table 1.3 the operational requirements and design specifications for an NTP reactor are very different than those for an NEP reactor. As a result, different approaches may be needed to address some safety assurance requirements (see the discussion of safety assurance, below). Similarly, propellant storage temperature requirements greatly vary: 20 K for LH_2 (NTP), 110 K for LOX (NEP), 90 K for liquid methane (NEP), and supercritical storage of xenon (NEP). The propellant mass of an NTP system will far exceed the propellant mass for the electric thrusters in an NEP system; the latter, however, will need to store a sizeable mass of propellant for its ancillary chemical propulsion system. System complexity is another consideration. NTP systems have a smaller number of subsystems to integrate, whereas the nature of NEP enables initial subsystem separability for ground testing.

Given the above circumstances, meaningful and objective trade studies will require expertise in all the above technologies as they apply to NTP and NEP systems scaled to meet the needs of the baseline mission.

FINDING. ***Trade Studies.*** 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.

RECOMMENDATION. ***Trade Studies.*** **NASA should develop consistent figures of merit and technical expertise to allow for an objective comparison of the ability of nuclear electric propulsion and nuclear thermal propulsion systems to meet requirements for a 2039 launch of the baseline mission.**

DEVELOPMENTS COMMON TO BOTH NTP AND NEP SYSTEMS

Despite the many differences between NEP and NTP systems and subsystems, there are some areas of synergy, including the following:

- *Nuclear reactor fuels.* Ongoing work to develop advanced fuels, such as TRISO particles and high-assay, low-enriched uranium (HALEU), may be applicable to both NTP and NEP reactors.
- *Materials.* High temperature materials play a role in many aspects of reactor designs, and such materials are often developed agnostic of the application. NTP and NEP systems have very different reactor operating temperatures, interface requirements, and operational considerations. Even so, there is a general need for high-temperature

materials, and materials applicable to NTP systems may be useful for NEP systems (though not necessarily vice versa). This includes the commonality of high-temperature materials for fuels, cladding, cermet and cercer fuel matrices, and moderators (if included in the reactor design), reflectors, and neutron absorbers for reactor control and criticality. A second class of common materials lies in high-temperature, radiation-hardened sensors and electronics, which are needed for either system to assure controllability, safety, and reliability, and life.

- *Additional reactor technologies.* Reactor designs for NTP and NEP systems share common components such as shielding, actuators for control drums or rods, and instrumentation. Both design principles and materials may be common in these areas, although the specific designs will ultimately address different conditions of operation.
- *Cryogenic fluid management technology.* Technologies developed for long-term storage of LH_2 (most challenging) may also be applicable to the long-term storage of LOX and liquid methane.
- *Modeling and simulation (M&S).* Validated M&S tool significantly reduce the number of costly physical tests of NTP designs and accelerate component and integrated level qualification schedules. Modeling of reactor core neutronics, fluid flows through reactor coolant channels, and dynamic codes to model startup and other transient behaviors share some common fundamentals. The adequacy of M&S tools to accurately capture the rapid system dynamics of NTP designs needs to be examined. Given the exponential growth in computer power and similar advances in multi-physics flow modeling, the potential for high-fidelity coupled simulations of the thermal and fluid flow in power systems, including flow structural interactions, may be possible. Such integrated simulations can provide insight into component interactions and transient and feedback effects.
- *Testing.* NTP and NEP systems share commonality in separate effects testing of fuels and materials (including coupon and fuel element testing) and for some reactor subsystem testing, although the fuel temperature requirements are different. However, the recommended full-scale ground test facilities for an NTP reactor that is about 500 MWth and must capture the engine exhaust would be much more extensive than facilities for an NEP reactor that produces about 3 to 10 MWth and is a closed cycle.
- *Safety assurance.* Safety assurance for nuclear systems is essential to protect operating personnel as well as the general public and Earth's environment. Safety assurance policies and practices are inherent in all U.S. nuclear endeavors conducted by or for NASA, DOE, and other federal agencies. Safety goals are generally achieved by a combination of system design and operational safety measures. Such safety measures include, for example, (1) launching reactors with fresh fuel before they have operated at power to ensure that the amount of radioactivity onboard remains as low as practicable at launch,[1] (2) ensuring safe, reliable in-space system operation while providing adequate shielding for the crew and radiation-sensitive spaceflight hardware, (3) restricting reactor startup and operations in space until spacecraft are in nuclear safe orbits or trajectories that ensure safety of Earth's population and environment, and (4) ensuring that reactors remain in a safe state in the event of a launch failure. Additional policies and practices need to be established to prevent unintended system reentry during return to Earth (after

[1] An NTP or NEP reactor only builds up appreciable fission products when operated at power for a period of time.

reactors have been operated for extended periods of time). The safety analysis and launch approval process for the baseline mission will be similar for either an NEP or NTP system. Relevant functional design and operational safety criteria have been identified and applied to prior U.S. space reactor programs.[2,3] Incorporating lessons learned from these programs is vital to ensure adequate safety for operational NTP and NEP systems.[4,5,6]

- *Regulatory approvals.* Presidential memorandum (NSPM-20), which was released in August 2019, provides the most recent guidance on the launch approval process for space nuclear systems. This memorandum addresses safety issues such as potential inadvertent criticality stemming from a launch or reentry accident.[7] NSPM-20 also instructs NASA to develop guidance for safe nonterrestrial operation of nuclear fission reactors. These guidelines can be applied to either NEP or NTP systems. If HALEU fuels are adopted for NEP or NTP systems, regulatory issues will also be common. NEP or NTP systems will also face common regulatory requirements related to indemnification and to the construction and transportation of systems before launch.

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

HEU VERSUS HALEU

The decision between HEU (in this context, uranium with an enrichment greater than 90 percent)[8] and HALEU (less than 20 percent enrichment) fuel involves more than feasibility and system performance. No such comprehensive assessment that compares the fuel types head-to-

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[2] Marshall, A.C., Bari, R.A., Brown, N.W., Cullingford, H.S., Hardy, A.C., Lee, J.H., Niederauer, G.F., Remp, K., Rice, J.W., Sawyer, J.C., and Sholtis, J.A. Jr., Nuclear Safety Policy Working Group Recommendations on Nuclear Propulsion Safety for the Space Exploration Initiative, NASA Technical Memorandum 105705, Final Report of the Joint NASA/DOE/DoD Nuclear Safety Policy Working Group, National Aeronautics and Space Administration, April 1993.

[3] Sholtis, J.A. Jr., "Proposed Safety Functional Guidelines for Space Reactors," paper presented at the ANS 2005 Space Nuclear Conference (SNC-05), 5-9 June 2005, San Diego, CA, in Proceedings of the ANS Embedded Topical Meeting - Space Nuclear Conference 2005, ISBN: 0-89448-696-9, ANS Inc., LaGrange Park, IL, June 2005.

[4] Sholtis, J.A., Jr., Winchester, R.O., Brown, N.W., Connell, L.W., Marshall, A.C., McCulloch, W.H., Mims, J.E., and Potter, A., "U.S. Space Nuclear Safety: Past, Present, and Future," Chapter within *A Critical Review of Space Nuclear Power and Propulsion 1984-1993*, American Institute of Physics (AIP) Publishing, New York, NY, ISBN 1-56396-317-5, pp. 269-303, 1994.

[5] Nuclear Power Assessment Study – Final Report, Johns Hopkins University – Applied Physics Laboratory Report# TSSD-23122 under NASA Contract NNN06AA01C, Task NNN13AA17T, Chapter #4, February 4, 2015 (Released June 1, 2015).

[6] Marshall, A.C. (Editor), and Haskin, F.E., Usov, V.A. (Co-Editors), Space Nuclear Safety, ISBN-13: 978-0-89464-061-2 and ISBN-10: 0-89464-061-5, Krieger Publishing Company, Malabar, FL, 2008.

[7] NSPM-20, available at https://www.whitehouse.gov/presidential-actions/presidential-memorandum-launch-spacecraft-containing-space-nuclear-systems/.

[8] HEU refers to uranium enriched to the point that it contains at least 20 percent uranium-235. HEU fuels used in space nuclear propulsion and power systems would likely be enriched to greater than 90 percent uranium-235.

head (as distinct from a standalone assessment of the feasibility of an HALEU system) for either an NTP or NEP system was available to the committee. Key factors to be included in a comparative assessment of HEU and HALEU for both systems are as follows:

- *Technical feasibility and difficulty.* A HALEU reactor has never been built, tested, or flown for either NTP or NEP applications, and there are no experimental data on the behavior of HALEU NTP reactors to benchmark modeling and simulation codes. In contrast, HEU NTP reactors have been built, tested, and benchmarked using prior M&S software. Technical feasibility and difficulty considerations favor HEU for NTP systems, but they do not clearly favor one fuel enrichment level over the other for NEP systems.
- *Performance.* Fuel enrichment affects the performance of the system. For example, the relative mass and size of NTP and NEP systems (including shielding) is a function of fuel enrichment and other parameters such as each reactor's power level and neutron spectrum (fast vs. moderated). Data from the Rover/NERVA programs provide insight into the operational performance of HEU NTP reactors; equivalent data does not exist for HALEU reactors for NTP or NEP systems. Performance considerations do not clearly favor one fuel enrichment level over the other.
- *Proliferation and security.* HEU fuel, by virtue of the ease with which it could be diverted to the production of nuclear weapons, is a higher value target than HALEU, especially during launch and reentry accidents away from the launch site. As a result, HEU is viewed by nonproliferation experts as requiring more security considerations. In addition, if the United States uses HEU for space reactors, it could become more difficult to convince other countries to reduce their use of HEU in civilian applications. Proliferation related concerns also affect other factors such as cost, schedule, the ability of the commercial space sector to participate in reactor development, and the extent to which domestic politics becomes a factor in obtaining launch approval. Proliferation and security considerations favor HALEU.
- *Safety.* The selection of fuel enrichment, in conjunction with the reactor's neutron spectrum, can affect the design approach and difficulty in preventing inadvertent criticality events during launch and reentry accidents. This may require different emergency planning, accident response, and recovery protocols, even if there are no radiological consequences to the public. Safety considerations are design dependent, and do not clearly favor one enrichment level over the other.
- *Fuel availability.* It may be possible to obtain HEU from DOE's National Nuclear Security Administration stockpile. Producing HALEU would either require down-blending HEU from the stockpile or enriching lower enriched uranium. The latter would require new infrastructure. DOE is investigating production of HALEU to support near-term terrestrial power reactor needs, but there are concerns about the long-term availability of HEU. Overall, fuel availability considerations do not clearly favor one enrichment level over the other.
- *Cost.* The costs of HEU and HALEU systems differ because of factors such as safeguards and physical security, facilities, fuel procurement and fabrication, and system development. From a launch approval perspective, HEU systems require Presidential approval. While this may have schedule implications, it may not have cost implications as the cost of launch approval will likely be dominated by the safety analysis, which will

be similar for HEU and HALEU systems. Cost considerations do not clearly favor one enrichment level over the other.

- *Schedule.* Use of different enrichment levels will affect the design, development, testing, and launch preparations schedule. Possible locations for test facilities may be more limited for HEU due to the different security requirements, which could protract schedule, but there is a more historical data on HEU reactors. Schedule considerations do not clearly favor one fuel enrichment level over the other.
- *Supply chain.* The use of HEU would restrict the number of private-sector organizations which are able to participate in system development and manufacture. HEU would limit participation to DOE laboratories and the small number of private companies with licenses to work with HEU. Use of HALEU, on the other hand, would permit the involvement of a larger number of private companies and enable a variety of public-private partnerships. Supply chain considerations favor HALEU.

While there is some clarity on each of the criteria above, they are not equally important. Performance, security, and safety concerns are significantly more important than those related to the supply chain. This weighting must be considered prior to making a fuel enrichment decision.

FINDING. *Enrichment of Nuclear Fuels.* A comprehensive assessment of HALEU versus 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, safety, fuel availability, cost, schedule, and supply chain as applied to the baseline mission.

RECOMMENDATION. *Enrichment of Nuclear Fuels*. In the near term, NASA and DOE, with inputs from other key stakeholders, including commercial industry and academia, should conduct a comprehensive assessment of the relative merits and challenges of highly enriched uranium and high-assay, low-enriched uranium (HALEU) fuels for nuclear thermal propulsion and nuclear electric propulsion systems as applied to the baseline mission.

INDUSTRIAL BASE

A growing number of private-sector companies are developing system concepts for space nuclear systems. These concepts include applications for orbital maneuvering, deep space exploration, and planetary surface electrical grids.

No single entity—public or private—has all the requisite expertise or facilities to develop a space nuclear propulsion system. As has been demonstrated in recent space launch initiatives, NASA can leverage private-sector expertise interests and investments, along with DOE and NASA facilities, to spur the development of necessary technologies.

Several engine manufacturing and launch services providers have developed or are developing LOX/LH_2 engines for in-space propulsion. Many of the needed non-nuclear engine components have heritage from these product development and demonstration efforts, but additional investment is required to convert these systems for application to an NEP or NTP propulsion system.

Cryogenic fluid management, which is critical for both NEP/chemical and NTP systems, has primarily been a government-led development effort. Private-sector fuel tank and pressure vessel manufacturers exist, but the technically challenging nature of multiyear containment of cryogenic hydrogen (necessary for NTP) will require sustained government investment in the design, fabrication, and testing of these systems.

Very few private-sector entities have the capability to develop nuclear reactor fuels, cores, shields, and control systems. However, several are investing in these capabilities and can be expected to contribute directly to the design, manufacturing, and assembly of space nuclear propulsion systems.

If efforts to develop a space nuclear system are scaled up on an accelerated timeline, there may be shortfalls in the workforce needed for such systems. A significant space nuclear power development effort would benefit from concomitant efforts to enhance relevant aspects of the science, technology, engineering, and mathematics educational pipeline, particularly nuclear engineering. This pipeline faces the following three principal challenges:

1. The sector suffers from a lack of gender and ethnic diversity.
2. Non-aerospace technology companies compete with the aerospace sector for talent, especially in information technology fields.
3. Export control regulations and the classified nature of some of research and technologies preclude non-U.S. citizens from participating, constraining the size and quality of the pipeline.

LESSONS LEARNED FROM THE HISTORY OF DEVELOPING SPACE NUCLEAR SYSTEMS

Since 1961, the United States has launched 47 radioisotope power systems of eight different types in support of 30 navigational, meteorological, communications, and space science satellites, spacecraft, and planetary landers and rovers. In contrast, the United States has launched only one fission power system—the 500 We SNAP-10A reactor power system was launched in 1965 as an experimental test of an NEP system concept. At least a dozen other programs have been initiated to develop fission systems for space applications. While none of these additional programs launched a nuclear reactor, several lessons have emerged from these efforts that are worth incorporating in future space nuclear propulsion development efforts.

- *Need must be compelling.* Development and testing of space nuclear propulsion systems are expensive and time consuming relative to non-nuclear propulsion technology. Ambitious robotic and human exploration programs have succeeded without the need for space nuclear propulsion systems. Operational space nuclear propulsion systems are only likely to be developed and deployed if they are enabling or strongly enhancing for a particular mission of national importance.
- *Mission and product focus are critical.* Once the need for space nuclear propulsion systems is clearly established, having a specific mission with a clear customer, adequate funding, well-defined requirements, and a firm schedule serves as the best stimulus for development of an acceptable product that will be delivered on time and within cost. Mission-pull also ensures that technology development is focused on the critical need.

- *Limit technical risk impacts early in program.* Identification of the highest technical risk areas and selection of necessary technologies in need of maturation must be completed early. The program must consider the benefits of existing and emerging technology options and trade technical, schedule, and cost risks. During the development process, it is critical to maximize hardware production and testing at each level of integration to obtain key validation data (test-as-you-fly, fly-as-you-test). Once demonstration is complete, additional enhancements to system performance, reliability/life, and utility for a greater range of missions would require only incremental tests to validate the enhancements.

KEY TECHNICAL RISKS

As detailed in Chapters 2 and 3, there is uncertainty regarding the ability to predict whether a complete space nuclear propulsion system can be developed in time to launch cargo missions to Mars beginning in 2033 and to execute the baseline mission in 2039. The level of uncertainty is presently lower for NTP than for NEP. Each system is characterized by a small number of significant risks (see Table 4.1). The fundamental NTP challenge 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. The fundamental NEP challenge is to scale up the operating power of each NEP subsystem and to develop an integrated NEP system suitable for the baseline mission.

PROGRAMMATICS

The roadmaps of Section 2.6 and 3.6 show the key milestones necessary to execute the baseline 2039 human Mars mission preceded by cargo missions beginning in the 2033 opportunity. These roadmaps assume that NASA accelerates development decisions and maturation of the requisite technologies through an aggressive and focused development program, beginning in 2021 (18 years before the planned departure of the first crew and 12 years prior to the flight of the first full-scale cargo mission). NASA previously demonstrated greater expediency from less of a technical base in the successful Mercury, Gemini, and Apollo programs (e.g., Mercury was announced in October 1958 with a first successful crewed flight 31 months later; Apollo was announced in 1961 with the first human lunar landing 8 years later, including programmatic recovery from a major failure that resulted in the death of three astronauts). The International Space Station (from Freedom proposal in 1984 to first sustained crew presence 16 years later) provides another comparable. The committee believes that should the federal government choose to invest aggressively in this space nuclear propulsion technology, there is sufficient schedule to achieve the baseline mission. In addition, as presented in Figure 1.2, over the 17-year synodic cycle, 9 of 10 Earth-departure opportunities are feasible within the propulsive capability of a space nuclear propulsion system sized for the 2039 opportunity. As such, the next opportunities of 2042, 2045, and 2047 provide fallback potential and schedule mitigation for the chosen path.

TABLE 4.1 Major Challenges for Developing Nuclear Electric Propulsion (NEP) and Nuclear Thermal Propulsion (NTP) Systems for the Baseline Mission

Category	NTP	NEP
Reactor Core Fuel and Materials	• High reactor fuel operating temperature (more than 2700 K)	
System Operational Parameters	• Rapid system startup to full operating temperature (preferably in 1 min or less)	• Long system operational reliability (4 years for power generation, 1 to 2 years for thrust)
Scale		• Power conversion and thermal subsystem tests conducted to date have been at power levels orders of magnitude below that required for baseline mission • Limited full scale, short duration electric propulsion subsystem testing at power levels an order of magnitude below that required for baseline mission
Ground-Based Testing	• Need to capture and process engine exhaust (resulting in high cost) • Facility preparation time (stresses baseline schedule) • Little integrated system testing experience; none of it recent • Last relevant-scale tests were nearly 50 years ago	• No fully integrated system testing experience
In-space Propulsion Technology Needs	• Long-term storage of liquid hydrogen in space at 20 K with minimal loss	• Parallel development of a chemical propulsion systems
System Complexity		• Highly complex: six NEP subsystems and a chemical propulsion system

5

Mission Applications

If a nuclear electric propulsion (NEP) or nuclear thermal propulsion (NTP) system is successfully developed for a crewed Mars mission, it will also be able to support the accomplishment of additional space missions. Separately, the Department of Energy (DOE) and the Department of Defense (DoD) are developing small nuclear fission systems for terrestrial applications. These programs are expected to precede the baseline Mars mission and, if planned synergistically, may provide space nuclear propulsion technology advancement. Potential synergies across these missions and development programs are summarized in this chapter.

SCIENCE MISSIONS

The use of NEP has been considered repeatedly over the decades for robotic exploration missions to Mars, Saturn, Neptune, and Pluto and for a range of sample return missions. NEP systems can potentially provide extraordinary power capability to science instruments in addition to propulsion. Power levels considered have generally been 100 kWe or less.[1] The Jupiter Icy Moons Orbiter (JIMO) mission would have visited three Jovian moons with an NEP system designed to produce 200 kWe. Most recently, an NEP system at power levels of 1 to 8 kWe has been examined for outer planet missions.[2] NTP systems and megawatt electric (MWe)-class NEP systems have seldom been considered for these science missions, primarily due to the large total cost and mass of the system, the inability to launch these systems on a single launch vehicle, the lack of significant transfer time constraints, and the desire to avoid in-space assembly of science missions.

Mission concepts for destinations from 100 to 1,000 astronautical units from Earth have focused on NEP systems or even more advanced propulsion concepts. An NEP system developed for the baseline Mars mission would provide a starting point for developing an NEP system for an interstellar mission. The latter would need to provide a higher specific impulse (I_{sp}) at a lower specific mass (in kilograms per kilowatt-electric [kg/kWe]) than is needed to execute the

[1] "Priorities in Space Science Enabled by Nuclear Power and Propulsion," Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion, National Academies Press, (2006).

[2] Gibson, M. A. et al., "NASA's Kilopower Reactor Development and the Path to Higher Power Missions" NASA/TM—2017-219467.

baseline mission to Mars.[3] The lower I_{sp} of NTP systems makes them less suited for missions beyond the solar system.[4]

POTENTIAL FOR HIGHER PERFORMANCE SPACE NUCLEAR PROPULSION SYSTEMS

Beyond 2040, both NTP and NEP offer the potential for higher performance, beyond that required for the baseline mission. For NTP, increasing I_{sp} from 900 s to 1,000 s, for example, would require a propellant temperature of approximately 3100 K at the reactor exit. Fundamentally, this challenge derives from the thermal propellant acceleration process, because I_{sp} scales as the square root of the reactor temperature. Increasing the operating temperature by 400°C would significantly increase development risk for materials and fuel forms, ground testing, and spaceflight.

In contrast, NEP offers several different approaches to future higher-performance systems. First, a scaled-up power system using existing technology would produce more power without increasing reactor temperature. Second, advanced power conversion subsystems could potentially be developed with a lower specific mass, which would reduce the specific mass of the NEP system as a whole. Third, use of a higher-I_{sp} electric propulsion (EP) system with the same power and heat rejection system could enable high total velocity increment (ΔV) missions, albeit with lower acceleration levels (unless power is increased). Finally, developing a reactor capable of operating at 1500 K without a significant increase in support system mass would also reduce the specific mass of the system. Ongoing research and technology development for both NTP and NEP is necessary to allow them to achieve their potential, even if they are not selected as the propulsion system for the first human Mars exploration mission.

SURFACE POWER USE OF NEP REACTORS

Nuclear fission power has been identified as a technology priority for sustained human presence on both the Moon and Mars.[5] The development of the reactor and power conversion subsystems of an NEP system may contribute to the development of surface power systems and vice versa, especially if the megawatt electric capacity of the NEP system greatly exceeds the power requirements for the surface power system. Even so, key differences in the operational environment, such as gravitational effects and the presence of a potentially corrosive atmosphere or dust layer (on Mars) impose different design requirements on the reactor, core cooling, and thermal management system. There would also be different design requirements for the radiation shield. NEP systems use shadow shielding to reduce radiation only in the conical region where equipment and personnel on the spacecraft are located. The shield for a planetary-based reactor would need to reduce radiation in all directions, although it could be buried to allow regolith to provide some of the required shielding. Thermal management systems for surface applications

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[3] K. T. Nock, "TAU-A Mission to a Thousand Astronomical Units," AIAA-87-1049, 19th AIAA/DGLR/JSASS Int'l Electric Propulsion Conf, Colorado Springs, May 11-13, 1987.

[4] James R. Powell, J. Paniagua, G. Maise, H. Ludewig, Michael Todosow, "High performance nuclear thermal propulsion system for near term exploration missions to 100 A.U. and beyond," Acta Astronautica, Volume 44, Issues 2–4, January–February 1999, Pages 159-166.

[5] Fission surface power systems have not been identified as a priority for NASA science missions.

would need to account for the effects of gravity on coolant flow and the presence of planetary surface rather than space for one half of the view factor for radiation heat rejection.

The Kilopower system's output power of 7 to 10 kWe is estimated to be suitable for life support and, with multiple units, in situ resource utilization (ISRU) for initial lunar bases. Some studies of augmented ISRU production estimate power level requirements of 40 to 125 kWe. Potential long-term growth of lunar basing could drive power requirements to the 100s of kWe, at which point a derated NEP reactor and/or power system could prove to be advantageous.

Mars ISRU power requirements were also assessed in planning the Kilopower program. An early power level for ISRU is estimated to be 40 kWe, which could be provided by four 10 kWe Kilopower units. A larger base could require power levels on the order of 150 kWe, similar to longer-term lunar requirements.

SYNERGIES WITH NATIONAL SECURITY MISSIONS

Space nuclear propulsion and power systems have the potential to provide the United States with military advantages. DoD and other federal agencies with an interest in national security have historically been interested in nuclear power and propulsion for space. The utility provided by either NTP or NEP is mission dependent. An NTP system could provide DoD with a rapid response capability in cislunar space to address counter-space and anti-satellite threats on critical timescales. The primary differentiator between these two systems is whether the vehicle needs to move rapidly (which would require an NTP system) or if it can remain quasi-stationary or accelerate slowly (which is compatible with an NEP system). Additionally, an NEP system could potentially provide megawatts of power to a spacecraft dedicated to power beaming, long-distance communications, and long-distance sensing.

The Defense Advanced Research Projects Agency (DARPA) presently has an NTP program named Demonstration Rocket for Agile Cislunar Operations (DRACO).[6] 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.

Threats to U.S. space assets are increasing. They include anti-satellite weapons and counter-space activities.[7,8] Crossing vast distances of space rapidly with a reasonably sized vehicle in response to these threats requires a propulsion system with high I_{sp} and thrust. This could be especially important in a high-tempo military conflict. For high ΔV missions, an NTP system that fits within the mass and volume limits of a single launch vehicle would be ideal, whereas an in-space chemical system might be prohibitively large. This is the driving rationale behind the selection of an NTP system for the DRACO program.[9]

Some of the technologies and methods that are applicable to the development and construction of an NTP system for DRACO could contribute to NASA's development of an NTP system for the baseline mission to Mars, despite the difference in scale between the two systems.

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[6] DRACO Program Page, DARPA website, https://www.darpa.mil/program/demonstration-rocket-for-agile-cislunar-operations.

[7] U.S.-China Economic and Security Review Commission, 2019 Report to Congress, November 2019.

[8] U.S.-China Economic and Security Review Commission, Hearing on China in Space: A Strategic Competition? written testimony of Namrata Goswami, April 25, 2019, 82.

[9] Broad Agency Announcement, DARPA, Demonstration Rocket for Agile Cislunar Operations, HR001120S0031, June 29, 2020.

Areas of common interest include (1) fundamental questions about the development and testing of materials (such as reactor fuels and moderators) that can survive NTP conditions and (2) advancing modeling and simulation (M&S) capabilities that are relevant to NTP, such as in the area of dynamic, time-dependent reactor predictions. Furthermore, a NASA NTP system could potentially use a scaled-up version of a DoD reactor, depending on the design. Additionally, NASA could benefit programmatically by working with a DoD program having national security objectives, which establishes a level of prioritization for use of national assets.

SYNERGIES WITH TERRESTRIAL NUCLEAR SYSTEMS

Dozens of companies are currently pursuing advanced reactor designs for various applications. Several of these efforts focus on development of terrestrial microreactors, which are on the scale of hundreds of kilowatts to a few megawatts of electric power for both commercial and military applications. As such, they are on the same scale as the NEP systems under consideration for the baseline mission.

Funded by DOE, DoD, and private industry, developers of terrestrial microreactors are focused on similar concepts of interest to NEP systems, such as factory assembly and fueling, easy transportability, autonomous or semi-autonomous operation, and long-life operation (e.g., on the order of 5 to 10 years) without refueling and minimal maintenance. Although terrestrial systems seek to be transportable by standard means (truck, rail, barge, and aircraft), they likely have less stringent mass and volume constraints relative to systems intended for space. Additionally, these systems would be accessible for maintenance in the event of a sensor malfunction or equipment degradation, despite the overall desire to operate without intervention throughout the planned fuel cycle length.

Demonstration of the first terrestrial microreactors is expected in the mid-2020s, offering operational data for fuels and materials that can support code validation that is also applicable to NEP designs, and with some but reduced applicability to NTP designs. These demonstrations will be supported by the Advanced Reactor Demonstration Program of the DOE Office of Nuclear Energy (DOE-NE), the DOE National Reactor Innovation Center, and the DoD Pele Program.[10] The acquired operational data can support evaluation of system integrity and reliability, reducing risk to mission success for areas common to terrestrial and space propulsion systems, and providing confidence in the ability to obtain launch approval. There is significant private investment in development of some of these systems, either via private-public partnerships or fully private investment.

Microreactor concepts include heat pipe, gas, and liquid metal cooled designs, as have been evaluated for NEP across various historical programs; gas-cooled designs may also provide some similarity to NTP designs, albeit limited due to the significant differences in operational approaches. There are also many similarities in the nuclear fuel forms under consideration for terrestrial and space systems, including high-assay, low-enriched uranium (HALEU; e.g., uranium dioxide and uranium nitride) and TRISO. Hence, the NASA program may be able to leverage the fuel and component fabrication and testing facilities and resultant property

[10] More information can be found for these programs at the following sites: ARDP, https://www.energy.gov/ne/nuclear-reactor-technologies/advanced-reactor-demonstration-program; NRIC, https://inl.gov/nric/; DoD Pele, https://www.defense.gov/Newsroom/Releases/Release/Article/2105863/dod-awards-contracts-for-development-of-a-mobile-microreactor/.

measurements, performance characterization, and test data to accelerate the development roadmap for space missions.

Moderator materials are considered for many advanced reactor designs to allow use of HALEU fuels. Development programs for such moderators, including yttrium hydride, are in process for the DOE-NE Microreactor program. These programs could support the needs of either NEP or NTP designs that include a moderator block, but additional testing points at higher temperatures may need to be included to ensure that the data covers the operational envelope for NEP or NTP applications.

Approaches for manufacturing and assembly may also be similar across terrestrial and space applications for some of these concepts. The recently established DOE-NE Transformational Challenge Reactor and Advanced Methods for Manufacturing programs seek to advance the state of the art for nuclear component fabrication. These programs will expand and demonstrate the methods by which nuclear equipment, components, and plants are manufactured and assembled. Similar approaches may be of interest to space nuclear systems as a means to reduce cost, increase reliability, and establish a secure supply chain. The fabrication experience, mechanical testing data, and material characterization data (pre- and post-irradiation) will support the case for use of advanced manufacturing in nuclear systems, providing a jump start on the regulatory and launch approval paths for crewed nuclear missions. Operational temperatures are expected to be lower and operating lifetimes longer for terrestrial systems relative to NEP, such that test data on these components will likely need to be extended.

Some microreactor and NEP designs rely on advanced Brayton power conversion systems, including supercritical carbon dioxide and helium working fluid designs, for electricity generation, allowing for lessons learned from terrestrial systems development to inform NEP systems for both cargo and crewed missions.

FINDING. *Synergies with Terrestrial and National Defense Nuclear Systems*. 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 DARPA DRACO program could potentially contribute to the development of NTP systems for the baseline mission.

RECOMMENDATION. *Synergies with Terrestrial and National Defense Nuclear Systems*. NASA should seek opportunities for collaboration with the Department of Energy and Department of Defense terrestrial microreactor programs and the Defense Advanced Research Projects Agency DRACO (Demonstration Rocket for Agile Cislunar Operations) program to identify synergies with NASA space nuclear propulsion programs.

Appendixes

A

Statement of Task and Additional Guidance

STATEMENT OF TASK

The National Academies of Sciences, Engineering, and Medicine will convene an ad hoc committee to identify primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion technologies of interest to future exploration missions. Nuclear propulsion has been shown to offer the potential for rapid human transit to Mars with one-way transit times less than 9 months and total roundtrip times including Mars surface stays less than 3 years. The committee will also determine the key milestones and a top-level development and demonstration roadmap for each technology. Additionally, the committee will identify missions that could be enabled by successful development of each technology.

The space nuclear propulsion technologies of specific interest are:

1. High-performance nuclear thermal propulsion (NTP) that heats hydrogen propellant to 2500 K or more and produces specific impulse of at least 900 s.
2. Nuclear electric propulsion (NEP) that converts thermal energy to electricity to power plasma thrusters for highly efficient and rapid transport of large payloads (e.g., a propulsion system with a power level of at least 1 MWe and a mass-to-power ratio (kg/kWe) that is substantially lower than the current state of the art of NEP systems).

ADDITIONAL STUDY PARAMETERS

After the committee was appointed, NASA further 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 committee accepted this additional guidance in preparing this report.

The committee also determined that an NTP system with a hydrogen propellant temperature of approximately 2700 K at the reactor exist corresponds to a specific impulse of at 900 I_{sp}, and so the report consistently refers to 2700 K rather than 2500 K as the target propellant temperature.

B

Findings and Recommendations

All of the findings and recommendations that appear in the report appear below. Those that apply specifically to NEP or NTP systems appear in Table A.1, with corresponding findings and recommendations appearing side-by-side. The table is followed by those findings and recommendations that are not specific to NEP or NTP systems.

TABLE A.1 Findings and Recommendations Specific to Nuclear Thermal Propulsion (NTP) or Nuclear Electric Propulsion (NEP) Systems

Findings and Recommendations Specific to NTP Systems	Findings and Recommendations Specific to NEP Systems
FINDING. NTP Fuel Characterization. A significant amount of characterization of reactor core materials, including fuels, remains to be done before NASA and DOE will have sufficient information for a reactor core design. RECOMMENDATION. NTP Fuel Architecture. If NASA plans to apply NTP technology to a 2039 launch of the baseline mission, NASA should expeditiously select and validate a fuel architecture for an NTP system that is capable of achieving a propellant reactor exit temperature of approximately 2700 K or higher (which is the temperature that corresponds to the required I_{sp} of 900 sec) without significant fuel deterioration during the mission lifetime. The selection process should consider whether the appropriate fuel feedstock production capabilities will be sufficient.	

TABLE A.1 Findings and Recommendations Specific to Nuclear Thermal Propulsion (NTP) or Nuclear Electric Propulsion (NEP) Systems (continued)

Findings and Recommendations Specific to NTP Systems	Findings and Recommendations Specific to NEP Systems
FINDING. NTP Storage of LH_2. NTP systems for the baseline mission will require long-duration storage of LH_2 at 20 K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission. **RECOMMENDATION. NTP Storage of LH_2. If NASA plans to apply NTP technology to the baseline mission, NASA should develop high-capacity tank systems capable of storing LH_2 at 20K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission.**	
	FINDING. NEP Power Scaling. Developing a MWe-class NEP system for the baseline mission would require increasing power by orders of magnitude relative to NEP system flight- or ground-based technology demonstrations.
FINDING. NTP Modeling and Simulation, Ground Testing, and Flight Testing. Subscale in-space flight testing of NTP systems cannot address many of the risks and potential failure modes associated with the baseline mission NTP system and therefore cannot replace full-scale ground testing. With sufficient M&S and ground testing of fully integrated systems, including tests at full scale and thrust, flight qualification requirements can be met by the cargo missions that will precede the first crewed mission to Mars.	**FINDING. NEP Modeling and Simulation, Ground Testing, and Flight Testing.** Subscale in-space flight testing of NEP systems cannot address many of the risks and potential failure modes associated with the baseline mission NEP system. With sufficient M&S 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. Fully integrated ground testing may not be required.

TABLE A.1 Findings and Recommendations Specific to Nuclear Thermal Propulsion (NTP) or Nuclear Electric Propulsion (NEP) Systems (continued)

Findings and Recommendations Specific to NTP Systems	Findings and Recommendations Specific to NEP Systems
RECOMMENDATION. NTP Modeling and Simulation, Ground Testing, and Flight Testing. To develop an NTP system capable of executing the baseline mission, NASA should rely on (1) extensive investments in M&S, (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.	**RECOMMENDATION. NEP Modeling and Simulation, Ground Testing, and Flight Testing. To develop an NEP system capable of executing the baseline mission, NASA should rely on (1) extensive investments in M&S, (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 of the NEP system that will be incorporated into the first crewed mission.**
FINDING. NTP Prospects for Program Success. An aggressive program could develop an NTP system capable of executing the baseline mission in 2039. **RECOMMENDATION. NTP Major Challenges. NASA should invigorate technology development associated with the fundamental 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).**	**FINDING. NEP Prospects for Program Success.** 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 in 2039. **RECOMMENDATION. NEP Major Challenges. NASA should invigorate technology development associated with the fundamental NEP challenge, which is to scale up the operating power of each NEP subsystem and to develop an integrated NEP system suitable for the baseline mission. In addition, 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 large-scale chemical propulsion system that is compatible with NEP.**
	RECOMMENDATION. NEP Pace of Technology Development. If NASA plans to apply NEP technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development.

Findings and Recommendations Applicable to Both NTP and NEP Systems

FINDING. Trade Studies. 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.

RECOMMENDATION. Trade Studies. NASA should 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.

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

FINDING. Enrichment of Nuclear Fuels. A comprehensive assessment of HALEU vs 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, safety, fuel availability, cost, schedule, and supply chain as applied to the baseline mission.

RECOMMENDATION. Enrichment of Nuclear Fuels. In the near term, NASA and DOE, with inputs from other key stakeholders, including commercial industry and academia, should 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.

FINDING. Synergies with Terrestrial and National Defense Nuclear Systems. 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 DARPA DRACO program could potentially contribute to the development of NTP systems for the baseline mission.

RECOMMENDATION. Synergies with Terrestrial and National Defense Nuclear Systems. NASA should seek opportunities for collaboration with the DOE and DoD terrestrial microreactor programs and the DARPA DRACO program to identify synergies with NASA space nuclear propulsion programs.

C

Committee Member Biographies

ROBERT D. BRAUN, *Co-Chair*, is the director for planetary science at the Jet Propulsion Laboratory, California Institute of Technology, where he has leadership and management responsibility for the portfolio of planetary science formulation, technology, implementation, and operations activities at the laboratory. Prior to this role, he was dean of the College of Engineering and Applied Science at the University of Colorado, Boulder. In 2010 and 2011, as the NASA chief technologist, he served as the agency's senior executive for technology policy and programs. Formerly, he was a faculty member at the Georgia Institute of Technology (Georgia Tech) where he led a research and education program focused on the design of advanced flight systems and technologies for planetary exploration. Prior to joining the Georgia Tech faculty, Dr. Braun worked for 16 years at the NASA Langley Research Center. While at NASA, he contributed to the design and flight operations of multiple spaceflight projects, including the Mars Pathfinder mission. Dr. Braun is a member of the National Academy of Engineering (NAE), a fellow of the American Institute of Aeronautics and Astronautics (AIAA) and the American Astronautical Society, and the author or co-author of more than 300 technical publications in the fields of atmospheric flight dynamics, planetary exploration systems, multidisciplinary design optimization, and systems engineering. He received his Ph.D. in aeronautics and astronautics at Stanford University. He has previously served on several National Academies of Sciences, Engineering, and Medicine committees and as vice chair of the Space Studies Board.

ROGER M. MYERS, *Co-Chair*, is the owner of R. Myers Consulting. He is a senior aerospace consultant with more than 30 years of experience in space technology development, flight programs, and in-space mission architecture planning. He currently provides expertise in space propulsion and power systems (both conventional and nuclear), program management, and strategic planning to multiple clients. He retired from Aerojet Rocketdyne, where his most recent position was executive director of Advanced In-Space Programs. In that role, he oversaw programs and strategic planning for next-generation in-space missions and architectures, propulsion systems, power systems, and space vehicles for the Department of Defense (DoD), NASA, and the commercial sector. These included nuclear thermal propulsion and nuclear electric power systems in addition to chemical and non-nuclear electric propulsion systems. He also served as Aerojet Rocketdyne's executive director of electric propulsion and integrated systems, where he led efforts focused on the development and production of next-generation chemical and electric space propulsion systems and vehicles. Dr. Myers has also served as deputy lead of Aerojet Rocketdyne's Space and Launch Systems and general manager of Redmond Operations. Prior to joining Aerojet Rocketdyne, he held supervisory and research positions at NASA's Glenn Research Center, conducting research for the On-Board Propulsion Branch. He has authored more than 80 publications on spacecraft propulsion and advanced mission architectures, he is a former chair of the AIAA Electric Propulsion Technical Committee, and he is a former associate editor of the *Journal of Propulsion and Power*. Dr. Myers is past president of the Electric Rocket Propulsion Society (ERPS), the president of the Washington State Academy of Sciences, the chair of the Washington State Joint Center for Aerospace Technology Innovation, and a member of the board of directors of the ERPS and Seattle's Museum of Flight. He is a fellow of the AIAA and has received the AIAA Wyld Propulsion Award and the ERPS Stuhlinger Medal for Outstanding Achievement in Electric Propulsion. He holds a Ph.D. in mechanical and aerospace engineering from Princeton University.

SHANNON M. BRAGG-SITTON is the lead for integrated energy systems in the Nuclear Science and Technology Directorate at the Idaho National Laboratory (INL), Battelle Energy Alliance. In this role, Dr. Bragg-Sitton serves as the co-director for the INL Laboratory Initiative on Integrated Energy Systems (IES), which includes focus areas for thermal energy generation, power systems, data systems, and chemical processes and industrial applications. She also serves as the INL lead for the Department of Energy (DOE) Applied Energy Tri-Laboratory Consortium, which includes INL, the National Renewable Energy Laboratory, and the National Energy Technology Laboratory. Dr. Bragg-Sitton has held multiple leadership roles in the DOE Office of Nuclear Energy (DOE-NE) programs since joining INL. She currently serves as the national technical director for the DOE-NE IES program within Crosscutting Technologies Development. Prior to joining INL, Dr. Bragg-Sitton was an assistant professor in the Nuclear Engineering Department at Texas A&M University and a technical staff member at Los Alamos National Laboratory, during which time she was on assignment at NASA Marshall Space Flight Center. In each of these capacities, her primary research area was in-space nuclear power and propulsion systems, including system design, analysis, and testing for nuclear electric and nuclear thermal propulsion and nuclear surface power for applications on the Moon or Mars. Dr. Bragg-Sitton also led fuel development work for nuclear thermal propulsion while at INL. She holds a Ph.D. in nuclear engineering from the University of Michigan.

JONATHAN W. CIRTAIN is the president of Advanced Technologies, LLC, a subsidiary of BWX Technologies (BWXT), which is the sole manufacturer of nuclear reactors for the U.S. Navy. Previously, Dr. Cirtain was the director of the Transformational Challenge Reactor program at Oak Ridge National Laboratory. This was a demonstration program to design and manufacture a high-temperature gas reactor using 3-D manufacturing and artificial intelligence systems. Dr. Cirtain has also served as manager of the Science Office at NASA Marshall Space Flight Center. At BWXT, Dr. Cirtain leads the development of advanced reactor programs for various government and commercial customers, as well as novel radiopharmaceutical product development and manufacturing. Dr. Cirtain has received numerous awards, including the Presidential Early Career Award for Scientists and Engineers, the NASA Exceptional

Achievement Award, and the NASA Exceptional Science Achievement Award. He received his Ph.D. in physics from Montana State University.

TABITHA DODSON is an engineer-scientist, SETA with Gryphon-Schafer Government Services, LLC. She is also the chief engineer of the Demonstration Rocket for Agile Cislunar Operations (DRACO) program at the Defense Advanced Research Projects Agency (DARPA) that is developing a nuclear thermal propulsion system. Previously, Dr. Dodson was an adjunct professor in the Aeronautics and Astronautics Department of the Air Force Institute of Technology (AFIT). She has worked in various positions within the U.S. Air Force, including aerospace engineer and senior scientist, in the fields of spacecraft engineering, space power, and space propulsion. Her research interests and experiences include nuclear thermal propulsion fuels development; advanced space propulsion; and nuclear, quantum, and plasma physics and plasma engineering. She has a Ph.D. in applied physics from the Air Force Institute of Technology and a Ph.D. in mechanical and aerospace engineering from George Washington University.

ALEC D. GALLIMORE is the Robert J. Vlasic Dean of Engineering, the Richard F. and Eleanor A. Towner Professor of Engineering, and an Arthur F. Thurnau Professor in the Department of Aerospace Engineering at the University of Michigan (UM), where he is founder and co-director of the Plasmadynamics and Electric Propulsion Laboratory. Previously, Dr. Gallimore served as associate dean for academic affairs and associate dean for research and graduate education at the UM College of Engineering and as associate dean at the Horace H. Rackham School of Graduate Studies. His primary research interests include electric propulsion and plasma diagnostics. He has experience with a wide array of electric propulsion technologies including Hall thrusters, ion thrusters, arcjets, radiofrequency plasma sources, 100-kW-class steady magnetoplasmadynamic (MPD) thrusters, and megawatt-level quasi-steady MPD thrusters. Dr. Gallimore has implemented a variety of probe, microwave, and optical/laser plasma diagnostics. He is a member of the NAE and has served on advisory boards for NASA and DoD, including the U.S. Air Force Scientific Advisory Board. He was awarded the Decoration for Meritorious Civilian Service by the U.S. Air Force and is a fellow of the AIAA. He has a Ph.D. in aerospace engineering from Princeton University.

JAMES H. GILLAND is a senior scientist at the Ohio Aerospace Institute and has worked there for 19 years. Dr. Gilland has performed and led mission and system studies for solar and nuclear electric propulsion systems, and he has performed research in high-power electric propulsion thruster concepts, including magnetoplasmadynamic thrusters, Hall thrusters, and innovative wave heated concepts. Dr. Gilland is a fellow of the NASA Institute for Advanced Concepts and an associate fellow of the AIAA. He received his Ph.D. in nuclear engineering and engineering physics from the University of Wisconsin, Madison.

BHAVYA LAL is the acting chief of staff at NASA. Before coming to NASA, she led the space technology and policy portfolio at the IDA Science and Technology Policy Institute (STPI). Over the last quarter century, Dr. Lal has developed and applied her expertise in engineering systems and innovation theory and practice to topics in space, making analytic contributions in a range of areas spanning commercial activities in low-Earth orbit and deep space, on-orbit servicing assembly and manufacturing, human exploration, space nuclear power, and space science. Before joining STPI, Dr. Lal was president of C-STPS, LLC, a science and technology policy research and consulting firm in Waltham, Massachusetts. Prior to that, she was a researcher at and the director of the Center for Science and Technology Policy Studies at Abt Associates, Inc., in Cambridge, Massachusetts. Dr. Lal holds bachelor's and master's degrees in nuclear engineering from the Massachusetts Institute of Technology (MIT), a second master's in technology and policy also from MIT, and a Ph.D. in public policy and public administration from George Washington University.

PARVIZ MOIN is the Franklin P. and Caroline M. Johnson Professor of Mechanical Engineering and the director of the Center for Turbulence Research (CTR) at Stanford University. Established in 1987, CTR is devoted to fundamental studies of multi-physics turbulent flows and is widely recognized as the international focal point for turbulence research, attracting diverse groups of researchers from engineering, mathematics, and physics. Dr. Moin pioneered the use of direct numerical simulation and large eddy simulation techniques for the study of turbulence physics, control, and modeling of fluid mechanics, and he has written widely on the structure of turbulent shear flows. His current research interests include hypersonic flows, two-phase flows, aerodynamic noise, hydro-acoustics, aero-optics, propulsion, numerical methods for multi-scale problems, and flow control. Dr. Moin is the co-editor of the Annual Review of Fluid Mechanics and associate editor of the Journal of Computational Physics. He is the recipient of the NASA Exceptional Scientific Achievement Medal, the AIAA Lawrence Sperry Award, American Physical Society (APS) Fluid Dynamics Prize, AIAA Fluid Dynamics Award, and NASA Outstanding Leadership Medal. Dr. Moin is a member of the Royal Spanish Academy of Engineering. He is a member of the National Academy of Sciences and the NAE, a fellow of the American Physical Society, AIAA, and the American Academy of Arts and Sciences. Dr. Moin received a Ph.D. in mechanical engineering from Stanford University.

JOSEPH A. SHOLTIS, JR., is the owner and principal of Sholtis Engineering & Safety Consulting, providing expert nuclear, aerospace, and systems engineering services to government, national laboratories, industry, and academia since 1993. Prior to that, he retired from the U.S. Air Force as a lieutenant colonel, having spent 22 years as a nuclear research officer and a system development program manager spearheading a wide variety of advanced nuclear technologies and systems for space, missile, and unique terrestrial applications. Mr. Sholtis is an expert in space nuclear systems, their safety and reliability, and the risks associated with their launch and use in space. He has been involved in the design and development of U.S. space reactor and radioisotope power systems (RPS), including conception and advancement of particle-based fuels and fuel forms to enhance the design, performance, and safety of future RPS. He has participated in launch safety and mission risk analyses and evaluations of 15 U.S nuclear-powered or nuclear-heated space missions; served as program manager of the SP-100 space reactor program; advised the U.S. delegation to the United Nations Committee on the Peaceful Uses of Outer Space (in particular, the Working Group on Nuclear Power Sources for Space); and served on NASA's Nuclear Safety Policy Working Group on Nuclear Propulsion for the Space Exploration Initiative and on NASA's Nuclear Power Assessment Study. He is an associate fellow of the AIAA, a member of the AIAA Aerospace Power Systems Technical Committee (leading a team developing an AIAA White Paper on U.S. Space Nuclear Power Systems), an emeritus member of the American Nuclear Society (ANS) and the ANS Trinity Section, and a former Nuclear Regulatory Commission licensed senior reactor operator and reactor facility director of the Armed Forces Radiobiology Research Institute's 1.0 MWt TRIGA

Mark-F pulsing research and test reactor, with more than 2,000 h of console time, and more than 100 pulse operations. He has authored more than 100 technical publications, including chapters in four textbooks, and has received numerous awards and citations from DoD, U.S. Air Force, U.S. Army, DOE, Sandia National Laboratories, NASA, the Jet Propulsion Laboratory, and the White House.

STEVEN J. ZINKLE is the Governor's Chair Professor for Nuclear Materials in the Departments of Nuclear Engineering and Materials Science and Engineering at the University of Tennessee, Knoxville. Previously, he was chief scientist for the DOE Oak Ridge National Laboratory's (ORNL) Nuclear Science and Engineering Directorate and director of ORNL's Materials Science and Technology Division. Dr. Zinkle's research encompasses physical metallurgy and advanced manufacturing of structural materials and the investigation of radiation effects in ceramics and metallic alloys for fusion and fission energy systems. He is a member of the NAE. He received a Ph.D. in nuclear engineering from the University of Wisconsin, Madison.

D

Acronyms

AC	alternating current
AEPS	Advanced Electric Propulsion System
ANL	Argonne National Laboratory
B_4C	boron carbide
BeO	beryllium oxide
cercer	ceramic-ceramic
cermet	ceramic-metal
DARPA	Defense Advanced Research Projects Agency
DART	Double Asteroid Redirection Test
DC	direct current
DoD	Department of Defense
DOE	Department of Energy
EP	electric propulsion
FRC	field reversed configuration
FSP	Fission Surface Power program
HALEU	high assay low enriched uranium (i.e., uranium enriched to contain from between 5 and 20 percent uranium-235)
HEU	highly enriched uranium (i.e., uranium enriched to contain from more than 20 percent uranium-235)
I_{sp}	specific impulse
JIMO	Jupiter Icy Moons Orbiter

kWe	kilowatt-electric
LH_2	liquid hydrogen
LiH	lithium hydride
LOX	liquid oxygen
M&S	modeling and simulation
Mo	molybdenum
MPD	magnetoplasmadynamic
MWe	megawatt electric
MWt	megawatt thermal
NaK	sodium-potassium alloy
NbC	niobium carbide
NEP	nuclear electric propulsion
NERVA	Nuclear Engine for Rocket Vehicle Application program
NEXT-C	NASA's Evolutionary Xenon Thruster–Commercial
NextSTEP	Next Space Technologies for Exploration Partnerships
NSTAR	NASA Solar Technology Application Readiness
NTP	nuclear thermal propulsion
PMAD	power management and distribution
PMS	propellant management system
PPU	power processing unit
SEP	solar electric propulsion
SNAP	Systems for Nuclear Auxiliary Power
SNTP	Space Nuclear Thermal Propulsion program
Ta	tantalum
T_e	(reactor) exit temperature
TFE	thermionic fuel element
TOPAZ	Thermionic Operating Reactor Active Zone
UC	uranium carbide
UC_2	uranium dicarbide
UCO	uranium oxycarbide
UN	uranium nitride
UO_2	uranium dioxide
W	tungsten
WUO_2	tungsten uranium dioxide
ZPC	zero-power critical
ZrC	zirconium carbide
ZrH	zirconium hydride

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