NASA/TM-20210016968

Nuclear Power Concepts and Development Strategies for High-Power Electric Propulsion Missions to Mars

Lee S. Mason
National Aeronautics and Space Administration, Washington, DC

Steve R. Oleson and David T. Jacobson
Glenn Research Center, Cleveland, Ohio

Paul C. Schmitz
Power Computing Solutions, Inc., Avon Lake, Ohio

Lou Qualls, Michael Smith, Brian Ade, and Jorge Navarro
Oak Ridge National Laboratory, Oak Ridge, Tennessee

March 2022

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM-20210016968

Nuclear Power Concepts and Development Strategies for High-Power Electric Propulsion Missions to Mars

Lee S. Mason
National Aeronautics and Space Administration, Washington, DC

Steve R. Oleson and David T. Jacobson
Glenn Research Center, Cleveland, Ohio

Paul C. Schmitz
Power Computing Solutions, Inc., Avon Lake, Ohio

Lou Qualls, Michael Smith, Brian Ade, and Jorge Navarro
Oak Ridge National Laboratory, Oak Ridge, Tennessee

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

March 2022

Acknowledgments

This work was performed for the NASA Office of Strategic Engagement and Assessments under the Mars Transportation Assessment Study (MTAS). The authors wish to acknowledge the support of the MTAS Study Leads, Dr. Ave Kludze and Mr. Leonard Dudzinski, who provided outstanding leadership and direction throughout the study.

Level of Review: This material has been technically reviewed by technical management.

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Nuclear Power Concepts and Development Strategies for High-Power Electric Propulsion Missions to Mars

Lee S. Mason
National Aeronautics and Space Administration
Washington, DC 20546

Steve R. Oleson and David T. Jacobson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Paul C. Schmitz
Power Computing Solutions, Inc.
Avon Lake, Ohio 44012

Lou Qualls, Michael Smith, Brian Ade, and Jorge Navarro
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Summary

Under the Mars Transportation Assessment Study (MTAS), NASA and the Department of Energy are performing analyses and generating concepts for crewed nuclear electric propulsion (NEP) missions to Mars. This report presents the results of trade studies and concept development for the nuclear electric power system, consisting of the fission reactor, radiation shielding, power conversion, heat rejection, and power management and distribution (PMAD). The nuclear power team completed trade studies to evaluate different reactor and power conversion technologies and developed preliminary concepts for the crew shielding, waste heat radiators, and PMAD. The initial results suggest that a modified terrestrial microreactor combined with supercritical CO_2 Brayton conversion could be used to perform the crew and cargo missions with satisfactory performance and modest risk. The report includes preliminary development strategies that could bring the NEP technology to fruition for Mars missions in the late 2030s or early 2040s.

Mars NEP Mission Concept

Mission studies conducted by the NASA Glenn Research Center COMPASS Team identified the need for a 1.9-MWe power system to perform a 2-year round-trip crewed mission to Mars using a hybrid nuclear electric propulsion (NEP) and chemical propulsion architecture, as shown in Figure 1 (Ref. 1). The chemical stage uses two 15-klbf liquid oxygen and liquid methane (LOX/LCH_4) engines to perform the high-thrust burns at Earth departure, Mars capture, and Mars departure; The NEP stage performs the interplanetary transfers and Earth capture. The COMPASS studies evaluated multiple crewed mission opportunities spanning 2035 to 2042 that utilize a (1) low Earth orbit (LEO) aggregation orbit, (2) uncrewed LEO-to-near rectilinear halo orbit (NRHO) spiral where the NEP vehicle rendezvous with the deep space crew habitat, and (3) 760-day opposition-type round-trip mission that includes a 30-day Mars stay. Additional mission analysis indicated that a duplicate NEP stage, using the same 1.9-MWe nuclear power system and EP thrusters—but without the chemical propulsion—could perform precursor cargo missions delivering payloads of about 200 t to Mars after a LEO spiral and 535-day one-way Mars trip.

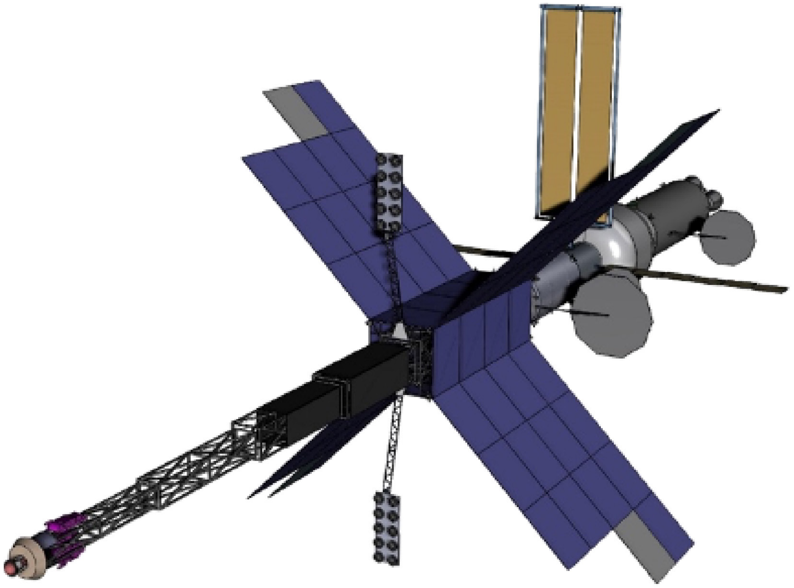


Figure 1.—Hybrid nuclear electric propulsion and chemical propulsion vehicle concept.

TABLE I.—COMPASS MISSION DESIGN CASES[a]

	2035 opposition	2039 opposition	2042 opposition		2035 crew conjunction	2039 crew conjunction	2037 cargo conjunction
Total trip time, d	760	760	760		1,058	1,047	535 (1-way)
Power to EP, MWe	1.8	1.8	1.8		1.8	1.8	1.8
Specific impulse, s	2,600	2,600	2,600		2,600	2,600	2,600
Mars parking orbit stay time, d	40	40	40		300	300	N/A
Dry NEP stage, t	75	75	75		75	75	75
Payload mass, t	45	45	45		45	45	3×65
Usable Xe, t	131	124	122		59	60	81
Usable LOX/LCH_4, t	139	187	180		25	38	0
Earth departure mass, t	418	460	448		226	240	346
No. of launches for NEP/chemical stage	2 SLS + 5 Starships				1 SLS + 2 Starships		1 SLS + 1 Starship

[a] All cases assume 1,200 K low-enriched uranium reactor with supercritical carbon dioxide Brayton conversion, 20×100 kWe Hall thrusters, lunar distant high Earth orbit (LDHEO) crew departure, 2-sol Mars parking orbit.

The COMPASS study mission design results are summarized in Table I. The mission studies considered crewed opposition missions in 2035, 2039, and 2042 using the same NEP and LOX/LCH_4 propulsion elements. That vehicle uses a 1.8-MWe array of EP thrusters (leaving 100 kWe for vehicle housekeeping loads) with a specific impulse of 2600 s to deliver the 45-t crew habitat to Mars and return the crew to Earth in 760 days. The Xe and LOX/LCH_4 propellant loads vary across the opportunities, but all the missions can be accomplished using a combination of two Space Launch System (SLS) launches and five Super Heavy commercial launch vehicles (CLVs) (e.g., Starship) fuel deliveries. The COMPASS team also evaluated 2035 and 2039 crewed conjunction missions that exceed the 2-year mission goal but increase the crew time at Mars from 40 to 300 days and decrease the Earth launch fleet. The final case shows an all-NEP cargo conjunction mission that can deliver up to 195 t to Mars in 535 days using a duplicate NEP stage as the one envisioned for the crew mission with only one SLS and one Super Heavy CLV tanker.

NEP Power System

The NEP power system consists of the reactor, shield, power conversion, heat rejection, and power management and distribution (PMAD) components. The reactor uses nuclear fission of uranium-235 to produce thermal energy. It also produces potentially harmful neutron and gamma radiation that must be attenuated by the shield to prevent damage to crew and equipment. The reactor's thermal energy is converted to electrical power by the power conversion subsystem. Because the conversion is less than 100 percent efficient, waste heat is generated that must be dissipated by the heat rejection subsystem. The PMAD subsystem provides the electrical interface to the vehicle by transmitting the power generated by the power conversion and modifying it as needed for the vehicle power loads. The PMAD also provides command and control for power system functions and operations.

Historical Review

Nuclear power systems for NEP applications have been studied extensively, dating back to 1955 when Ernst Stuhlinger published "Electric Propulsion System for Space Ships With Nuclear Power Source" in the Journal of the Astronautical Sciences (Ref. 2). In the late 1950s and 1960s, the U.S. Atomic Energy Commission developed both radioisotope and fission nuclear power sources under the Systems for Nuclear Auxiliary Power (SNAP) Program (Ref. 3). In 1965, the SNAP10A reactor was launched from Vandenberg Air Force Base as part of the U.S. Air Force SNAPSHOT mission, which included a 500-W reactor power system and a 400-W cesium ion thruster—the first and only NEP space flight mission performed by the United States. In the 1980s, the SP–100 Program, involving NASA, the Department of Energy (DOE), and the Strategic Defense Initiative Organization (SDIO), sought to develop a 2.5-MWt lithium-cooled, fast-spectrum reactor using 93-percent-enriched uranium nitride (UN) fuel pins with refractory alloy cladding coupled to SiGe thermoelectric conversion to produce 100 kWe net output (Ref. 4). Among the applications studied for SP–100 were EP missions for outer planet science and Mars. Although detailed designs were generated and considerable component testing was performed, the SP–100 system was never completed.

In the early 2000s, NEP was revisited under the Prometheus Program and the Jupiter Icy Moons Orbiter (JIMO) mission. That effort focused on 200-kWe-class fission power systems using either a lithium-cooled or gas-cooled reactor coupled to Brayton power converters (Ref. 5). It was an extremely challenging mission that included visits to the Jupiter moons of Callisto, Ganymede, and Europa with a mission life of approximately 20 years. NASA worked collaboratively on the power plant with DOE Naval Reactors, who performed detailed design studies that led to a reactor down-select decision (Ref. 6). A series of JIMO-related hardware tests were performed at NASA Glenn, including an integrated 2-kW Brayton-NSTAR ion thruster test, 50-kW Brayton PMAD testbed, 25-kW dual-Capstone Brayton test loop, long-duration Ti/H_2O heat pipe testing, large-scale composite radiator thermal-vacuum test, and numerous research and development (R&D) tasks on refractory alloys, superalloys, and high-speed gas bearings. The JIMO project was canceled in 2005 before any flight systems could be developed.

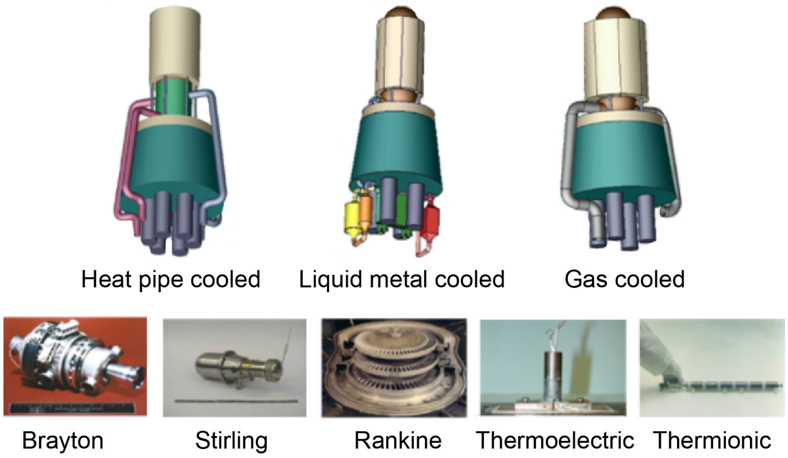
Beginning in 2010, NASA and DOE collaborated on small fission power systems as an alternative to radioisotope power systems under a Planetary Science Decadal Survey feasibility study (Ref. 7). Those studies eventually led to the Space Technology Mission Directorate (STMD) Kilopower project, which conducted a nuclear test of a 1-kW-class reactor prototype in 2018 with technology that is extensible to 10-kW systems and 50-kW missions (Ref. 8). Even though that is still a far distance from megawatt-class NEP, it represents a realistic and viable technology starting point.

MTAS NEP Power Concept

This report is focused on the NEP power concepts evaluated during the NASA Mars Transportation Assessment Study (MTAS). The reactor cooling method and power conversion choice are a major influence on system design and reliability. Figure 2 presents examples of the design space for reactor heat transfer and power conversion in nuclear fission systems. The three major primary heat transfer methods for space reactors are heat pipes, pumped liquid metal, and pumped gas. Heat pipes work on a passive two-phase evaporation-condensation cycle that requires no external power, whereas liquid metal or gas cooling requires drive pumps or compressors to circulate the fluid. The benefit of active cooling over passive heat pipes is flexibility in design and higher thermal throughput. Typical liquid metals used in pumped cooling loops are lithium, sodium, potassium, or a mixture of sodium and potassium (NaK). Gas-cooled systems have the option of directly coupling to a Brayton converter, simplifying the reactor heat transport. However, this leads to a single shared gas circuit for the reactor and power conversion, which impacts the system fault tolerance.

Among the power conversion options are Stirling, Brayton, and Rankine thermodynamic cycles, as well as thermoelectric and thermionic devices. Each option presents different characteristics on conversion efficiency and power throughput, and therefore on the system mass. On the low end of the efficiency scale, thermoelectric conversion has a long history of use in radioisotope power systems. However, the lower efficiency is a challenge for high-power fission systems because of the larger reactor, radiation shield, and waste heat radiator. The Stirling cycle has high efficiency but does not scale well to higher power. Brayton systems utilizing a mixture of helium and xenon (HeXe) fare better at higher power, but the lower heat rejection temperature results in a larger radiator. A supercritical CO_2 (SCO_2) (or perhaps other supercritical working fluid) Brayton system may perform better than the HeXe system, but that technology has been mainly focused on terrestrial applications. A potassium Rankine cycle has the potential for high efficiency and heat rejection temperature, but the two-phase system design is a challenge and the maturity is low.

Rejecting the power conversion waste heat represents a major design challenge. The vacuum of space requires radiative heat rejection, which is dependent on large, bulky radiators. In fact, the limiting design factor for the reactor power system in this study was the stowed radiator volume that could be accommodated in a single launch vehicle. Preliminary radiator stowage concepts have indicated a maximum radiator area of approximately 2,500 m^2 for the 8.4 m SLS fairing. The 2,500 m^2 radiator limit proved to be the primary design constraint in determining the maximum NEP power output.


Heat pipe cooled Liquid metal cooled Gas cooled

Brayton Stirling Rankine Thermoelectric Thermionic

Figure 2.—Potential reactor and power conversion options.

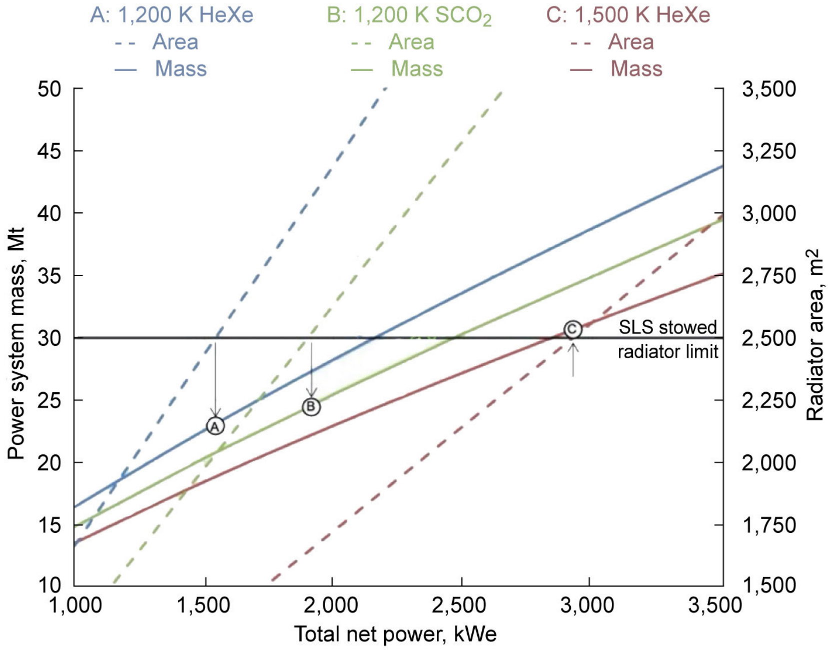


Figure 3.—Parametric system analysis for three different reactor-Brayton combinations, showing the maximum power outputs 1,600, 1,900, and 2,900 kWe for the three cases A, B, and C, respectively.

Figure 3 shows a parametric analysis of radiator area and system mass across a range of relevant power levels for three different reactor-Brayton combinations. System mass includes the reactor, shield, power conversion, heat rejection, and PMAD. Given the 2,500 m^2 SLS radiator limit, the 1,200 K HeXe case A permits 1,600 kWe maximum power output, the 1,200 K SCO_2 case B permits 1,900 kWe, and the 1,500 K HeXe case C permits 2,900 kWe. The 1,200 K SCO_2 case B was selected as the study reference, supplying 1,900 kWe with a total system mass under 25 t. Although the 1,500 K case may appear attractive from a performance standpoint, it introduces considerable development risk relative to the other two cases. The 1,500 K reactor would require a new fuel form and refractory alloy cladding and structural material beyond what was demonstrated during the SP–100 Program. It would also require new, higher temperature materials for the Brayton converters and radiators beyond the current experience base for those technologies.

Reactor and Shield Subsystems

The reactor concept in the parametric analysis above assumed a fast-neutron spectrum core with pin-type refractory-clad fuel using highly enriched uranium (HEU). The DOE Oak Ridge National Laboratory (ORNL) was added to the team to evaluate different reactor design options and fuel enrichment levels. They evaluated two reactor concepts: (1) a derivative of the SP–100 that is a fast-spectrum system using UN pin fuel with pumped Li primary heat transport and (2) a derivative of the transformational challenge reactor (TCR) that uses UN particle fuel in a solid SiC element with interspersed yttrium hydride (YH) moderator (Ref. 9). The TCR derivative could use either direct Brayton gas cooling or the primary Li loop, although the Li option was the preferred configuration for this study based on overall system reliability. Both the SP–100 and TCR reactor approaches were evaluated with HEU (93 percent enrichment) and high-assay low-enriched uranium (HALEU) (19.75 percent enrichment).

The ORNL reactor study assumed a thermal power of 10 MWt, coolant outlet temperature of 1,200 K, and operational life of 2 years at full power. The results showed the SP–100 HEU option to be the lightest mass reactor at approximately 2,400 kg including fuel, vessel, reflector, instrumentation and control, and Li primary loop. The LEU version of the fast-spectrum SP–100 reactor was found to be prohibitively heavy. The HEU TCR option with YH moderator had a similar reactor mass as the fast-spectrum HEU SP–100, but the larger reactor diameter resulted in a 70-percent increase in shield mass. The mass of the LEU TCR reactor with YH moderator was about twice the HEU version at 4,800 kg and required the heaviest shield because of the large reactor diameter. However, the total 3,500 kg mass increase (including the shield) for the LEU TCR option relative to the HEU SP–100 option did not significantly impact the mission design. According to U.S. space reactor policy, the use of HEU should be limited to applications for which the mission would not be viable with other nuclear fuels or nonnuclear power sources (Ref. 10). Thus, the LEU TCR reactor shown in Figure 4 was selected as the reference approach for the mission study, with the HEU SP–100 as the study alternative. The 10-MWt thermal power rating provides an approximately 40-percent thermal power margin at 1.9 MWe.

A key challenge for the reactor is to shield the mixed neutron and gamma radiation field. The amount of radiation is directly correlated to the thermal power and operating duration of the reactor, which adds an additional motivation for high power conversion efficiency. The need for shielding is driven by both electronic and materials tolerances as well as human dose limits for crewed missions. Low-atomic-number materials like hydrogen, beryllium, lithium, and boron provide efficient shielding for the neutron flux, and high-atomic-number materials like tungsten or depleted uranium effectively shield the gamma flux.

For this study, ORNL compared several design variants for their effectiveness in attenuating radiation at three key locations: (1) the Brayton units, (2) the PMAD electronics, and (3) the crew habitat. The starting point was a conical LiH/W shield with a 26° half angle that limited radiation to 25 krad and 1,011 n/cm^2 at 50 m from the reactor (at the PMAD electronics) after 2 years of reactor operation.

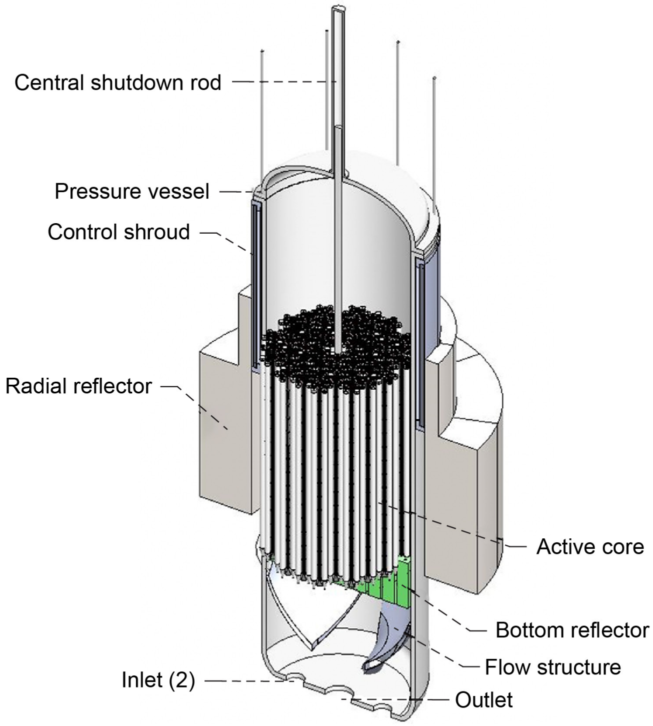


Figure 4.—Transformational challenge reactor-derivative reactor concept for NEP.

Further analysis revealed that this shield design was not sufficient for the crew habitat. Figure 5 presents the four shield configurations evaluated by ORNL. The LiH/W starting point assumed a constant shield thickness for the entire 26° half angle. The two compound shields assumed a thicker central section, or "plug," for increased protection of the vehicle centerline elements and crew habitat (within a 3° half angle). One of the compound shields assumed a combination of $Be/B_4C/LiH/W$, while the other assumed only LiH/W. The fourth shield option used LiH/W and retained the central plug but included cutouts in the perimeter to form a cruciform with four 26° extensions corresponding with the location of the radiator wings.

The desire to limit radiation at the crew habitat to 50 rem/yr became the driving requirement for shield mass. The ORNL analysis incorporated the benefits provided by the in-line Brayton engines, reactor boom, PMAD equipment, Xe propellant, and tanks in attenuating crew radiation. The mass comparison among the four configurations revealed that the full-thickness LiH/W shield was the heaviest at 13,800 kg, followed by the hybrid compound at 4,800 kg, the LiH/W compound at 3,500 kg, and the LiH/W compound cruciform at 2,800 kg. The compound cruciform was selected as the design reference, and the corresponding radiation flux maps are presented in Figure 6. This shield results in a total absorbed dose at the Brayton converters and PMAD electronics after 2 years of operation of 100 Mrad and 25 krad, respectively. The effective human dose at the forward external face of the crew habitat is 3 mrem/hr, corresponding to 100 rem in 2 years. The total mass of the reference HALEU reactor and crew-rated radiation shield is about 7,600 kg. The equivalent HEU version is about 4,100 kg.

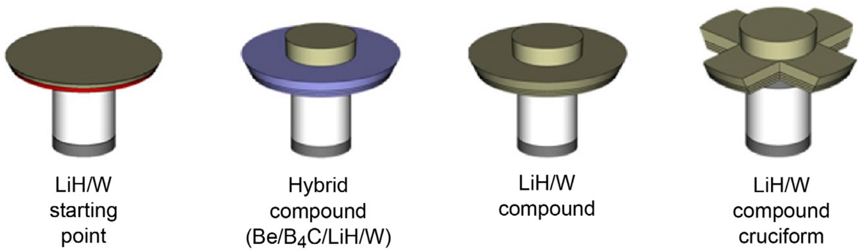


Figure 5.—Shield options evaluated for NEP system reactor shield.

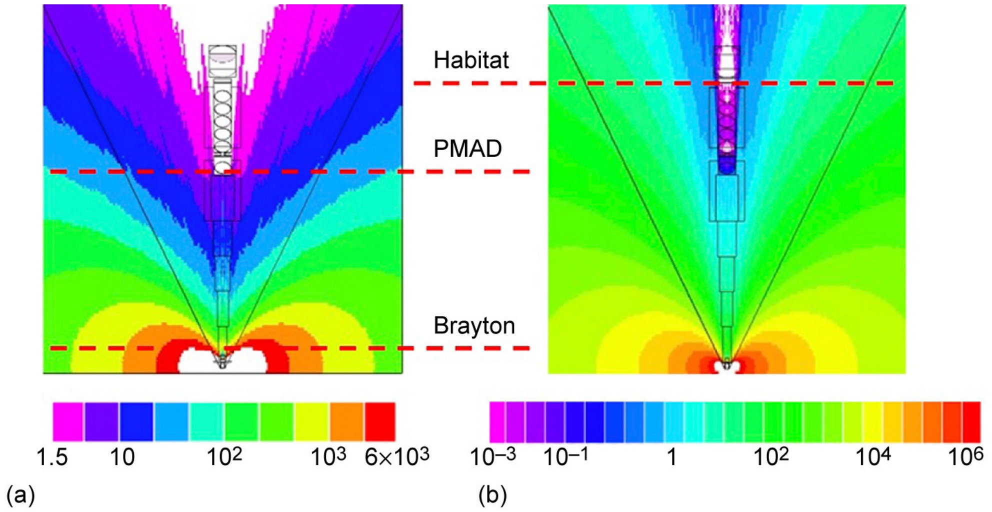


Figure 6.—Radiation flux map for compound cruciform shield. (a) Total absorbed dose (rad/hr) at PMAD electronics and Brayton converters. (b) Effective human dose (rem/hr) at crew habitat.

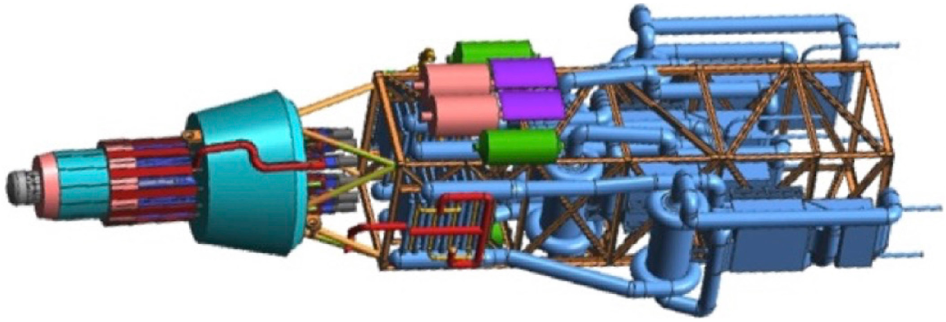


Figure 7.—NEP reactor: Brayton configuration.

Power Conversion Subsystem

The power conversion trade studies comparing HeXe and SCO_2 Brayton favored the SCO_2 option. The SCO_2 option yielded a ~20-percent increase in power output for the same total radiator area. The reference 1.9 MWe power system concept assumes four SCO_2 Brayton converters, each producing 25 percent of the total power, shown in Figure 7 coupled to the Li-cooled reactor through four liquid-to-gas heat exchangers. The use of a primary loop with separate heat exchangers permits the system to produce partial power should one or more Brayton units fail. Each Brayton unit includes a turboalternator-compressor, recuperator, and gas cooler. The development of a ~500-kWe-class Brayton unit is a significant scaleup from the experience base for HeXe Brayton technology, represented by the 10-kWe Brayton rotating unit (BRU), the 2-kWe mini-BRU, the 36-kWe converter for the Space Station Freedom Solar Dynamic Power Module, and the 100-kWe converter for the Prometheus/Jupiter Icy Moons Orbiter mission (Ref. 11). Legacy HeXe Brayton technology, with superalloy hot-side materials that permit turbine inlet temperatures up to 1,150 K, has undergone considerable NASA testing to demonstrate performance in relevant environments and for extended operating times (e.g., ~50,000 hr of BRU testing).

Conversely, SCO_2 Brayton development has focused on megawatt electric levels of power but has been mostly limited to terrestrial applications with systems that are not designed for space use (Ref. 12). If SCO_2 Brayton is pursued for Mars NEP, the emphasis will be on adapting high-power terrestrial technology and demonstrating performance in relevant environments. If HeXe Brayton is pursued, the emphasis will be on scaling the legacy technology to higher power levels. The four 500-kWe SCO_2 Brayton converters in the reference concept have a total mass of about 2,100 kg.

Heat Rejection Subsystem

The heat rejection subsystem (HRS) assumes each Brayton converter has a dedicated pumped-NaK cooling loop and a one-fourth segment radiator assembly. The NEP radiators would operate at temperatures between 375 and 550 K and reject about 4 MWt. This temperature regime was studied extensively during the Prometheus and Fission Surface Power projects. Technology development was completed on high-temperature Ti/H_2O heat pipes (both life testing and microgravity research), polymer-matrix composite (PMC) radiator panels (both subscale and full-scale thermal vacuum tests), and pumped NaK fluid loops (at temperatures up to 875 K) (Ref. 13). Leveraging those developments, the NEP radiators use PMC panels with embedded Ti/H_2O heat pipes. The 2,500-m^2 total NEP radiator surface comprises four radiator segments, each having 17 individual radiator panels (~4 by 5 m) that are coupled to the NaK coolant manifold, as shown in Figure 8. For comparison, the total radiator area of the pumped NH_3 External Active Thermal Control System (EATCS) employed on the International Space Station is about 1,200 m^2. The total mass of the NEP HRS concept is about 9,500 kg with 68 radiator panels at ~100 kg each.

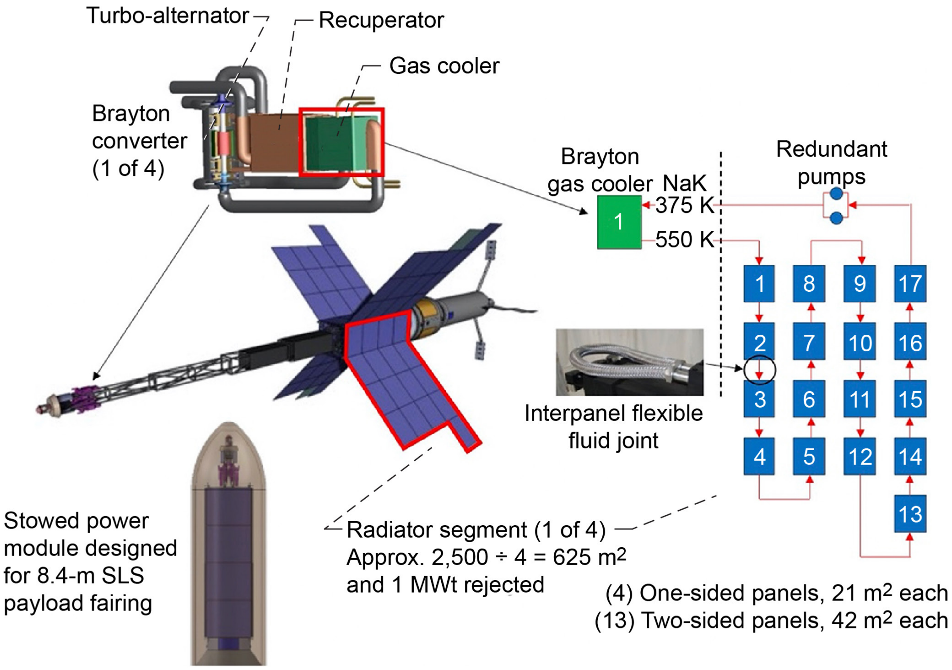


Figure 8.—NEP radiator configuration.

PMAD Subsystem

The NEP PMAD electrical schematic is shown in Figure 9. The four Brayton units produce high-frequency (~2.5 kHz) three-phase power at 960 Vac that is transmitted through cables to the PMAD electronics located 50 m away. The power system produces sufficient electric output to power the EP thrusters, spacecraft bus, and system parasitic loads. Each Brayton unit has a dedicated PMAD channel with a high-voltage alternating-current (AC) bus that feeds the 650-Vdc Hall thruster direct-drive units (DDUs) and the 120-Vdc spacecraft bus, using the appropriate voltage conversion stages. Brayton rotor speed control is accomplished via a pulse-width-modulated direct-current (DC) parasitic load radiator (PLR) that maintains a constant load on the alternator. The PLR is sized to reject the entire 500-kWe Brayton output (at 550 °C), allowing the Brayton units to operate at full power even if there are no external loads. The four PLRs (~30 m^2 each) are located on the perimeter of the truss sections that comprise the reactor boom. The spacecraft receives power from the Brayton units, but also supplies power for startup and control via batteries and solar arrays. Startup power is delivered to a start inverter that allows the Brayton units to be electrically motored. The spacecraft also feeds power to the PMAD controller-processor that manages system operations and distributes DC power to the auxiliary loads (pumps, drive motors, etc.). Each of the four PMAD channels includes a cold plate and dedicated thermal radiator (~20 m^2 each) that rejects 15 kWt (~3 percent) at 100 °C. The total PMAD mass for the four channels including cabling, electronics, and thermal management is about 5,800 kg.

NEP Power System Scaling Relationships

Figure 10 presents projections for the MTAS NEP power system specific mass and radiator area versus power level for the two design cases. At the current 1.9 MWe NEP design point, the power system specific mass is about 13 kg/kWe for the HALEU case and 11 kg/kWe for the HEU case. Either option can be employed to meet the proposed MTAS mission. The radiator area is fairly linear over the power range evaluated and is independent of fuel enrichment. Modest improvements in system specific mass can be realized with increased power output, but those are accompanied by fairly large increases in radiator area. Radiator sizes above 2,500 m^2 would require the radiator to be packaged in separate SLS launches with complex radiator assembly and fluid connections performed in space. Power regression specific mass curve fit equations are provided for both the HALEU and HEU power systems.

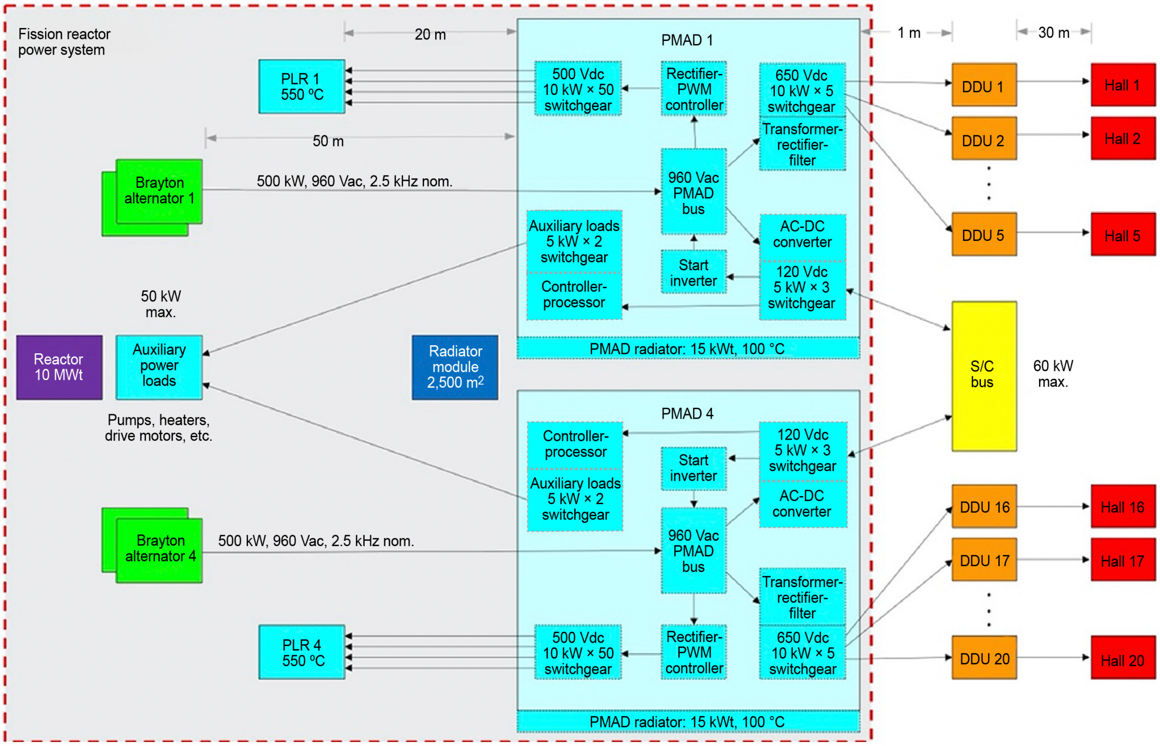


Figure 9.—NEP PMAD schematic. PLR is parasitic load radiator, DDU is direct drive unit, PWM is pulse-width modulated, S/C is spacecraft.

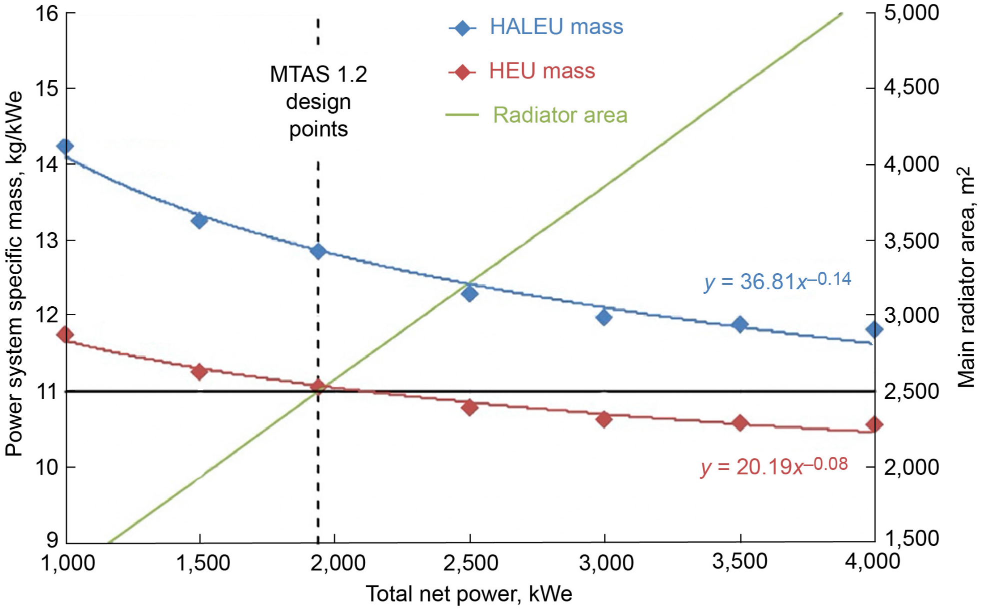


Figure 10.—1,200 K UN/Li and supercritical CO_2 Brayton NEP power system scaling relationships: highly enriched uranium (HEU) and high-assay low-enriched uranium (HALEU) specific mass and radiator area.

NEP Development Strategy

Current Technical Maturity

The proposed MTAS NEP power system has an overall starting technology readiness level (TRL) of 2 to 3 with the reference moderated HALEU reactor. The key challenges for the reference reactor is the development of a 1,200 K-suitable tristructural isotropic (TRISO) fuel form and stable, long-life hydride moderator materials as well as a responsive control system. A slightly higher starting TRL of 3 to 4 is projected for the system derived from HEU SP–100 based on the extensive reactor fuel testing performed during the SP–100 Program and the absence of the moderator in the fast-spectrum reactor design. The high-power NEP reactor would benefit significantly from infrastructure established and experience gained by flying a fission surface power system on the Moon first, regardless of the size or configuration differences.

The MTAS power conversion and PMAD subsystems are projected to have a starting TRL of 3 to 4. Brayton technology readiness is based on prior space system experience with HeXe systems in the 10- to 100-kWe class and current terrestrial experience with SCO_2 systems in the megawatt class. The primary challenge for HeXe Brayton systems is the power scaleup, whereas the challenge for SCO_2 Brayton systems is the required adaptation for space missions. The high-voltage, high-frequency AC PMAD architecture is a significant departure from the current state of the art for space vehicles, but it could leverage technology being developed for electrified aircraft and recent advances in SiC and GaN semiconductor devices. A starting TRL of 4 to 5 is projected for the HRS based on prior efforts under Prometheus to develop 500 K composite radiators with embedded Ti/H_2O heat pipes, prior experience with NaK heat transfer loops, and leveraging of the flight-proven packaging and deployment approach from the International Space Station pumped-ammonia radiators.

Preliminary Development Plan

A preliminary MTAS NEP development plan is presented in Figure 11. It consists of three major phases: technology maturation; design, development, test, and engineering (DDT&E): and flight system development. The first step is the development of detailed Government reference designs of the NEP reactor power system and EP system to inform hardware procurement efforts with industry. Although the MTAS concept studies provide a good starting point, they are not of sufficient fidelity to establish design requirements for an industry request for proposal (RFP).

The technology maturation phase would include three main elements: power and EP technology demonstration units (TDUs), reactor fuel characterization, and PMAD and DDU parts assessment. The power and EP TDUs will focus on representative-scale breadboard subsystems that could be combined for integrated system tests to advance the TRL. A nonnuclear power system TDU, shown in Figure 12, would integrate a 500-kWt reactor simulator, 1,200 K lithium primary loop, 100-kWe Brayton unit, 500 K NaK heat rejection loop, and two 40-m^2 radiator panels for a 1,000-hr performance test at the Glenn Vacuum Facility #6 (VF6). The power TDU would include an external 1,000-Vac PMAD assembly coupled to simulated 650-Vdc Hall thruster loads. Similarly, full-scale 100-kWe Hall thruster, 650-Vdc DDU, and xenon flow controller (XFC) breadboard test articles will be procured and tested at the Glenn Vacuum Facility #5 (VF5).

In parallel, the Department of Energy (DOE) would lead efforts to characterize and qualify the NEP reactor fuel and moderator through several test iterations. The DOE fuel development effort is envisioned to be similar to the Advanced Gas Reactor TRISO fuel qualification performed by Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), and BWX Technologies, Inc. (BWXT) with tasks for production, irradiation, postirradiation examination, and modeling (Ref. 14). The final element of the technology maturation phase is the electronic parts assessment for the PMAD and DDU. This activity will focus on a combination of radiation and thermal testing to evaluate high-voltage electronics with an emphasis on wide-band-gap devices using SiC or GaN materials. The technology maturation phase will conclude with the mission Preliminary Design Review (PDR) in year 4, at which time the majority of the power and EP technologies will have reached TRL 5.

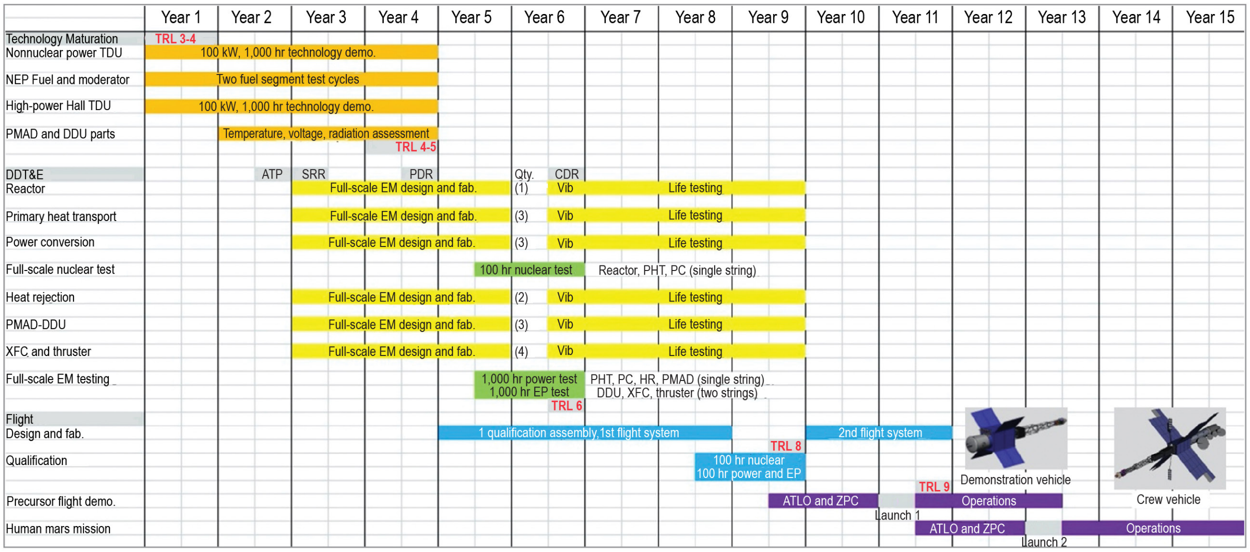


Figure 11.—Preliminary NEP power development plan.

ATLO	Assembly, Test, and Launch Operations	PC	power conversion
CDR	Critical Design Review	PHT	primary heat transport
DDU	direct drive unit	PMAD	power management and distribution
demo.	demonstration	SRR	System Requirements Review
EM	engineering model	TDU	technology demonstration unit
fab.	fabrication	Vib	launch vibration test
HR	heat rejection	XFC	xenon flow controller
PDR	Preliminary Design Review	ZPC	zero-power critical

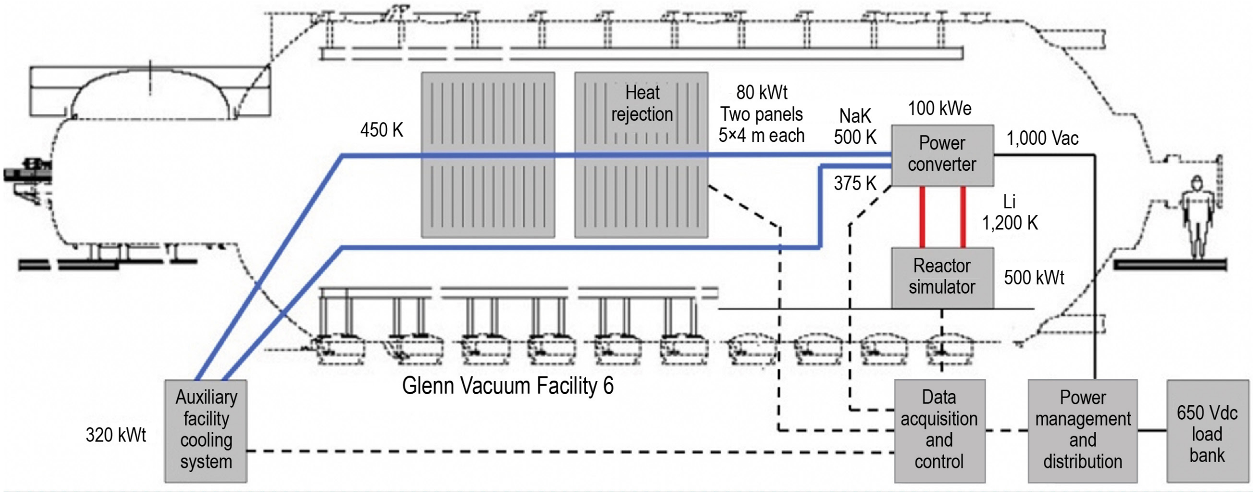


Figure 12.—Nonnuclear power technology demonstration unit (TDU).

The DDT&E phase of the NEP power plan starts with the mission System Requirements Review (SRR) in year 2. The design of full-scale engineering model (EM) subsystems will occur in parallel and be informed by the TDU testing. The plan is to build multiple full-scale EMs that would be used to support various test objectives. A complete full-scale power string will be assembled with a high-fidelity reactor simulator, single Brayton unit, heat rejection loop, and PMAD power channel for an integrated 1,000-hr nonnuclear system test, most likely in the Space Power Facility at NASA's Neil A. Armstrong Test Facility. A second set of EM units will be subjected to launch vibration environments and placed on long-duration tests to evaluate performance relative to the mission design life, currently estimated at about 27,000 hr for the power system and 23,000 hr for the EP system. A third Brayton unit will be supplied to the DOE reactor team for use in a full-scale 100-hr reactor prototype test to demonstrate nuclear performance. Candidate nuclear facilities to accommodate the reactor prototype test include the INL Experimental Breeder Reactor II facility and the Nevada National Security Site, U1A facility. Similar testing will be performed on full-scale EM thrusters, DDUs, and XFCs, culminating in an end-to-end performance verification test at the Glenn VF5. The three separate integrated tests of full-scale EM test articles (i.e., nonnuclear power string, reactor prototype, and EP string) combined with the subsystem launch vibration tests would provide critical data to support the mission Critical Design Review (CDR) and establish TRL6 for the key NEP elements by year 6.

The flight system development phase will include design, fabrication qualification, and acceptance testing of flight components. A full set of subsystem qualification hardware elements will be built and tested. The first complete set of flight components would be used for a NEP demonstration mission, possibly an all-NEP Mars cargo delivery mission that would precede the crew mission. That flight mission would validate the overall NEP propulsion stage performance in-space before a duplicate version would be used on the crew vehicle. The NEP demonstration vehicle would be assembled, and checkout testing of the power and EP elements would be performed using a reactor simulator. After checkout, the flight reactor would be integrated and a zero-power critical (ZPC) test would be performed to validate reactor neutronic performance before the demonstration vehicle launch in year 10. The second set of flight components will be fabricated and tested in parallel with the demonstration mission and readied for launch with the crew vehicle in year 13. Even though the proposed NEP development schedule in Figure 11 is presumed achievable, it is very aggressive and success oriented, with little margin for setbacks.

The proposed development test campaign is summarized in Table II. The combination of TDU, EM, and flight hardware ground testing provides the means to thoroughly verify the design prior to flight. The demonstration flight mission provides additional in-space operating experience to validate the stage performance prior to the crew use. The data presented in Table II summarizes the number of test and flight units that will be produced for each major subsystem as well as the cumulative operating time achieved at key junctures in the development timeline. A benefit of the proposed development approach is the leveraging of "shakedown" flights that occur before the crewed Mars mission. The current mission timeline includes three separate shakedown missions: a 6-month cargo vehicle spiral, a 535-day cargo vehicle transit, and a 14-month crew vehicle spiral—all occurring before the crew boards their Mars transit vehicle. The cumulative operating hours on test hardware prior to beginning crew vehicle flight hardware fabrication, relative to full mission life, is 1.2× for the reactor, 1.1× for the power subsystems, and 2.4× for the EP thrusters. The cumulative operating hours achieved prior to the crew boarding their Mars transit vehicle is over 2× for the reactor, about 5× for the power subsystems, and about 24× for the EP thrusters.

TABLE II.—NEP DEVELOPMENT TEST CAMPAIGN

Phase	Reactor	Brayton	Heat rejection subsystem	PMAD	EP
Technology maturation					
TDU nuclear fuel segment	2				
TDU nonnuclear performance units	1	1	1	1	3
TDU hours	1,000	1,000	1,000	1,000	1,000
Design, development, test, and engineering (DDT&E)					
EM nuclear units	1	1			
EM nuclear hours	100	100			
EM nonnuclear performance units	1	1	1	2	2
EM nonnuclear vibration/life units	1	1	1	1	2
EM nonnuclear hours	27,000	27,000	27,000	27,000	23,000
Flight					
Qualification nuclear units	1	1			
Qualification nuclear hours	100	100			
Qualification nonnuclear units	1	1	2	2	3
Qualification nonnuclear hours	1,000	1,000	1,000	1,000	1,000
Cargo mission flight units	1	4	4	4	20
Cargo acceptance hours	10	100	100	100	100
Cargo spiral hours	4,320	4,320	4,320	4,320	4,320
Cargo Mars transfer hours	12,840	12,840	12,840	12,840	9,630
Cargo total hours	17,170	17,260	17,260	17,260	14,050
Crew mission flight units	1	4	4	4	20
Crew acceptance hours	10	100	100	100	100
Crew spiral hours (without crew)	10,080	10,080	10,080	10,080	10,080
Crew Mars transfer hours	6,912	6,912	6,912	6,912	5,184
Crew Earth return hours	10,128	10,128	10,128	10,128	7,596
Crew total hours	27,130	27,220	27,220	27,220	22,960
SUMMARY					
Total test units	8	6	5	6	10
Total flight units	2	8	8	8	40
Cumulative hours before crew flight hardware fabrication	31,210	29,600	30,400	30,400	54,000
Ratio relative to crew mission hours	1.2×	1.1×	1.1×	1.1×	2.4×
Cumulative hours before crew flight	58,460	138,960	139,760	139,760	536,600
Ratio relative to crew mission hours	2.2×	5.1×	5.2×	5.2×	23.5×

NEP Roadmap

The MTAS NEP technology roadmap is presented in Figure 13. There is tremendous potential to leverage existing and funded projects, both internal and external to NASA, to jumpstart a Mars NEP technology effort. There are at least four ongoing activities that could provide relevant technology contributions to support a future Mars NEP capability.

(1) The first is the Advanced Electric Propulsion System (AEPS) development by STMD for solar electric propulsion (SEP) applications. AEPS plans to complete the development and flight qualification of 12-kW Hall thrusters for use on the Gateway power and propulsion element (PPE) in the early 2020s (Ref. 15). Proposals have already been submitted to the Game Changing Development Program to mature a derivative, 100-kW version of AEPS that could serve either SEP or NEP Mars missions in the future.

(2) Next, is the STMD Fission Surface Power (FSP) project, which is seeking to demonstrate a 10-kW-class fission power system on the lunar surface in the late 2020s. FSP provides a more straightforward first step for space reactors before embarking on a high-power NEP system. The more-complex, high-power NEP reactor would benefit from the testing infrastructure and community-of-practice that would be established for FSP, providing a means for the developers to gain confidence on a relatively simple first system. Specific benefits would include ground testing facilities, modeling techniques, launch processing experience, and most importantly the means to exercise the new launch safety approval process with a much simpler first system.

(3) The third activity that could contribute to NEP is the Aeronautics Research Mission Directorate (ARMD) Electrified Powertrain Flight Demonstration (EPFD) project, which plans to demonstrate megawatt-scale electric aircraft with high voltage power distribution in the mid-2020s (Ref. 16). There is great potential to share technology development on PMAD components between EPFD and NEP, given the similarity in power level and operating voltage.

(4) Finally, the DOE and DOD have numerous ongoing efforts related to terrestrial energy that could positively impact a NASA NEP initiative. Several key areas include megawatt-scale microreactors for off-grid power generation, mobile military reactors for forward operating bases (Pele), HALEU TRISO particle fuel production, and SCO_2 Brayton systems for high-efficiency solar power applications. There are several promising microreactors currently in development, including the Westinghouse eVinci^{TM} system, that provide a viable starting point for megawatt-scale space power reactors (Ref. 17). The DOE also has plans to demonstrate microreactor technology in the late 2020s under the Advanced Reactor Demonstration Program, having recently awarded contracts to Xenergy and Terrapower (Ref. 18). The ongoing SEP, FSP, electrified aircraft, and terrestrial energy activities can all contribute to reducing the risks, cost, and schedule of a Mars NEP development. In summary, a future Mars NEP capability is the logical extension of many existing efforts within NASA, DOE, and DOD.

Furthermore, the liquid oxygen and liquid methane (LOX/LCH_4) chemical propulsion stage needed for the hybrid NEP/chemical crew vehicle has similar requirements to those expected for the LOX/LCH_4 propulsion systems on lunar and Mars landers. This provides an excellent opportunity for shared development and potential use of duplicate systems.

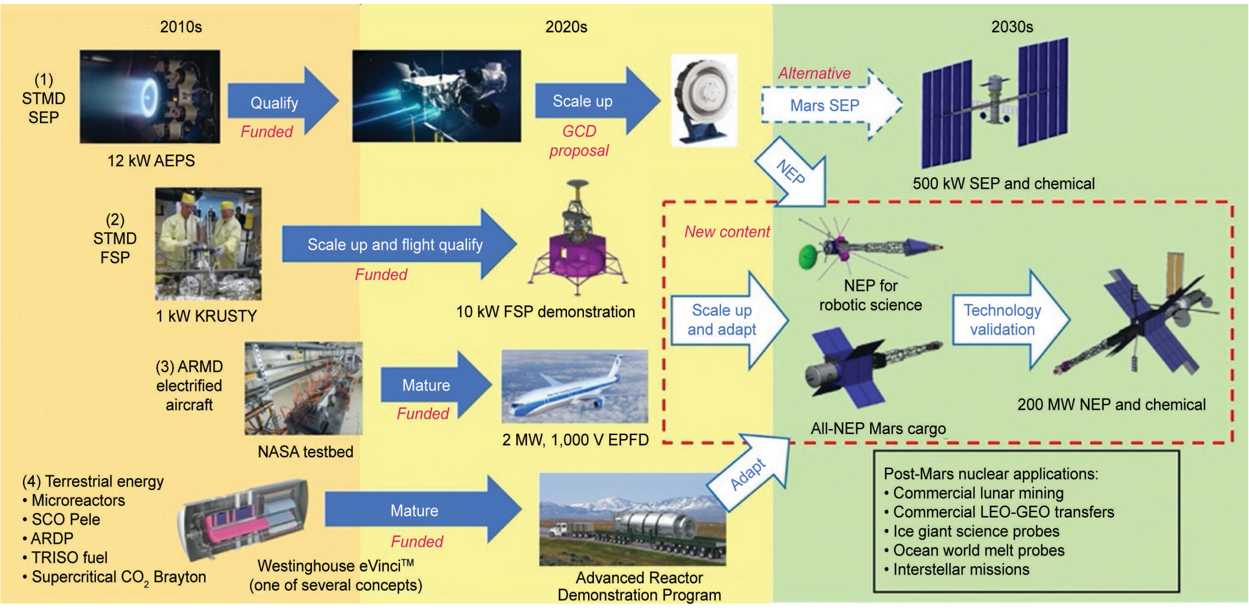


Figure 13.—NEP technology roadmap.

(1) Advanced Electric Propulsion System (AEPS) development by Space Technology Mission Directorate (STMD) for solar electric propulsion (SEP) applications. PPE is power and propulsion element and GCD is Game Changing Development.
(2) STMD Fission Surface Power (FSP) project; KRUSTY is Kilopower Reactor Using Stirling Technology.
(3) Aeronautics Research Mission Directorate (ARMD) Electrified Powertrain Flight Demonstration (EPFD) project.
(4) Department of Energy and Department of Defense terrestrial activities. SCO Pele refers to Strategic Capabilities Office Project Pele, ARDP is Advanced Reactor Demonstration Program, and TRISO is tristructural isotropic.

Conclusions

Trade studies and analyses were performed to produce a nuclear electric power system conceptual design suitable for 1.9-MWe crewed Mars nuclear electric propulsion (NEP) missions. The reference concept uses a modified Li-cooled terrestrial microreactor with high-assay low-enriched uranium (HALEU) fuel, LiH/W crew-rated radiation shield, supercritical CO_2 Brayton power conversion, pumped-NaK heat rejection with composite heat pipe radiators, and 960-Vac power management and distribution (PMAD). Key design drivers were the maximum radiator size that could be accommodated in the Space Launch System (SLS) fairing, the high-voltage EP electrical interface and the crew radiation dose. The reference concept has a total system mass of about 25,000 kg (~13 kg/kWe). The use of highly enriched uranium (HEU) for the reactor could reduce the system mass by 3,500 kg (14 percent).

The Mars NEP capability can be developed under a methodical and aggressive program that starts with technology maturation, transitions to engineering development, and culminates in a full-scale flight demonstration in about 10 years. The first flight could be used to deliver cargo to Mars in advance of the human mission that would come after. A duplicate version could be provided 3 years later to support an opposition-class crewed Mars mission. There is considerable and challenging new work needed for the megawatt-scale NEP systems proposed under the Mars Transportation Assessment Study (MTAS), but opportunities exist to leverage current funded activities by NASA, the Department of Energy (DOE), and the Department of Defense (DOD) that provide a strong starting foundation.

References

1. Oleson, Steven R., et al.: A Combined Nuclear Electric and Chemical Propulsion Vehicle Concept for Piloted Mars Opposition Class Missions. AIAA 2020–4055, 2020.
2. Stuhlinger, Ernst: Electrical Propulsion System for Space Ships With Nuclear Power Source. J. Astronaut. Sci., 1955. https://ia802801.us.archive.org/11/items/nasa_techdoc_19660081611/19660081611.pdf
3. Voss, Susan S.: SNAP Reactor Overview. AFWL–TN–84–14, 1984.
4. Mondt, Jack F.: Development Status of the SP–100 Power System. AIAA 89–2591, 1989.
5. Mason, Lee S.: A Power Conversion Concept for Jupiter Icy Moons Orbiter. NASA/TM—2003-212596, 2003. https://ntrs.nasa.gov
6. Ashcroft, J.; and Eshelman, C.: Summary of NR Program Prometheus Efforts. LM–05K188, 2006.
7. Mason, L. et al.: A Small Fission Power System for NASA Planetary Science Missions. NASA/TM—2011-217099 (NETS–2911–3318), 2011. https://ntrs.nasa.gov
8. Gibson, Marc A., et al.: Kilopower Reactor Using Stirling TechnologY (KRUSTY) Nuclear Ground Test Results and Lessons Learned. NASA/TM—2018-219941, 2018. https://ntrs.nasa.gov
9. Ade, B.J., et al.: Candidate Core Designs for the Transformational Challenge Reactor. Proceedings of PHYSOR 2020: Transition to a Scalable Nuclear Future, Cambridge, United Kingdom, 2020. Available at http://energy.gov/downloads/doe-public-access-plan.
10. Trump, Donald J.: Memorandum on the National Strategy for Space Nuclear Power and Propulsion (Space Policy Directive–6). Presidential Memoranda, The White House, 2020. Space Policy Directive-6 Accessed March 1, 2022.
11. Mason, Lee S.: Dynamic Energy Conversion: Vital Technology for Space Nuclear Power. J. Aerosp. Eng., vol. 26, no. 2, 2013.
12. Wright, Steven A., et al.: Operation and Analysis of a Supercritical CO_2 Brayton Cycle. Sandia National Laboratories Report SAND2010–0171, 2010. https://www.osti.gov/servlets/purl/984129 Accessed March 1, 2022.
13. Sanzi, James L.; and Jaworske, Donald A.: Heat Pipes and Heat Rejection Component Testing at NASA Glenn Research Center. NASA/TM—2012-217205 (NETS–2011–3497), 2012.
14. Electric Power Research Institute: Uranium Oxycarbide (UCO) Tristructural Isotopic (TRISO) Coated Particle Fuel Performance. Topical Report EPRI–AR–1(NP), 2019.
15. Jackson, Jerry, et al.: 13kW Advanced Electric Propulsion Flight System Development and Qualification. Presented at the 36th Electric Propulsion Conference, Vienna, Austria, 2019.
16. Jansen, Ralph: Electrified Powertrain Flight Demonstration Project (EPFD) Technical Measures of Effectiveness. NASA EPFD–02–06, 2020.
17. Arafat, Yasir; and Van Wyk, Jurie: eVinci™ Micro Reactor. Nucl. Plant J., 2019, pp. 34–37.
18. U.S. Department of Energy Office of Nuclear Energy: Advanced Reactor Demonstration Program. https://www.energy.gov/ne/advanced-reactor-demonstration-program Accessed Oct. 29, 2021.