



# **NASA Utilization of Space Nuclear Systems for Robotic and Human Exploration Missions**

Response to EO 13972: Promoting Small Nuclear Reactors for National Defense and Space Exploration



*July 2022*

## Executive Summary

Space Nuclear Systems (SNS) technology development offers a wide range of capabilities to support NASA's current and future missions. Executive Order (EO) 13972, "Promoting Small Modular Reactors for National Defense and Space Exploration" [1], issued 5 January 2021, directs NASA to define requirements for NASA utilization of nuclear energy systems for human and robotic exploration missions through 2040 and analyze the costs and benefits of such requirements." Although it is premature to define requirements and cost for future exploration missions that have not yet been formulated, this report describes planned objectives and missions by 2040 that are enabled or enhanced by nuclear systems while taking into account a number of unique considerations for nuclear energy in the space environment. Nuclear energy systems are enabling for space missions and critical capabilities where conventional forms of energy production are impractical or impossible due to mass constraints, mission duration, or distance from the Sun.

Space nuclear technologies available or in development for use by 2040 utilize radioisotope decay or nuclear fission and fall into three categories: heat, power, and propulsion. Current applications utilize radioisotope power systems that provide consistent and reliable performance in the sub-kilowatt power range. More advanced SNS can enable new mission objectives where high-energy density solutions are critical or where access to solar solutions is prohibitive. Higher power radioisotope and fission systems are under development within NASA for a wide variety of human exploration and science mission applications. Planned missions designed to use radioisotope systems include Dragonfly, a rotorcraft that will explore the surface of Titan, and Persephone, a mission concept for a Pluto orbiter. Nuclear fission systems have the key advantage of providing significantly higher power, lower mass solutions from tens to even thousands of kilowatts (kW). Fission power is enabling a sustained human presence on the Moon and developing a robust lunar economy. Fission propulsion is enabling for missions within and beyond cislunar space.

This report examines NASA-envisioned mission applications and associated performance needs for SNS over the next twenty years leading to 2040 along with the unique technical considerations posed by space nuclear technology development. This includes engineering and operational logistics for ground handling, thermal management, survival of the space environment, operational safety, power requirements, and service longevity. Safety to the public, the NASA workforce, and Agency assets remain a top priority for NASA, and particular attention is given to this aspect in the design, hardware assembly, ground operation, launch, and mission operation of an SNS. NASA relies on the Department of Energy as nuclear authority and its legacy of rigorous safety procedures as standards for ground development, test, transportation, and launch site operation. The principal concern is preventing unintended radiological release to the public or environment. Radioisotope system experience has established processes, including ground operation, transportation, and launch, that are considered directly applicable to emerging fission systems; however, fission systems have unique design needs that impact safety and performance requirements.

High-efficiency power conversion from both fission and radioisotope systems requires high-operating temperatures necessitating both passive and active thermal management to maintain safe and nominal operating conditions. Effective cooling and waste heat rejection have special considerations for space applications, whether in zero-g or reduced gravity. Fluid and heat transfer within the reactor system is not anticipated to be impacted by reduced or zero-g environments. Cryogenic working fluids and propellant supplies utilized in some space nuclear applications will need low-mass, high-capacity cryocoolers to meet the long-term storage and near zero-boiloff needs. Integrated, high-power density SNS capable of being packaged in a single vehicle is a key consideration for NASA. Due to concerns for complexity and reliability, in-space reactor assembly and reactor refueling are not current design considerations.

Expanding into a new era for space exploration depends on mass-efficient, high-energy solutions to power deep space vehicles, operate in harsh environments, and increase mission flexibility. NASA nuclear technology investments are targeting power for surface operations and propulsion for fast-transit, deep space missions, all with the ability to reliably operate without the need for repair or refueling. NASA's goals, enabled by nuclear technologies, provide for exciting advances in scientific objectives and human exploration, ushering in a new space age that enables a human presence on bodies beyond Earth.

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## 1. Introduction

The first United States (U.S.) spacecraft powered with nuclear energy was launched into orbit by the U.S. Navy on June 29, 1961, by the Atomic Energy Commission, predecessor to the Department of Energy (DOE). Powered by a radioisotope thermoelectric generator (RTG), the Transit 4A satellite served the U.S. Navy as a navigation system. With proven reliability and longevity, RTGs have been the standard for six decades of nuclear-enabled space exploration. RTGs have powered thirty missions from NASA's first successful launch and use of space nuclear power during Nimbus III, through the many planetary missions within our solar system and Voyager's traverse beyond our heliosphere into interstellar space, to NASA's recently launched mission, Mars 2020 Perseverance Rover. These missions are shown in Figure 1-1.

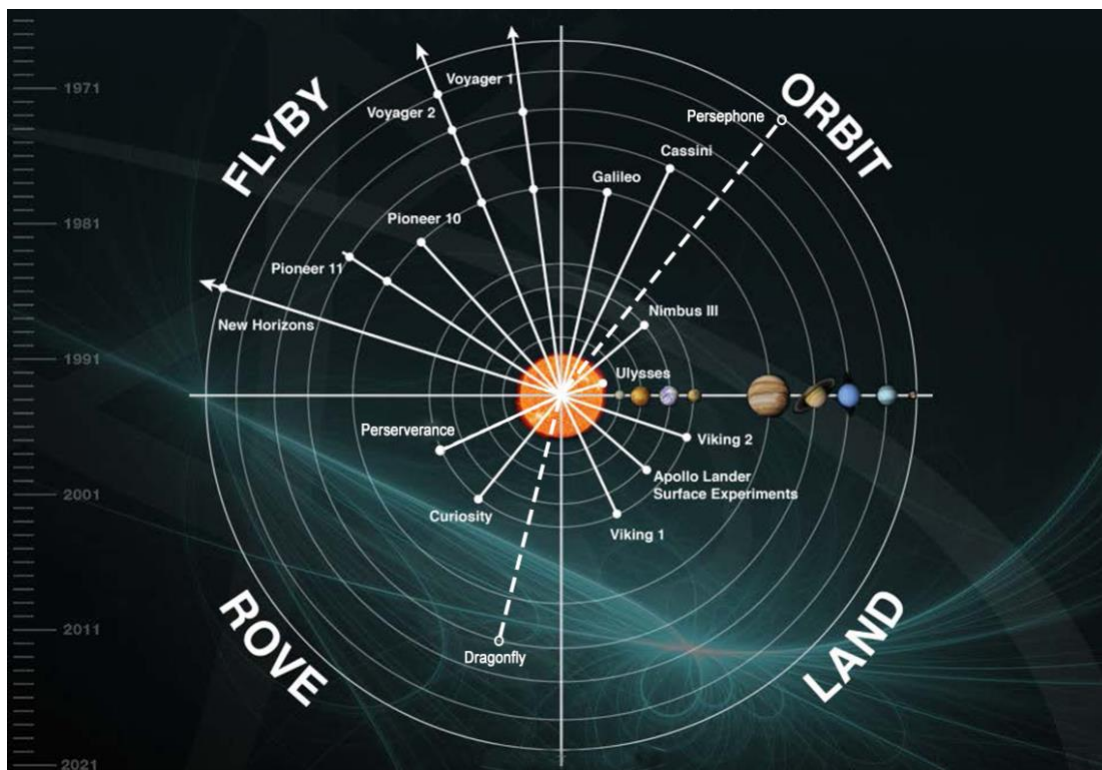


Figure 1-1: Over 60 years of RPS missions.

In addition to radioisotope power systems (RPS), the Systems for Nuclear Auxiliary Power 10A (SNAP-10A), part of the Space Nuclear Auxiliary Power Shot (SNAPSHOT) program, was launched on April 3, 1965, as the world's first nuclear reactor in space. It was also the first nuclear electric propulsion (NEP) system, as the reactor powered an ion thruster system in orbit. SNAP-10A remains the only fission power reactor launched by the U.S. [2]. During this time, NASA was also developing nuclear thermal propulsion (NTP) rocket engines through the Nuclear Engine for Rocket Vehicle Application (NERVA) program. While no NTP engines have been launched into space, NASA tested numerous reactors and engines with varying levels of capability from 1959 to 1972. Reactor and engine concepts were tested at partial and full power with multiple restarts and performance levels. Systems were tested with thrust levels up to 250,000 pound-force (lbf), maximum cumulative burn times of about 100 minutes, specific impulse ( $I_{sp}$ ) over 800 s, and peak fuel temperatures up to 2,750 Kelvin (K) [3, 4].

Recently, nuclear applications for space have been receiving increasing attention and funding and NASA looks to enhance existing capabilities to achieve additional scientific objectives as well as develop new technologies that would enable never-before achieved feats such as long-duration human lunar missions and possible crewed missions to Mars. Various policy updates have focused the Nation's nuclear technology research and development efforts. A primary driving force is the National Strategy for Space Nuclear Power and Propulsion's (SNPP) Space Policy Directive (SPD)-6 issued on December 16, 2020,

which laid the policy and directed the development of a roadmap for the Nation's plan to develop SNPP technology with a focus on safety, security, and sustainability. Additional guidance has been developed through National Security Presidential Memorandum 20 (NSPM-20), issued on August 20, 2019, which established new regulations for launches with spacecraft containing nuclear systems allowing for alternative approval authorities, "based upon the characteristics of the system, the level of potential hazard, and national security considerations" [5]. SPD-6 and NSPM-20 provide a path forward to bolster NASA's space nuclear developments. In addition, NASA has shifted to a greater emphasis on low-enriched uranium (LEU) nuclear systems. These systems contain uranium enriched below 20 percent making them non-weapons grade, eliminating non-proliferation concerns, and reducing security requirements. These policies and priorities enable a pathway for nongovernment space nuclear development and launches, increasing competition to promote innovation and cost reduction.

NASA's portfolio of projects that may employ nuclear technologies include both science and human exploration missions. A new Planetary Science and Astrobiology Decadal Survey (2023-2032) is in development and will prioritize scientific missions to be achieved within the next decade, many of which may use existing or new nuclear systems for space power, heat, and eventually propulsion [6]. Human space exploration will include NASA's Artemis program, a series of increasingly complex missions that will enable human exploration farther into the solar system than ever before. NASA plans to send humans—including the first woman and first person of color—to the Moon, the first crewed lunar mission since 1972. By the end of the decade, NASA intends to put an outpost called the Gateway into the Moon's orbit, providing essential support for sustainable, long-term human return to the lunar surface and to serve as a staging point for other deep space exploration [7]. These objectives will be enabled through the use of advanced nuclear power and will be a stepping-stone for space nuclear propulsion systems.

*"Nuclear power has opened the solar system to exploration, allowing us to observe and understand dark, distant planetary bodies that would otherwise be unreachable. And we're just getting started," said Dr. Thomas Zurbuchen, Associate Administrator for NASA's Science Mission Directorate. "Future nuclear power and propulsion systems will help revolutionize our understanding of the solar system and beyond and play a crucial role in enabling long-term human missions to the Moon and Mars" [17].*

This report has been prepared in response to Executive Order (EO) 13972, "Promoting Small Modular Reactors for National Defense and Space Exploration" [1], issued January 5, 2021. It discusses development programs for space nuclear heat, power, and propulsion systems and presents existing capabilities, planned objectives, and missions by 2040 that are enabled or enhanced by nuclear systems. While the report does not assess the cost of developing and implementing space nuclear capabilities, it does address the benefits of those capabilities while taking into account a number of unique considerations for nuclear energy in the space environment.

The information presented in this report includes input from NASA's Space Technology Mission Directorate, Exploration Systems Development Mission Directorate, Science Mission Directorate, the Office of Safety and Mission Assurance, and contributions from the DOE. This report should not be viewed as constituting NASA policy or prioritizations, though it may form a basis for high-level planning for NASA space nuclear technologies. Any requirements are subject to change in response to updates or changes to NASA official direction and subject to available funding.

## 2. NASA Space Nuclear Systems

Nuclear technologies offer many advantages for aerospace applications. The primary interests for NASA include higher energy density systems and greater propellant efficiency. The energy density of a system is the amount of energy available per unit mass. Nuclear reactions inherently produce millions of times more energy than chemical reactions, thus their technological systems offer considerably higher energy density values. This attribute can decrease the total spacecraft mass or enable more payload, such as life support systems for astronauts or science payloads to an outer planet, for the same total mass. Greater propellant efficiency means propellant mass is more efficiently converted into thrust supporting larger payload delivery to other planets, as well as reduced trip times. Nuclear systems also provide the ability to operate in harsh environments or where solar or chemical energy is impractical or impossible.

The primary source of energy throughout the solar system is the Sun, and the vast majority of space systems harvest solar energy for heat and electrical power generation. However, solar technology options are limited or infeasible when: 1) the Sun's energy is reduced or unavailable, 2) planetary or space weather covers or damages solar panels, or 3) mission operations call for higher power than solar technologies can provide. Table 1 lists mission concepts for which solar technologies are limited.

*Table 1. Limitations on Solar Technologies for Space Applications [8]*

<b>Mission Concept</b>	<b>Limitation on Solar Technologies</b>
Outer planetary missions beyond Saturn	Limited performance capabilities at low solar irradiance and low-temperature environments, increased risk of asteroid damage, and reduced maneuverability.
Low-altitude Venus aerial and surface missions	Limited capabilities at high temperatures, high/low solar irradiance, and corrosive environments.
Long-duration and/or high latitude Mars surface solar-powered missions	Dust accumulation on solar arrays and potential for obstructed deployment by surface landscape and boulders.
High-power, solar electric propulsion missions to small bodies and outer planets	Low intensity, low temperature environments require solar arrays that are heavy and bulky significantly decreasing maneuverability and increasing risk of asteroid impact damage.
Earth's Moon: Night time or during solar eclipse	Limited or no access to the Sun for up to 14 days, potential for obstructed deployment by surface landscape and boulders.

Additionally, current, and near-term state of the art (SoA) solar technologies are limited to 30 to 40 percent maximum efficiency and degrade over time [9, 10]. These considerations indicate that solar power is an impractical option for high power, especially with increasing distance from the Sun, due to increases in size, mass, complexity of structure and deployment, and cost of the system. Chemical power sources, such as fuel cells or batteries, may provide much larger amounts of power for a limited time until recharged; however, the current (SoA) technologies' mass becomes prohibitive. For these reasons, nuclear power options may be required to enable mission objectives.

Key NASA space nuclear technologies include the various heat, power, and propulsion technologies shown in Figure 2-1. The sections that follow present a high-level summary of each of these nuclear technologies, including an overall system description, benefits of the nuclear technology over alternative systems, potential NASA reference missions, and the performance goals required to achieve those missions. While both radioisotope and fission system capabilities have target applications for power and propulsion, an intended primary use for fission to keep hardware and electronics warm is not a practical consideration. There are many other missions that may utilize nuclear systems by 2040 included in the current and upcoming decadal survey; these reference missions are intended to represent a snapshot of the capabilities and projected future use cases.

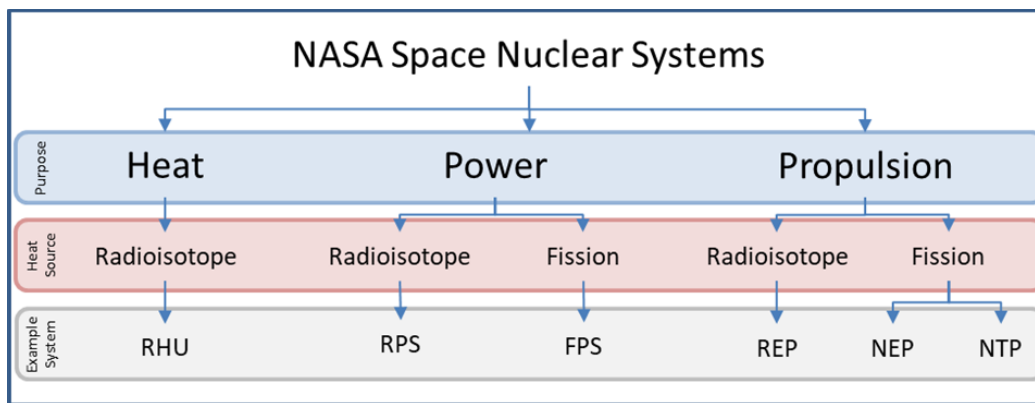


Figure 2-1: Taxonomy of space nuclear systems.

EO 13972 requested that NASA respond to nine unique technical considerations posed by space nuclear technologies.

1. transportability of a reactor prior to and after deployment.
2. thermal management in a reduced- or zero-gravity environment in a vacuum or near-vacuum.
3. fluid transfer within reactor systems in a reduced- or zero-gravity environment.
4. reactor size and mass that can be launched from Earth and assembled in space.
5. cooling of nuclear reactors in space.
6. electric power requirements.
7. space safety rating to enable operations as part of human space exploration missions.
8. period of time for which a reactor can operate without refueling.
9. conditioning of reactor components for use in the space environment.

Sections 2.1. through 2.3. address considerations that are technology dependent, including thermal management, cooling, operational life, sizing, and power. Additional technical considerations called out in the EO that are relatively independent of technology are addressed in Section 3.

**Thermal Management and Cooling:** Nuclear heat systems use conduction and radiation to directly transfer their thermal energy to nearby systems. Convection is not effective in zero-g. Waste heat must be rejected into space via radiation to maintain thermal dynamic efficiencies and provide proper cooling for the nuclear heat source.

**Operational Life:** Space nuclear systems are currently designed for a specific lifetime, with additional margin, without the need for replacement of the nuclear fuel referred to as refueling. Refueling frequently occurs for terrestrial fission reactor systems, but in-space nuclear refueling capabilities are not anticipated to be a design consideration. To meet desired lifetime requirements for space nuclear reactors, fuels will need to be carefully designed to meet the power density, temperature, and endurance requirements of a mission.

**Sizing:** Mass is a top consideration for any space system due to its correlation to mission cost and constraints imposed by launch vehicles for mass delivery. Launch vehicle volume constraints also impact considerations for large components such as radiators and propellant storage. If a system is too large for a single launch vehicle, it will require in-space assembly.

**Power:** Electric power is a key performance parameter that is established by NASA to meet identified mission goals. Power requirements will vary significantly depending on the mission objectives. Current and projected power capabilities produced by nuclear systems are covered in Section 2.2.

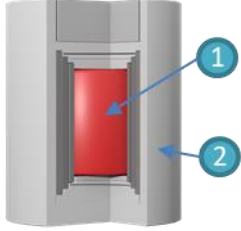
## 2.1. Nuclear Systems for Heat

Nuclear systems that focus on generating heat are primarily provided by radioisotope heater units (RHUs) due to their simplicity, reliability, and compactness. RHUs have enabled several missions accomplishing many 'firsts' for NASA, such as the first visit to Jupiter with Pioneer 10, the first spacecraft to reach



interstellar space with Voyager 1, and the first spacecraft to land on Mars and study the Martian soil with the Mars Sojourner Rover [11, 12, 13].

### 2.1.1. Radioisotope Heater Units

<b>Description</b>	 <p>(1) HEAT SOURCE: Decay (Pu-238) (2) PROTECTIVE LAYERS</p>
Radioisotope heater system that provides heat for in-space and surface systems on both robotic and crewed missions.	
<b>State of the Art</b>	
<b>Status:</b> In-Use (>300 flown)	
<b>Qualified Lifetime:</b> 10-15 years	
<b>Thermal Power Generated:</b> 1 W <sub>t</sub> (LWRHU) [14]	
<b>Performance Goals by 2040</b>	
No reference missions planned prior to 2040 require increased performance of the heat units.	
<b>Projected Missions by 2040</b>	
No missions utilizing RHUs for heat by 2040 have been fully defined by NASA.	
Some potential missions include those to the ice giants: Uranus Orbiter, Neptune Orbiter, and Lunar Surface Science Missions.	

#### Overview

RHUs consist of two primary components: a nuclear heat source and its outer protective layers to maintain safety for personnel and the environment if there were to be a launch failure or inadvertent re-entry. Heat is generated through the natural radioisotope decay of Plutonium-238 (Pu-238). The current generation of RHU, the light-weight radioisotope heater unit (LWRHU), is well-developed and has been used on many robotic spacecraft applications in the past. No major technology advancements are planned for RHU systems, but existing technology may be used on future science missions.

#### Benefits

RHUs enable spacecraft to operate in locations where other heat sources are insufficient to maintain a safe operating temperature, such as locations with limited or reduced access to solar energy. RHUs are very low mass and size, modular, and provide consistent heat output irrespective of the availability of solar energy. These characteristics allow designers to address heat requirements with a low impact to the overall spacecraft mass.

RHUs have a passive design with no moving parts, making them simple and reliable; they do not require electrical power. “NASA uses the LWRHUs for warming critical components, instrumentation, lubricating fluids, and thruster fuel during planetary space exploration missions and some Earth-orbiting missions” [2]. “RHUs also provide the added benefit of reducing potential interference (electromagnetic interference) with instruments or electronics that might be generated by electrical heating systems” [14].

#### Energy Transfer

LWRHUs emit approximately 1 watt (W) of heat from the natural decay of Pu- 238 [14]. While this is a fixed thermal output without the ability to cycle on and off as with fission systems, the amount of thermal energy is small enough that no intentional cooling is required. All heat is either directly used to conductively warm the spacecraft component it is mounted to or radiated into space.

#### Operational Life

The power level of an LWRHU is quite consistent over the useful life due to the stable decrease of heat output by 0.787 percent each year. RHUs will continue to operate as long as nuclear material remains.

On a spacecraft utilizing an RHU for heat, the spacecraft will shut down when the operating temperature drops below the operating range. NASA does not envision the need for additional development of higher power RHUs by the 2040 timeframe.

## Sizing

Current LWRHUs are sized to emit 1 W<sub>t</sub> to allow for precise spot heating of the spacecraft. These LWRHUs are approximately 40 grams and the physical size of a size C battery, with a plutonium pellet about the size of a standard pencil eraser [14] as shown in Figure 2-2. LWRHUs are modular and the number of LWRHUs implemented can be tailored to the thermal management needs of an individual spacecraft.

## Technology Development

While technology developments for RHUs is not an envisioned need for planned missions, availability of the Pu-238 material is important. The supply of Pu-238 was cited as a “challenge” or “risk” to space exploration needing radioisotope power by the Vision and Voyages for Planetary Science in the Decade 2013-2022 due to the low inventory and long lead time for new supply [15]. (RPSs similarly utilize Pu-238.) Since the publication of the decadal survey in 2011, “NASA and the DOE have established a long-term relationship where NASA will fund the establishment and maintenance of a constant production line for Pu-238. This arrangement reduces mission risk by maintaining a qualified workforce and targeting equipment investments across the production chain” [16]. Under the current Constant Rate Production (CRP) model, NASA is now funding DOE to produce new Pu-238 and process it into heat sources, at an annual rate to meet expected need. The availability of Pu-238 is no longer an issue.



Figure 2-2: RHU size

*“The fuel pellet in an RHU, inside the small metallic cylinder at bottom center in this image, is about the size of a pencil eraser” [14].*

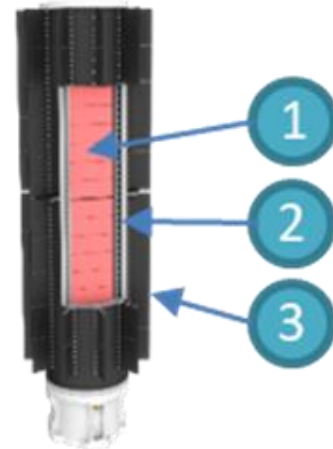
## 2.2. Nuclear Systems for Power

Historically, NASA has used and developed RPSs in support of robotic space exploration missions. Radioisotope-powered systems have been utilized since the 1960s with the first use by the U.S. Navy in 1961 on Transit 4A [17]. NASA has successfully used RTG systems since Nimbus III in 1969. RTGs enabled Viking 1 to send back the first photograph of Mars’ surface, Cassini to enter Saturn’s orbit, and New Horizons to visit Pluto. Each of these milestones would not have been possible at that time without nuclear technologies. NASA has ongoing efforts to develop and improve RPS system capabilities for current and future needs.

Fission power systems (FPS) are also under development within NASA for higher power requirements. To date, the only power reactor that has been launched into space by the U.S. is the SNAP 10-A reactor, but NASA aims to utilize fission systems for lunar surface operations under the Artemis campaign. Advances to these systems are envisioned to have application for other planetary missions.

## 2.2.1. Radioisotope Power System

<b>Description</b>	
RPSs are utilized to generate heat and power for space and surface mission on both robotic and crewed missions.	
<b>State of the Art</b>	
<b>Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)</b>	
Status: In-Use	
Qualified Lifetime: 17 years (14 years in flight and 3 years fueled in storage on the ground before flight).	
Total Heat Generated: 2,000 W <sub>t</sub>	
Power Generated: 110 W <sub>e</sub> at beginning of life	
Conversion Efficiency: 6.2%	
References: [18] [19] [20]	
<b>Dynamic Radioisotope Power System (DRPS)</b>	
Status: In Development (estimated launch availability 2030 [21])	
<b>Performance Goals by 2040</b>	
<b>Next Generation Radioisotope Thermoelectric Generator Mod 2 goals</b>	
Lifetime: 17 years (14 years in flight + 3 years fueled in storage on the ground before flight).	
Power Generated: ~400W <sub>e</sub> at beginning of life	
Conversion Efficiency: 10% at Beginning of Life	
<b>Dynamic Radioisotope Power System (DRPS)</b>	
Lifetime: 17 years (By 2030)	
Power Generation: Developments for 1 W <sub>e</sub> and 300-400 W <sub>e</sub> (By 2030)	
Conversion Efficiency: 20-25%	
References: [19] [20] [21, 22] [23]	
<b>Projected Missions by 2040</b>	
<b>Radioisotope Thermoelectric Generator</b>	
Planetary surface applications (Dragonfly)	
Deep space robotic missions (Persephone)	
Lunar surface applications	
Science applications such as SESAME ice penetration	
<b>Dynamic Radioisotope Power System</b>	
Lunar Resource Prospector	
Deep Space Missions, REP	



(1) HEAT SOURCE: Decay (Pu-238)  
 (2) POWER CONVERSION: Static or Dynamic  
 (3) HEAT REMOVAL: Radiator Fins

### Overview

RPSs utilize the natural heat generated by the radioisotope decay of Pu-238 to create electric power. They broadly contain three major components: the nuclear heat source, power conversion system, and radiator fins for excess heat removal to space.

**Heat Source:** The general-purpose heat source (GPHS) is a standardized heat module for all current and currently planned RPSs. “Each GPHS is a block about four by four by two inches in size, weighing approximately 3.5 pounds. (1.5 kilograms (kg)). They are nominally designed to produce 250 watts (thermal power) at the beginning of a mission” and can be used modularly [24].

**Power Conversion System:** RPSs are generally categorized by their power conversion method as either static (requiring no moving parts) or dynamic. Static RTGs typically use thermoelectric power conversion

utilizing the Seebeck effect to directly convert heat into electricity through a temperature gradient between two materials. Practical limits of RTGs are about 400 watts. Dynamic radioisotope power systems (DRPS) convert power using a thermodynamic engine. Concepts using Brayton and Stirling cycles are currently under development. All DRPS under consideration offer the potential of significantly increased conversion efficiencies that could reduce the amount of fuel needed to produce the same amount of power.

**Heat Rejection:** RPSs do not generate enough waste heat to require active heat rejection systems. Conductive radiator fins are the baseline solution for all RPSs. Additional thermal management such as insulation may also be required to prevent a negative impact to the environment, which may be a concern for missions to the surface of an icy world, where melting or sublimation of ice is to be prevented.

### Benefits

As a radioisotope-based system, RPSs provide consistent and stable power with a long operational lifetime regardless of its location throughout space. Radioisotope systems offer advantages to cislunar and inner planet missions due to a reduced vehicle footprint and inherent ability to operate closer to the Sun where irradiation and high external temperatures impose performance limitations for solar arrays systems. The specific power of RPS systems also improves relative to solar powered systems as the distance from the Sun increases, as shown in Figure 2-3. Thus, for deep space missions to Saturn or beyond, solar-powered systems become larger, heavier, and less effective making RPS systems both cost and mass enabling.

RPS systems are more compact, lightweight, and transportable than comparable fission systems up to about 5-10 kW<sub>e</sub>. Thus, RPSs are beneficial for lunar surface missions required to survive the lunar night. RPSs also produce more benign and less intense radiation for spacecraft systems and allow for human operations in close proximity with minimal shielding.

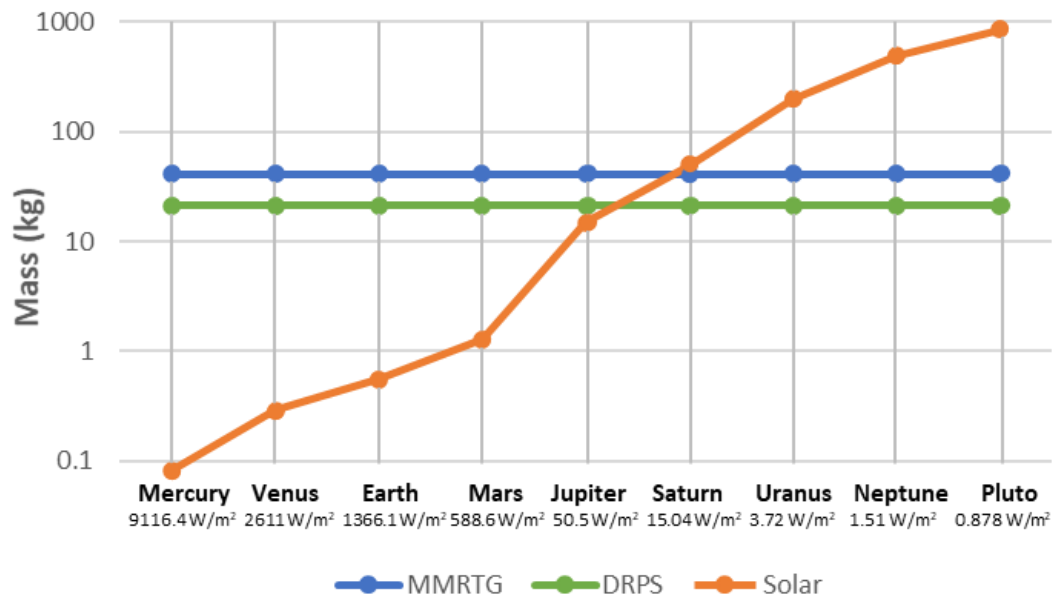


Figure 2-3: Comparison of solar and RPS masses for a 100 W<sub>e</sub> system. [8] [20]

### Energy Conversion

The efficiency of an RPS depends on the ability to maximize the heat utilized through power conversion, thereby minimizing the heat wasted. As a static process, thermoelectric generators are much simpler but are fundamentally limited to conversion efficiencies below 15 percent [25] and current SoA is below seven percent. The thermodynamic cycles in DRPS will be able to achieve efficiencies “on the order of three to four times greater than the current state of the art RTG” [26]. The performance goal is >20 percent efficiency, but up to 40 percent conversion efficiency has been demonstrated to date [27]. Besides generating power, RPS waste heat can be used as a utility to maintain proper operating temperatures of an onboard system in the cold space environment or dissipated into space through the radiator fins.

### ***Operational Life***

All RPSs are currently designed to have a 17-year life cycle which includes three years for vehicle assembly and storage on Earth and 14 years for flight operations [28] [20]. In practice, operational lifetime can be much longer as demonstrated by the RTGs on Voyager 1 and 2, which were launched in 1977 and are still operating at the time of this report [13]. RTGs require no moving parts and will continue to generate power as long as the supporting systems operate. As heat emitted from the Pu-238 fuel decreases, power levels will reduce, impacting the ability for the spacecraft's systems to continue operating. The fuel lifetime for a DRPS system will be essentially the same as an RTG as they both utilize Pu-238. However, DRPS systems are dynamic, and the total system lifetime may end up being limited by another aspect of the system yet to be determined. Other key system components for a RPS system, such as the radiator and power conversion systems, must be capable of extended lifetime through advanced material selection and technology maturation.

### ***Sizing***

The size of an RPS generally scales with power and conversion efficiency. Historical RTGs have ranged from the 2.7- $W_e$  SNAP-3B used on the U.S. Navy's Transit 4A, which was only 0.121-meter diameter and 0.14-m high and weighed a total of 2.1 kg, through to the GPHS-RTG, sized for approximately 300  $W_e$  and measuring 0.422-m diameter, 1.14-m high, and weighing approximately 56 kg [29] [30]. The increased efficiencies of DRPSs will enable even greater specific power and are estimated to reach between 8-10 W/kg [25], thereby reducing mass and size and/or allowing for higher power capacity for the same mass. RPSs must be considered in the overall spacecraft system design and mass budget but are not likely to drive additional launches or in-space assembly.

### ***Technology Development***

Advancing the SoA in RTG technology is an active pursuit. Advancements in thermoelectric generator technologies and changes to NASA's power needs has led to several RTG designs over a 60-year history of U.S. space nuclear power systems. NASA's current capability, called the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), generates about 110 W of electrical power and weighs less than 45 kg. MMRTGs currently power both the Curiosity and Perseverance rovers on Mars and will be used for Dragonfly. MMRTG thermoelectric conversion efficiency is about 6.2 percent at beginning of life, but degrades slightly each year, which limits long-term missions.

Overall, thermoelectric generators are considered simple, reliable, and lightweight, but conversion efficiency limits the electric power output. While the conversion efficiency of past thermoelectric technology, such as Silicon-Germanium (SiGe) used in the GPHS-RTG, has approached seven percent, NASA's Next-generation RTG (NGRTG) project seeks to increase this value further to support increased mission capabilities.

In March 2021, NASA established the current development path for NGRTG. When it was determined that current advances in thermoelectric technology were not mature for flight development and performance was not significantly better than SiGe, NASA revised the NGRTG project to pursue a reacquisition of the GPHS-RTG. Figure 2-4 depicts the revised path, which delivers two flight systems in 80 percent of the time, at half the cost, and less risk, while meeting the original NGRTG performance objective [21].

Research is also under way to understand the need for heat rejection methods for spacecraft and power systems operating in such environments as icy ocean worlds. “The largest science risk when using an RPS on an Ocean Worlds lander is altering, losing, or destroying traces of volatile compounds and biosignatures preserved in these ancient, low-temperature environments.” This creates an additional consideration for missions to places such as Europa and Enceladus due to the planetary protection requirements, which would require a system to prevent melting the surface ice and introducing a viable organism into a body of liquid water [28]. This challenge drives the need for high efficiency to reduce waste heat, which can be accomplished with dynamic power conversion.

While DRPSs are still in development, research in dynamic power conversion for radioisotope generators has been ongoing for decades, including the notable Advanced Stirling Radioisotope Generator (ASRG) concept, which was canceled in 2013 due to budget challenges [31]. Individual components and supporting technologies require advancement for a complete DRPS design. These include converter technologies, the controller, and insulation. In addition to the technology itself, ground support equipment, including for moving, storing, fueling, and testing a DRPS unit will need to be tailored. The dynamic system has unique characteristics compared with RTGs [32] [33].

Research is also under way to develop effective ways to utilize LWRHUs to produce a few watts of electric power for the purpose of powering “small sensor packages and repeaters for use in deep space and other areas where solar power is unfeasible” [34].

Finally, as was mentioned in the RHU section, Pu-238 availability has been noted as a potential challenge and is being addressed by NASA and the DOE.

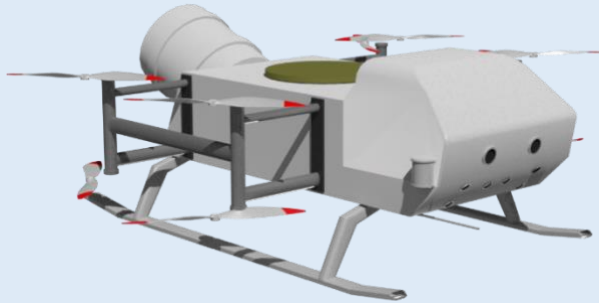
#### **Future RTG Mission**

One of the missions planned for RTG systems is a rotorcraft mission called Dragonfly. The mission’s primary goal is to “explore the chemistry and habitability of multiple surface sites covering a large area” on Saturn’s moon, Titan [35]. Nominal power is supplied to the dual-quadcopter drone by an MMRTG that is used to repeatedly charge a lithium-ion battery. On a single battery charge, Dragonfly will be capable of flying for approximately 30 minutes and cover distances up to roughly 10 kilometers (km) [36]. Because Titan’s atmospheric temperature is 94 K, Dragonfly’s RTG also provides sustained heat for the system.



*Figure 2-4: Current Development Path for RPS Program*

## DRAGONFLY



**Objective:** Robotic Rotorcraft Mission on Titan

**Time Frame:** 2027 launch, Titan arrival by 2034

**Mission Duration:** ~11 years (~980 days for science phase)

**Nominal Power:** 70 W

**Distance Covered:** up to ~10 km per flight

**Speed:** 10 meters/second (m/s)

**Max Altitude:** 4 km

**Key Benefits:** Operations designed for the Titan environment, regional mobility, data return, heat source

References [35] [36] [37] [20]

Dragonfly's MMRTG enables robotic rotorcraft missions on the surface of Titan powering a rechargeable lithium-ion battery, facilitating the exploration and study of multiple locations, and consistent communication relay.

### Reference DRPS Mission

The Lunar Geophysical Network (LGN) is a NASA concept that will provide a global, long-lived network of geophysical instruments on the Moon's surface in order to understand the nature and evolution of the lunar interior from the crust to the core. An LGN concept study published in 2015 considered the use of an ASRG, "enabling a small, reduced mass lander configuration with adequate power for the cruise and landing phases of mission operation, including continuous operations (day and night) on the lunar surface" [38]. The 2015 study compared ASRG with fuel cells, solar/battery, and a small RPS. The ASRG provided higher power with lower mass than the solar/battery option and was able to perform for the entire mission duration, unlike fuel cells.

The LGN reference mission is illustrated below to demonstrate the potential to enhance a missions' capabilities and objectives utilizing a dynamic RPS. The LGN mission was designed to utilize an ASRG at the time it was in development and enabled the mission because the ASRG was significantly less mass than the alternative solar power with energy storage and used a quarter of the Pu-238 needed to power a network of at least four landers versus an MMRTG.

## LUNAR GEOPHYSICAL NETWORK



**Objective:** "A global, long-lived network of geophysical instruments on the surface of the Moon to understand the nature and evolution of the lunar interior from the crust to the core"

**Time Frame:** 2030

**Mission Duration:** 6 – 10 years

**Nominal Power:** 144 W EOL (day), 122.5 W EOL (night)

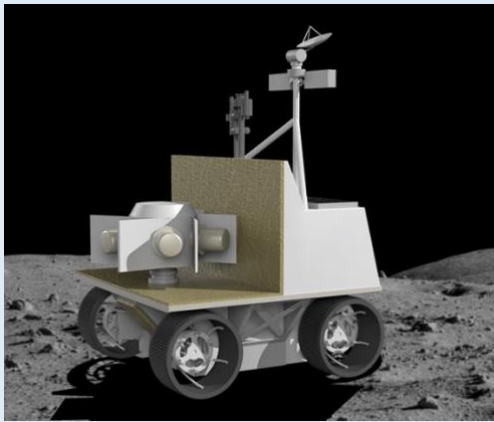
**Key Benefits:** Operates through the 15.5-day lunar night

References [38] [39]

This concept's ASRG is a lower mass system and provides higher power than a solar powered system with a battery or fuel cell. The ASRG provides power for the full duration of the mission compared to a fuel cell alternative. Fuel cells cannot support a six-year mission [38].

Additional concepts utilizing RPS, including DRPS, are under development and being considered for the 2023-2032 decadal survey. One such concept is a lunar resource prospecting mission that considers NASA's Volatiles Investigating Polar Exploration mission goals, which are being accomplished by a rover equipped with a DRPS for power instead of a solar and battery configuration. A DRPS will enable the rover to operate "through lunar night and in permanently shadowed regions where water will most likely be located" [40]. The higher power conversion efficiency of DRPS results in about 75 percent less waste heat, which could affect the condensed volatiles. The DRPS may also increase "science and range by [more than 5 times] during baseline mission duration of 18 months [due to the constant power from the RPS]" [40].

## DRPS PERMANENTLY SHADOWED REGION ROVER



**Objective:** A robotic lunar rover concept employing a DRPS that, like VIPER, explores the lunar South Pole in search of water ice.

**Time Frame:** 2030

**Mission Duration:** 18 months

**Nominal Power:** 330 W<sub>e</sub>

**Key Benefits:** Operates through lunar night and in permanently shadowed regions where water will most likely be located. Reduced waste heat, which could affect condensed volatiles. Increases science and range by >5X during baseline mission duration of 18 months.

References [40]

A DRPS enables the lunar rover to greatly expand the exploration of resources in the Lunar Polar compared with a solar and battery powered rover as it does not require access to solar power [40].

### 2.2.2. Fission Power System

#### Description

Fission power source for robotic spacecraft, rovers, surface transportation, human habitats, and ISRU.

#### State of the Art

**Status:** In development.

NASA and DOE research on Kilopower passed ground tests at that simulated start-up, steady-state operation at full power for 28 hours, and shutdown, for a 10-kW<sub>e</sub> class reactor design [41]. SNAP-10A in 1965 is the only fission power system ever launched by the U.S.

#### Performance Goals by 2040

**Operational Lifetime:** >10 years

**Power Generation:** 1,000 – 40,000 W (electric)

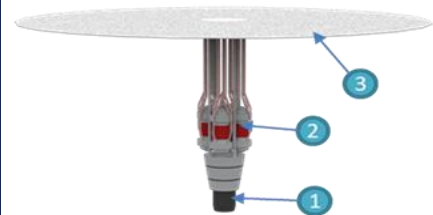
**Conversion Efficiency:** 25%

#### Projected Missions through 2040+

Lunar Surface Power Element (Artemis)

Martian Surface Power Element

Scientific Exploration Subsurface Access Mechanism for Europa



(1) **HEAT SOURCE:** Fission (U-235)  
 (2) **POWER CONVERSION:** Dynamic  
 (3) **HEAT REMOVAL:** Radiator Panels



## Overview

FPSs consist of a reactor, a power conversion system, and a heat rejection system. They are envisioned as a mission enabling capability for space and planetary surface operations where the power demand reaches tens to hundreds of kW<sub>e</sub>. The only historical example is the SNAP-10A reactor system, which was designed to produce 500 W<sub>e</sub> and operated in space for 43 days before a nonnuclear component failure ended operations [42].

**Reactor:** The FPS reactor design generates heat energy through fission events in the uranium-based fuel. The reactor system includes coolant flow channels (i.e., pumped flow, heat pipe), instrumentation and control, and radiation shielding to protect the spacecraft, crew, and critical system components. Fission heat is transferred to the electrical power conversion working fluid (such as a helium-xenon gas mixture) either directly or through a heat exchanger with the reactor coolant (such as liquid metals like sodium in a heat pipe for current SoA designs).

**Power Conversion System:** Thermal energy from the reactor system is transported to the power conversion system to generate electrical power. To maximize the efficiency of this process, advanced power cycles can be used to convert the heat into electric power, including Stirling and Brayton closed cycles with efficiencies approaching 30 percent or more.

**Heat Rejection System:** Planetary and space applications are limited on methods for heat removal from the FSP. Waste heat from the power conversion system must be removed from the system because FPS designs are operated on a closed cycle. To remove heat on the kW scale, a network of high-performance radiator panels transfers the heat from the system to the surrounding environment through radiative heat transfer.

## Benefits

An advantage for FPSs in space is the ability to provide multi-kilowatt power levels continuously in harsh environments for long periods without the need to refuel or rely on outside energy sources. FPSs offer utility in applications where solar energy is limited, including lunar and deep space applications, and require a smaller footprint than a solar power system providing equivalent power. These designs are capable of providing significantly higher electrical power levels at higher energy densities when compared with radioisotope power systems. The simple design of an FPS allows for modularity and extensibility to a wide range of electric power levels from a few kilowatts to megawatts to meet mission objectives. A single FPS design can support enough power for almost any robotic mission while a 40kW<sub>e</sub> unit would provide sufficient power for a crewed habitat, in-situ resource utilization (ISRU), and large-scale exploration of the planetary surface [43]. Multiple units can also be used to increase reliability, redundancy, and reduce down-mass per unit. Given its compact design, FPSs potentially decrease the required launch mass to provide equivalent power when compared with solar energy sources.

## Energy Conversion

Similar to DRPSs, the heat generated by the nuclear source is dynamically converted to electric energy through a Brayton or Stirling power conversion system. However, due to the significantly greater amounts of heat generated by the fission reactor compared with the radioisotope GPHSSs, the corresponding power conversion and heat rejection systems must be scaled accordingly. For Stirling converters, conductive heat plates in contact with the radioisotope heat source are generally replaced with heat pipes to transfer heat from a remote reactor. These are commonly proposed due to their perceived capability to enhance system safety and autonomy. Brayton power conversion systems are considered for larger power systems above about 10 kilowatts and may use either heat pipes or high-temperature coolants, such as sodium or NaK, to direct the energy to the power converter. Typical working fluids for both Brayton and Stirling include noble gas mixtures such as helium-xenon. While these systems operate at high temperatures, a large fraction (~75 percent) of the total heat produced by the reactor is not converted to electricity and must be rejected to the surrounding environment using radiator fins or paneling. Radiator geometry and performance directly impact the mass and efficiency of the entire FPS. A breakdown of the FPS critical components is seen in Figure 2-5.

### Operational Life

The stability of FPSs makes them well matched to power human and robotic outposts on the Moon and Mars because of their ability to operate continuously in harsh environments. Current mission objectives for lunar and Martian operational surface power reactors are aiming for at least a ten-year lifetime [44]. To reach this design metric, FPSs operate at an optimal thermal power level to minimize energy output from the fissionable material. Reactor structural materials, fuels, and moderator materials must be designed to retain performance over long-duration irradiations at high operating temperatures. Beyond the reactor, the key system components, including the radiator and power conversion system, must be capable of extended lifetime through advanced material selection and technology maturation. Material resilience to space debris still needs to be examined and researched for the potential failures, but risk mitigations will be simpler in execution than the more complex systems.

### Sizing

Compared with terrestrial nuclear reactors, FPS designs are considered extremely small. At the same time, due to their increased power levels and more complicated reactor systems, FPSs are significantly larger than RPSs. A reference 10 kW<sub>e</sub> fission surface power system design reaches 4 m tall deployed, with the reactor design and shielding mass between 1500 and 2100 kg depending on the fuel enrichment [45]. To reduce the required launch volume, the radiator paneling is capable of being retracted into a compact cylinder, as seen in Figure 2-5. In this launch configuration, systems will be less than 5 m in height and 1 m in diameter. Fortunately, even at the upper limits of the mass and size range, FPSs do not approach the design limits of current launch vehicles and payload fairings.

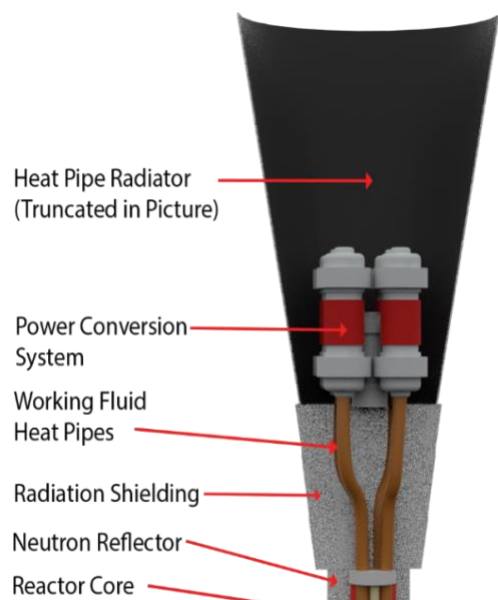


Figure 2-5: Example FPS cutaway design schematic.

### Technology Development

To improve technology readiness level (TRL) prior to in-space system demonstration, development efforts related to proposed FPS designs will focus on manufacturing techniques for key subsystems and testing to demonstrate that components are capable of enabling the desired mission performance metrics. The critical test for any space nuclear fission system is to demonstrate the reactor can be

controlled autonomously and maintain safe operation throughout a range of conditions and potential anomalies. The FPS will need to produce uninterrupted electrical power output given its environment conditions and provide a compact, low-mass system. Major decisions prior to a demonstration mission will also involve a down selection of fuel form, working fluid, and control systems to enable desired performance and safety margins. Extensive research into advanced Earth-based power reactors, especially for nuclear fuels and materials, may reduce the associated risks with modern FPS. Collaboration with the DOE, Department of Defense (DOD), and industry entities that focus on advanced nuclear technology will promote the maturation of terrestrial and FPS designs.

While the operating temperature for the reactor and power conversion in FPS (1200 to 1500 K) is lower than NTP systems, these temperature conditions are significantly higher than the current terrestrial reactor fleet. Temperature is driven up to achieve desired system efficiency and reduce the required heat rejection size. Advancements to modern power conversion systems to these higher temperatures will be required to increase the TRL of the FPS design space. FPSs for lunar and planetary habitats are currently designed to reject heat on the kW scale. Studies are considering different radiator geometry options and total surface area to optimize heat transfer and system mass. Studies have shown that two-dimensional planar radiator panel fins allow for the radiation to space to be maximized and avoid heat transfer between radiator panels [45]. Beyond system geometry, other considerations to improve performance and reduce mass may include

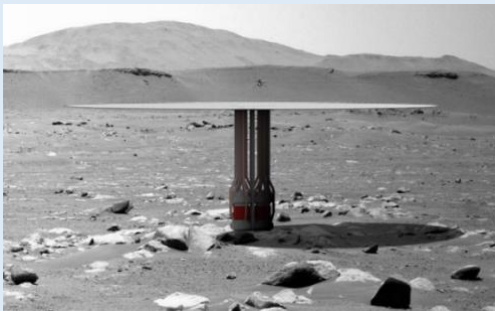
working fluid choice and high-performance material options for the power conversion systems and radiator heat pipes and paneling.

### **Reference Mission**

While FPSs are under development to power sustained lunar operations, a demonstration mission on the lunar surface is the preliminary step toward achieving that goal. Significant technology advancements will be required to meet the deadlines of the Artemis campaign. The proposed system utilizes a single 40-kW<sub>e</sub> reactor concept that will operate continuously for the duration of the mission. A breakdown of the proposed mission and system objectives are seen in the image below. Autonomous prototypic reactor operation with expected power generation and heat rejection will determine the success of this reference mission. Utilizing local terrain features or in-situ resources offers options to minimize external radiation dose to crew or key system components.

Following a lunar demonstration, FPS missions will expand to provide electric power for lunar habitats, ISRU, and potential crewed Martian expeditions in the 2040+ timeframe. As mentioned previously, these higher power missions will require larger reactor systems or several operating units in parallel.

## **Lunar Fission Surface Power**



**Objective:** Lunar System Demonstration

**Time Frame:** Late 2020s

**Mission Duration:** 1 year

**Number of Units:** 1

**Thermal Power:** 150 kW<sub>t</sub>

**Electrical Power:** 10 to 40 kW<sub>e</sub>

References: [44]

An FPS will provide continuous power to support human and robotic operations from a lunar post at any location, including in a permanently shadowed crater. An FPS would be primarily autonomous, with built-in safety and a low external radiation dose. A modular design enables increased power for expanding capabilities without system modifications.


## **2.3. Nuclear Systems for Propulsion**

For human spaceflight to extend beyond the Moon, advances for in-space propulsion technologies are required to execute the missions needed with reduced duration. Advanced propulsion will also enable more demanding robotic missions throughout the solar system and beyond. Technology development efforts are under way for NEP, NTP and Radioisotope Electric Propulsion (REP). Various subsystems required for NEP, such as power conversion systems and electric propulsion, have been developed to various levels of continued maturity over the past several decades under several initiatives, including SP-100 and Project Prometheus. However, no integrated NEP system has been tested on the ground or in space since SNAP-10A. NTP systems were demonstrated through the NERVA program of the 1960s and 1970s where 22 highly enriched uranium (HEU) reactors and engines were tested on the ground at 70 to 4,200 Megawatts (MW), cumulative burn times up to 100 minutes, up to 250,000 lbf thrust, and up to 2750 K peak fuel temperature. [3] Following the end of the lunar program, funding was reduced and the NERVA program was cancelled. No other NTP systems have been tested by the U.S. and none have ever been demonstrated in space by the U.S. or by others. Current development and technical requirements of nuclear systems for propulsion reference a human opposition class Mars mission in the late 2030s.

In 2020, NASA's Space Technology Mission Directorate requested the National Academies of Sciences, Engineering, and Medicine convene an ad hoc committee to identify primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion technologies for future exploration missions. The committee held 14 virtual meetings and drafted a report summarizing their

findings, titled, “Space Nuclear Propulsion for Human Mars Exploration (2021).” [46] This report provides detailed information on NTP and NEP systems, including key milestones, a roadmap, and missions that may be enabled by successful demonstration of these technologies.

### 2.3.1. Nuclear Electric Propulsion Systems

<b>Description</b>	
Propulsion source for robotic, cargo, and crew transportation.	
<b>State of the Art</b>	
<b>Status:</b> Concept Studies	
<b>Performance Goals by 2040</b>	
<b>Operational Lifetime:</b> 2-3 years (Mars crew or cargo), 10-20 years (science)	
<b>Power Generation:</b> 10 – 100 kW (science), multiple MWs (Mars crew or cargo)	
<b>Specific Impulse:</b> 2000-8000 s (thruster)	
<b>Projected Missions through 2040</b>	
Uncrewed Mars Cargo Mission (TBD) Crewed Mars Opposition Class Mission (TBD) Crewed Mars Conjunction Class Mission (TBD) Deep space robotic missions (TBD)	
	<p><b>PROPELLANT:</b> Xenon or lithium  <b>HEAT SOURCE:</b> Fission (U-235)  <b>POWER CONVERSION:</b> Dynamic  <b>HEAT REMOVAL:</b> Radiator Panels</p>

#### Overview

NEP systems use an FPS reactor and power conversion system to generate electricity for electric thrusters. Critical technology elements for NEP systems include the same technologies for reactor, power conversion system, heat rejection system, and power management and distribution (PMAD) system as for FPS, and for thrust production, add electric thrusters, power conditioning, and a propellant storage and feed system. Figure 2-6 shows an NEP system diagram.

**Reactor:** The NEP reactor is very similar to an FPS reactor. NEP reactors must be longer life for science applications and higher power for human class propulsion. The reactor transfers heat to the power generation system by a gas or liquid working fluid or by high temperature heat pipes.

**Power conversion system:** The power conversion system converts the thermal power of the reactor to electrical power used by the spacecraft’s thrusters. This power exchange results in waste heat due to the thermodynamics of the power conversion process which must be radiated to space through a heat rejection system. The power conversion system may be a turbine-based unit, an alternating piston Stirling system, or a static thermoelectric power system.

**Heat rejection system:** The heat rejection system takes the waste heat from a power conversion system and radiates it to space using radiators. Because power conversion system efficiencies are typically less than 35 percent, the amount of rejected heat can be two or more times that amount of generated electric power. For megawatt-class NEP the thermal radiators are typically thousands of square meters.

**Power management and distribution system:** The PMAD converts electricity produced by the power conversion system and processes it to an appropriate voltage for distribution to the thrusters and other spacecraft components. Electric thrusters, depending on the technology, require specific power conditioning provided by a power processing unit (PPU).

**Electric propulsion system:** There are multiple types of electric thrusters including Hall-effect thrusters (HET), ion thrusters, and magnetoplasmadynamic (MPD) thrusters. These thrusters are characterized by high  $I_{sp}$  in the thousands of seconds and lower thrust (compared with chemical propulsion). Choice of thruster may depend on specific mission requirements as each has unique thrust,  $I_{sp}$ , propellant requirements, and technology maturity. HETs and ion thrusters most commonly use xenon as propellant, and MPD thrusters most commonly use lithium, though other propellants are possible for each thruster type. Due to its low thrust, an electric propulsion system operates for long durations to impart a change in velocity to the spacecraft.

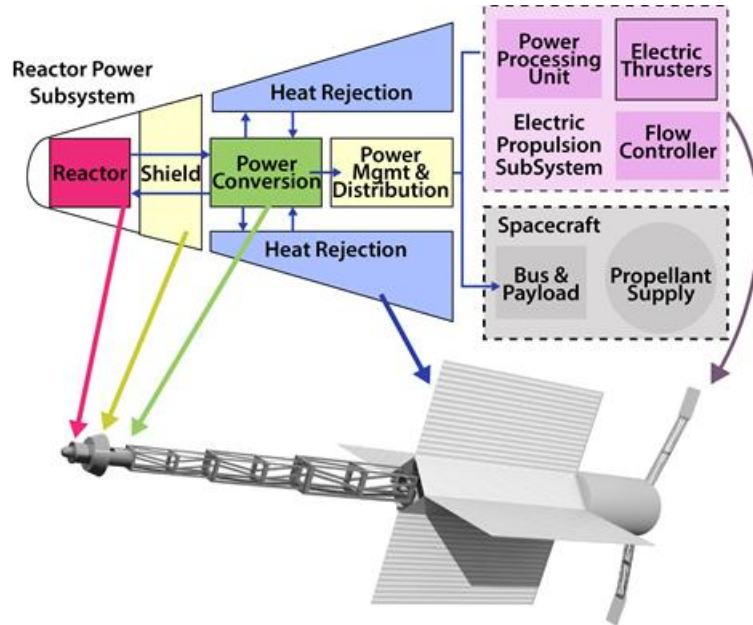


Figure 2-6: NEP System Diagram

### Benefits

The high energy density provided by the nuclear system enables an electric propulsion system with a higher thrust acceleration than the current SoA capability. Nuclear power also scales to power levels one to two orders of magnitude higher than achievable with solar power and allows operation throughout the solar system. Solar-powered electric propulsion systems are used on NASA science missions, such as the Dawn asteroid mission, and on geostationary spacecraft but are limited in maximum power by the practical size of their solar panels and by the availability of solar energy. The high-power level of the nuclear system coupled with electric propulsion's high  $I_{sp}$  enable delivery of significantly larger and more capable payloads as well as crewed Mars missions.

The long-thrust acceleration periods typical with electric propulsion provide opportunities to gradually steer a piloted vehicle in response to mission anomalies. Because of the benefits of high specific impulse, electric propulsion flattens the performance variation across the Mars opportunities, making more difficult missions in the synodic cycle achievable. High specific impulse also provides robustness to payload growth for different opportunities in an ongoing campaign of Mars missions.

Enhanced NEP capabilities are achieved by combining the NEP system with a chemical propulsion system to provide the necessary thrust to quickly capture into or escape planetary gravity wells. The inherent flexibility afforded by combined EP and chemical propulsion systems allows for flexibility in mission planning, enabling both conjunction and opposition-class Mars missions with the potential to reduce mission trip time. Shorter trip times reduce crew time in a zero-gravity environment and reduce radiation exposure as well as other hazards for both crew and systems.

Finally, the nuclear reactor onboard NEP systems provide electricity for both power and propulsion, eliminating the need for a separate power system and likely reducing mass and overall cost of the system.

### Energy Conversion

The method used to cool an NEP reactor must be matched to the power conversion system. A number of options and trades exist. For cases where the working fluid in the power conversion cycle is an inert gas, such as a helium-xenon mixture, this gas can be used to directly transfer thermal power from the reactor. Supercritical carbon dioxide ( $sCO_2$ ) is a very efficient working fluid for the Brayton cycle because it significantly reduces power consumed in the compressor to pump the fluid.  $sCO_2$  is not as attractive for direct reactor thermal power transfer because it is corrosive at supercritical conditions and would require

cladding or other protective coatings to prevent damage or corrosive reaction to the reactor components. Using a separate coolant loop for the reactor with an ideal coolant connected to the power conversion cycle via a heat exchanger is an approach to provide more optimal heat transfer, avoiding concerns with the power conversion working fluid. This separate loop can consist of high-temperature heat pipes or liquid metal coolants and can offer additional benefits like improved heat transfer in the reactor and reduced pressure drop in the power conversion cycle.

Since thermal radiation is the only mode of heat rejection available in space, radiator sizing and performance must be optimized as it can comprise more than a quarter of the NEP spacecraft's total mass for megawatt scale, human-class NEP systems [47] [46]. In order to optimize the radiator performance, higher radiating temperatures are desired, and this drives the preferred heat source temperature higher to maintain the power conversion efficiency.

### ***Operational Life***

NEP designs plan for continuous operation. For crewed or cargo missions to Mars, NEP systems will need to operate continuously for two to three years to provide both power and propulsion to the spacecraft. For science missions to the outer planets, the operational lifetime increases to 10 to 15 years. Two driving factors in NEP system operation lifetime are reactor criticality and fuel endurance. All designs must contain enough fuel to ensure the reactor can sustain operation (remain critical) over the planned lifetime. The fuel must also be reliable and robust to ensure no loss of functionality of the fuel at any time over the mission. For NEP systems, fuel must be capable of retaining its structural integrity by limiting any chemical reactions with reactor components, coolants or working fluids, minimizing irradiation effects such as undesirable fuel swelling or change in thermal or mechanical properties, and avoiding deleterious high-temperature effects on materials such as creep, recrystallization, or material decomposition. When moderator materials are used for a reactor designed for criticality in the thermal neutron spectrum, the issues of lifetime criticality and endurance extend to the moderator materials as well.

In addition, the electric thrusters are also a consideration in an NEP vehicle's lifetime. Electric thrusters are typically limited in propellant throughput, and propellant flow erodes thruster components over time. Project Prometheus showed that ion thrusters could achieve an  $I_{sp}$  of 6,000 to 8,000 s [48], and funded research into methods to extend thruster throughput at higher  $I_{sp}$  operation. However, this project also revealed that the higher  $I_{sp}$  in the ion thrusters decreased the lifetime of the thruster demonstrating that the highest possible  $I_{sp}$  might not always be the best design choice. There is an optimal  $I_{sp}$  for any mission, based on required vehicle acceleration, which is driven by several factors including power, vehicle mass, and operational lifetime.

### ***Sizing***

NEP vehicles can be sized for a wide variety of different missions, from robotic exploration of the outer planets such as the Jupiter Icy Moons Orbiter spacecraft [49] to crewed missions to Mars, as with the Human Exploration of Mars Design Reference Architecture 5.0 [50]. Sizing an NEP vehicle includes optimizing the trajectory with thruster power and  $I_{sp}$  to achieve trip time and payload mass requirements for the mission. The size and, thus, the mass of the subsystems, including the reactor, power conversion cycle, radiator, PMAD, and thrusters, is driven primarily by the power requirements of the electric propulsion thrusters. As discussed previously, the heat rejection system can account for a significant fraction of the total mass of the NEP vehicle. Radiator size is a consideration for launch vehicle packaging and mechanical deployment approaches. For vehicles above a few megawatts, the required size of the radiator likely requires multiple launches and necessitates some level of in-space assembly.

Pairing an NEP system with a chemical system in a hybrid vehicle for a high delta-v ( $\Delta v$ ) mission can improve some of these sizing considerations by reducing the required electric propulsion thruster power by a half or more. For crewed missions, the large size of the NEP and chemical propulsion systems will necessitate multiple launches and docking of multiple elements.

### ***Technology Development***

NEP missions require significant technology development for a number of critical technology elements, particularly the radiator, reactor, power conversion system, and PMAD.

NEP spacecraft heat rejection requirements drive technology development to improve radiator performance and reduce size and mass of the system. The radiator mass can be directly reduced with the development of low-mass and high-emissivity radiator paneling and optimizing the power conversion cycle for heat rejection temperature and waste heat. It is also important to develop efficient packaging methods and effective deployment schemes, and, to this end, high temperature, flexible fluid couplings will be important.

High-temperature reactor technology development is also needed for NEP. High-temperature property libraries for materials such as coolants, coatings, fuels, and moderators are important to properly model the reactor. These databases need to be expanded to fully include the pressures, temperatures, and lifetimes at which an NEP reactor will operate. Reactors under consideration for NEP include gas-cooled, liquid metal-cooled, and heat pipe-cooled. Additional research is needed to develop reactor components, such as fuels and moderators that are mass efficient while operating at high temperatures. Compounds containing hydrogen are the most effective moderator materials; however, hydrogen is easily liberated at high temperatures such as those required for NEP systems. Moderated, thermal spectrum reactors are key to making LEU fueled reactors for space power and propulsion mass efficient and are thus a critical technology development.

NEP power conversion systems will operate power levels that have been regularly demonstrated in terrestrial systems; however, NEP will require much higher temperatures and efficiencies than any terrestrial system. There is a history of development of high temperature power conversion cycles for space systems [51], but the power level of these systems is far lower than what would be required for human-class NEP missions. Investments in scaling the space power generation systems to the MW level is a vital part of NEP Mars missions. Improving the performance of components such as the recuperator, turbine, and compressor can improve this efficiency. High-efficiency components have been developed for projects like the Brayton rotating unit [52], which is of the size class for robotic NEP applications, but significant work is still needed to scale these systems to the size needed for a crewed Mars mission.

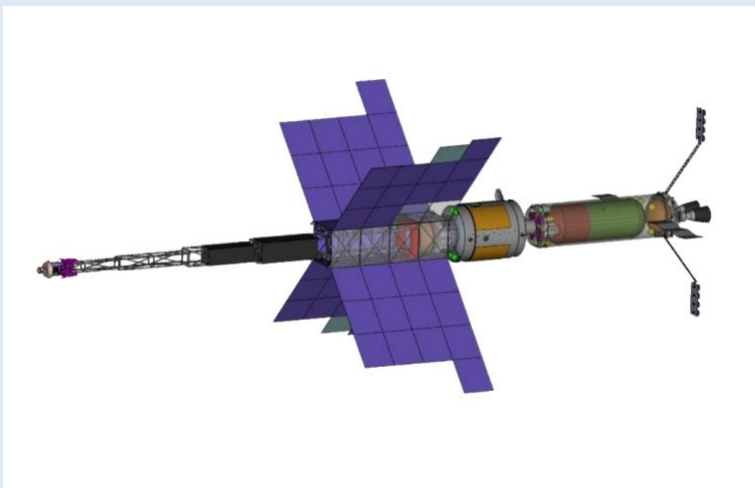
Additional technology development is needed for the PMAD equipment necessary to convert the alternating current power generated from the power conversion cycle to the direct current power and at the right voltage and current for the electric propulsion thrusters.

Given the megawatt scale and operational duration of NEP systems (months to years), these systems may be tested as modular components with simulated interfaces to reduce test facility size and complexity. A combination of modeling, ground testing, and flight demonstration may be required to certify a high-power, multi-thruster system for the long duration of Mars missions.

### ***Reference Mission***

One of the primary potential applications of NEP systems is a crewed opposition mission to Mars [53]. For this mission, a high-power (minimum of 1.6 MW<sub>e</sub>) NEP system is needed. For the opposition-class mission, the NEP system will be paired with a high-thrust chemical propulsion system to assist with entering or leaving planetary orbit. The NEP system will provide long-duration thrust over the transit that accomplishes most of the  $\Delta V$  needed for the mission. For the large payload of the crewed missions, multiple launches and in-space assembly of multiple vehicle elements will be needed for the NEP-chemical system and its propellant. For all Mars missions, the high  $I_{sp}$  of the NEP system enables a vehicle with less propellant than chemical or NTP options, likely resulting in overall less mass of the combined propulsion system.

## NEP CHEMICAL CREWED OPPOSITION MISSION TO MARS



**Objective:** Crewed Mars Mission

**Time frame:** 2040+

**Mission Duration:** ~700-900 days

**I<sub>sp</sub>:** 2500-6000 s NEP, 365 s chemical

**Thrust:** ~9lbf NEP, 25k-50k lbf chemical

**Number of reactors:** 1

**Number of engines:** ~40 NEP thrusters (depending on thruster type), engines 2 chemical

**Thermal Power:** 5-20 MW<sub>t</sub>

**Electrical Power:** 1.6-4 MWe

References: [53] [46]

An NEP system is scalable, provides high energy density, and extraordinary efficiency compared with other propulsion systems options. When combined with a chemical propulsion system, it enables a wide variety of crewed and uncrewed missions with large payloads to Mars and other interplanetary targets.

### 2.3.2. Nuclear Thermal Propulsion

#### Description

Propulsion source for robotic, cargo, and crew transportation.

#### State of the Art

**Status:** In development. NERVA program tested 22 NTP HEU reactors and engines at 70-4,200 MW, 30 s-62 min, up to 250,000 lbf thrust, and up to 2750 K peak fuel temperature. No NTP system has been flown in space [3].

#### Performance Goals by 2040

**Operational Lifetime:** 4 hrs. (throughout mission)

**Thrust:** 12,500-25,000 lbf required for mission (system inherently scalable ~5,000-250,000 lbf)

**Specific Impulse:** 850-1100 s

#### Projected Missions through 2040

Uncrewed Mars Cargo (TBD)

Crewed Mars Opposition Class (TBD)

Crewed Mars Conjunction Class (TBD)

Crewed or Uncrewed Cislunar Applications (TBD)



**PROPELLANT:** Hydrogen  
**HEAT SOURCE:** Fission (U-235)  
**HEAT REMOVAL:** Hydrogen



## Overview

NTP systems consist of a high-temperature reactor, non-nuclear rocket engine components, and a propellant management system.

**Reactor:** The reactor generates energy through nuclear fission and acts as a heat exchanger to directly transfer the energy to a propellant and bring it to extremely high temperatures. Numerous designs and high-temperature materials are in development to accommodate the NTP reactor design's extreme operating conditions.

**Nonnuclear engine components:** The nonnuclear components include turbomachinery, a pressure vessel, regeneratively cooled nozzle, and an engine controller. The turbomachinery interfaces with the propellant management system to prepare the propellant for entry into the reactor. The pressure vessel houses the reactor and interfaces with the turbomachinery and nozzle. The nozzle is cooled by the hydrogen before it enters the core. It then receives the high-temperature hydrogen propellant from the reactor and accelerates it out of the system at an extremely high velocity to generate thrust. The engine controller houses electronics and a control system to operate the engine.

**Propellant management system:** The propellant management system stores the propellants, maintains storage conditions, and delivers it to one or more engines during operations as well as a cool-down period. The NTP propellant used for current NASA reference missions is hydrogen, the lightest element, which can be accelerated to the highest velocity for greatest specific impulse. Because hydrogen must be maintained at less-than 20 degrees Celsius in liquid form long-term hydrogen storage and distribution is a key technology that is discussed in Section 3.4.

## Benefits

The value of NTP technology is its combination of high thrust and high  $I_{sp}$ , which enables smaller propulsion stages compared to chemical combustion propulsion and faster trajectories. It also enables missions with high  $\Delta V$  requirements and efficient propulsion within proximity to planetary bodies with relatively deep gravity wells. NTP offers an  $I_{sp}$  roughly double (900+ s) the highest performing chemical propulsion systems (~450 s) and can scale for various thrust requirements (~5 to 100s of klbf).

NTP systems offer flexibility in mission design and reduced trip time. NTP can support both fast conjunction-class and opposition-class missions to Mars with the capability to leave from low Earth orbit or cislunar space. This allows for optimization of the launch vehicle insertion orbit, which can minimize stage masses reducing vehicle development, production, and launch costs. This flexibility also provides tolerance for payload growth. The shorter trip times enabled by NTP reduce crew time in a zero-gravity environment and reduce radiation exposure as well as other hazards for both crew and systems.

## Energy Conversion

NTP systems operate at extremely high temperatures, thus loss of coolant could cause catastrophic damage to the system. Current NTP engine designs use hydrogen as the propellant. This hydrogen also serves the function of cooling the reactor. The dual purpose of the hydrogen provides a single point of failure for both propulsion and reactor cooling; therefore, reliability, redundancy, and safety systems are pivotal to success. Some examples of redundancy and safety systems include secondary emergency loops; redundant valves, pumps, and feed systems; excess hydrogen; and auxiliary thrusters in case of prolonged failure. Research and trades need to be performed on the full system to maximize prevention for loss of coolant scenarios while also optimizing the mass of the system.

## Operational Life

NTP systems maximize fuel power density to provide the most thrust for minimal mass. Thrust and  $I_{sp}$  are both directly proportional to the propellant's temperature as it exits the rocket nozzle, and, as such, the reactor must operate as hot as is considered safe. The amount of time at this high temperature is the dominant aspect of fuel endurance for NTP systems. In addition, NTP reactors do not operate continuously, instead rapidly starting and stopping for various burn durations, which heavily stress the fuel elements and provides control challenges. Burn periods are typically on the order of minutes up to an hour followed by periods of cooldown with sparse, periodic restarts over the years-long missions. Potential missions continue

to design and plan for operational lifetimes of two to three hours. Legacy NTP designs developed during the NERVA program successfully demonstrated NTP reliability at representative temperatures and durations, including engine restart capability for the set of HEU fuels tested. New candidate fuels, moderators, and full fuel elements must be tested and cycled at operational temperatures to assess the physical integrity and operational life of the materials, as well as prove the same operational reliability established under NERVA.

### ***Sizing***

NTP engines can be launched fully integrated with various current and planned launch vehicles. However, the full system for a human Mars mission will require multiple launches and in-space assembly of multiple propellant tank elements due to the requirements for hydrogen propellant volume and mass. The engine, propellant tanks and crew or cargo module will be launched in a phased approach and assembled in low Earth orbit or cislunar space, prior to the first NTP start-up and burn towards Mars.

### ***Technology Development***

Historic NTP systems were developed and tested utilizing HEU, such as during the NERVA program in the 1960s and 1970s. NERVA tested 22 reactor and engine concepts at partial and full power with multiple restarts and performance levels. However, no fully assembled system has been tested or flown in a flight configuration. The current plan to use high-assay low-enriched uranium (HA-LEU) is a departure from heritage designs. Further development and testing are needed to assess current fuel and moderator materials and designs that utilize HA-LEU. Lessons learned from heritage systems can be leveraged for design, including structural vibrations induced from the reactor design, neutron moderation, moderator and mass optimization, and high-temperature testing of various fuel forms in a hydrogen environment.

A key challenge for reactor development is gathering experimental data at high temperatures that can be used to validate models. Various modeling and simulation capabilities exist for the reactor core, thermal-hydraulics, and fluids; however, coupled models are somewhat limited in reliability due to lack of material properties at the extreme temperatures required for NTP. Nonnuclear testing of materials in the Compact Fuel Element Environmental Test, Nuclear Thermal Rocket Element Environmental Simulator, and Transient Reactor Test Facility are under way and will continue throughout development. Additional facilities will be required to test a full reactor and integrated engine at operational temperatures and durations with hydrogen propellant. Facility development and test planning is under way to develop a cost-effective approach to reactor and engine testing in support of validating models, verifying controllability, and certifying the NTP system for human space operations.

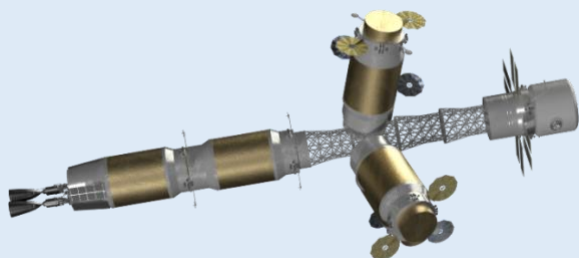
As discussed, NTP reactors will be required to operate for a cumulative time of several hours near the material and engineering limits of a nuclear fission core. This includes the critical periods of startup and shutdown when hydrogen flow is transitioning, since hydrogen density both has a major effect on reactivity and is necessary for reactor cooling to keep the high temperature fuel from melting. Design and control for stability during these transient periods is a major engineering challenge.

Finally, because NTP leverages low-density, low-temperature liquid hydrogen for the propellant, it requires larger propellant tanks and higher performance cryogenic fluid management (CFM) systems compared with chemical propulsion. These CFM systems must keep the liquid hydrogen at approximately 20 K with minimal boil-off to achieve mission objectives. CFM requires its own technology development to support NTP missions. See Section 3.4. for more information.

### ***Reference Mission***

The primary application under consideration for NTP systems is a crewed mission to Mars. The current reference mission for NTP is similar to NEP. It assumes an opposition class mission, preceded by a cargo mission to deliver supporting infrastructure and supplies to the Martian surface. Projected crew size is four, with two landing on the surface of Mars for approximately 30 days. These NTP systems are targeting a  $I_{sp}$  of 900 s with a thrust of 25 klbf and would require six to eight restarts of the engine. Similar to the NEP Mars mission, multiple launches and in-space rendezvous and docking of multiple vehicle elements will be needed for the NTP system and its propellant. A potential configuration for cargo and crewed NTP mission to Mars is shown below.

## CREWED MISSION TO MARS



**Objective:** Crewed Mars Mission  
**Time Frame:** 2040+ crewed  
**Mission Duration:** ~700-900 days  
**I<sub>sp</sub>:** 900 s  
**Thrust:** 25 klf  
**Number of engines:** multiple  
**Thermal Power:** ~550 MW<sub>t</sub>  
**References:** [46]

NTP is flexible, capable of providing double the efficiency of chemical systems while maintaining high thrust. It enables fast transits which reduce crew and system exposure to radiation and zero gravity.

### 2.3.3. Radioisotope Electric Propulsion Systems

#### Description

Propulsion system utilizing a radioisotope source for robotic spacecraft.

#### State of the Art

**Status:** Concept studies

#### Performance Goals by 2040

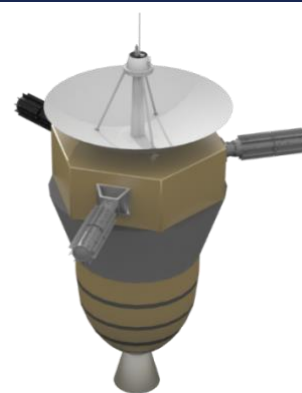
**Operational Lifetime:** 38+ years

**Power Generation:** 800-2,000 W<sub>e</sub>

**Specific Impulse:** ~1200s – 3500s (Hall thruster or small gridded ion thruster)

#### Projected Missions through 2040

Deep space robotic missions (Persephone)



**PROPELLANT:** Xenon or lithium  
**HEAT SOURCE:** Decay (Pu-238)  
**POWER CONVERSION:** Static or Dynamic  
**HEAT REMOVAL:** Radiator Fins or Panels

#### Overview

REP systems are a specific kind of nuclear electric propulsion, using a radioisotope heat source and power conversion system to generate electricity for electric thrusters. Critical technology elements for REP systems include the same technologies for RPS focused on power conversion system and heat rejection system improvements to increase power density, measured in specific power (watts/kilogram). Like larger NEP systems, REP system technologies also include power management and distribution, electric thrusters, power conditioning, and a propellant storage and feed system. REP systems importantly leverage launch vehicle capability to deliver their small spacecraft and propulsion system to a high escape velocity to enable faster missions to the outer planets. Chemical propulsion can also be leveraged with REP systems for high acceleration maneuvers, such as arrival into and departure from planetary gravity wells, with SoA being monopropellant hydrazine thrusters.

**Radioisotope power system:** REP systems require an RPS with a minimum specific power of 8 W<sub>e</sub>/kg to be competitive with alternative propulsion systems. Specific power is proportional to propulsive acceleration potential, and there is a minimum acceleration that is practical. This means that the currently available MMRTG systems cannot be used and development of advanced RTGs or DRPSs is required.

Multiple copies of a radioisotope power system will be required to produce the power for an REP system. There are practical limitations to the number of RPS that can be integrated onto a single spacecraft due to

configuration issues with heat rejection and operational constraints based on radiation to personnel working in close proximity to the RPS during spacecraft integration. Four is typically considered optimal.

**Electric propulsion system:** There are multiple types of electric thrusters applicable to REP in the sub-kilowatt to kilowatt per thruster range required. These options include HET and gridded ion thrusters. These thrusters are characterized by high  $I_{sp}$  and low power. Choice of thruster may depend on specific mission requirements as each has unique thrust,  $I_{sp}$ , and technology maturity. The more time an EP system has to provide thrust acceleration, the higher the optimal  $I_{sp}$ , and because REP is typically considered for outer solar system missions, optimal  $I_{sp}$  is typically higher. HETs and gridded ion thrusters most commonly use Xenon as propellant, though other propellants are possible for each thruster type. Due to their low thrust, the thrusters operate for long durations to impart a change in velocity to the spacecraft, and the lifetime potential of each thruster technology is a consideration.

### ***Benefits***

Studies over the last decade have shown that radioisotope-based nuclear electric propulsion will enhance and enable smaller robotic missions beyond the main asteroid belt in the far reaches of the solar system [55]. REP offers the performance advantages typically gained by reactor-powered electric propulsion while being more compact and mass advantageous in design. REP looks to push RPS capabilities well above current specific power levels to accomplish missions beyond the scope of what has been done to date.

REP provides a high specific impulse propulsion with long lifetimes from the Pu-238 fuel source in the RPS, with the capability to withstand harsh environments throughout the solar system and can go deep into interstellar space. REP systems are applicable to missions of much smaller scale of power and thrust than NEP or NTP systems, where the fission core mass would make such propulsion systems impractically oversized. Blending the two systems of electric propulsion for deep space transit and chemical propulsion for orbital maneuvers provides flexibility in operation of the REP system.

### ***Energy Conversion***

The standard REP system will be powered by several large-scale RPS in order to provide sufficient power to the electric propulsion system, which is anticipated to require several hundred watts to a few kilowatts of electricity depending on the mission and payload. This power is also available to the spacecraft's other subsystems and science instruments. The electric thrusters then convert the electric energy to kinetic energy for thrust and propulsion. REP systems are not anticipated to require additional cooling regardless of the type of RPS selected. In fact, some of the additional heat generated can be used to provide extra warmth to the spacecraft instruments or structures in the colder environments [56].

### ***Operational Life***

REP designs plan for near-continuous operation of the electric propulsion for periods of years. The cruising time for missions to the outer planets can take several decades [55]. RPS lose power over time due to the natural decay of the radioisotope fuel and degradation of the thermoelectric power conversion system, although dynamic power conversion systems can somewhat compensate for thermal power loss by changing operating conditions. The Persephone reference mission will require 28 years in transit to Pluto plus 3 years of operation at Pluto, bringing total mission lifetime to 31 years for the REP system [55]. While historical RTGs have operated for periods longer than this, neither the advanced RTGs, DRPSs, nor the electric propulsion thrusters required to support an REP system have been proven or are being designed to operate for these significant lengths of time.

### ***Sizing***

An REP system is generally composed of several compact components and is much smaller than other nuclear propulsion systems. For the reference Persephone mission, the combined weight of the electric propulsion and power subsystems, including the propellant and power management and distribution components, is roughly 45 percent of total spacecraft mass [55]. The primary volumetric impact of an REP system, if at all, will be due to the integration of the RPS with the spacecraft which may be placed on booms extending away from the spacecraft bus so as to minimize any radiation damage or unwanted heating to sensitive components. The number of RPS subsystems that can be integrated is constrained as there are challenges with spacecraft configuration to provide each RPS with a view to deep space for its radiators to

effectively radiate heat. REP subsystems are not expected to drive multiple launches or in-space assembly for the overall systems they support.

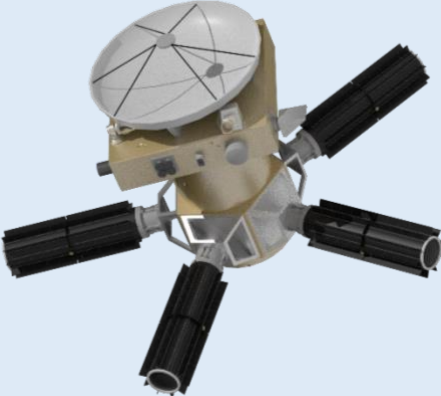
### **Technology Development**

REP has been evaluated before but has not been seriously considered for flight due to the low specific powers of traditional radioisotope generators, which range from 3 to 5W<sub>e</sub>/kg. NASA studies have shown that an RPS specific power of at least 8W<sub>e</sub>/kg is necessary for most REP applications [55]. Future power sources in development that could meet the specific power need to include the NGRTG and/or DRPS with increased efficiency. DRPS has the highest technical maturity for achieving the necessary performance. The integration of RPSs with ion electric propulsion has not been tested or flown in a flight system, but both systems have been independently flight proven numerous times.

Finally, as was mentioned in the RPS sections above, Pu-238 availability has been noted as a potential challenge. An REP mission will likely be the largest RPS mission to fly; and therefore, the working relationship with NASA and the DOE should be monitored closely to ensure REP development is not impacted.

### **Reference Mission**

Electric propulsion is the most mass-efficient technology that can satisfy the requirements of the Persephone reference mission. The REP system composed of XR-5 thrusters will provide the low thrust trajectory to Pluto in the Persephone reference mission. A small monopropellant blowdown (hydrazine) propulsion system will be used for orbit maintenance and altitude control. While the propulsion systems are using the SoA capabilities from Aerojet Rocketdyne, the advanced RPS systems are still under development to provide the needed power requirements for a mission of this size [55].

<b>PERSEPHONE</b>	
	<p><b>Objective:</b> Pluto Orbiter</p> <p><b>Time Frame:</b> Launch 2031, KBO flyby 2050, Pluto-system tour 2058-2061</p> <p><b>Mission Duration:</b> 31-39 years (dependent on extended mission approval)</p> <p><b>I<sub>sp</sub>:</b> ~1200s NEP, ~230s Chemical</p> <p><b>Thrust:</b> ~35-75mN NEP, 80lbf Chemical</p> <p><b>Number of engines:</b> 3 XR-5 thrusters, 16 Chemical</p> <p><b>Thermal Power:</b> ~15,000 W<sub>t</sub>, assuming 12% efficiency</p> <p><b>Electrical Power:</b> 1811 W<sub>e</sub> (launch), 857 W<sub>e</sub> (39 years)</p> <p>Reference: [56]</p>
	<p>REP systems offer the performance advantages typically gained by reactor powered electric propulsion while being more compact and mass advantageous in design (at the multi-kilowatt power level). REP looks to push the capabilities of RPS systems well above current standards in order to accomplish missions, such as Persephone, beyond the scope of what has been done before.</p>

## **3. Additional Considerations Unique to Space Nuclear Systems**

Additional unique considerations for space nuclear technologies requested in EO 13972 include transportability, space rating human rating, and fluid transfer.

### 3.1. Transportability

Nuclear material transportation is pursuant to legal and statutory requirements that ensure safe and secure delivery of the system. There are three discrete phases of transportation common among all space nuclear systems: ground, launch from Earth into space, and exo-Earth. The primary safety concern during all phases is preventing unintended criticality and/or radiological release to the public or environment. The primary security concern during all phases is capture of the nuclear material. This only applies to HEU systems where the material can be weaponized, as well as having implications for proliferation. Current concepts for NTP and NEP systems utilize HA-LEU and, therefore, do not have the same security concerns. Mission planners must thoroughly characterize, assess, report, and mitigate the potential associated safety and security risks of transporting nuclear components during each independent phase.

#### 3.1.1. Ground

Ground transportation of nuclear materials is well understood and occurs frequently with approximately three million shipments containing radioactive material transported in the U.S. every year. [57] The Department of Transportation (DOT), Nuclear Regulatory Commission (NRC), and DOE are the regulatory bodies that oversee all ground transportation of nuclear systems. Safe and secure ground transportation is primarily regulated through careful design and logistics of the transportation container or cask and reactor-specific design requirements. The stringent regulatory and safety requirements provide robust, reliable designs and transportation plans that have demonstrated an extremely low probability of a mishap occurring. For this report, it is assumed that all ground transportation and launches will occur within the U.S. and, therefore, transportation across country borders is not addressed.

Historically, space nuclear systems have been transported to Kennedy Space Center by cask via roadway. The 9904 Type B cask [58, 59] has sufficed for all RHUs and RPSs and can continue to be used for these systems until the size or design significantly changes. Unfortunately, the current cask size is too small and not approved to transport the fission-based space nuclear systems under consideration. This results in two options for fission systems. First, a new cask could be designed and manufactured. Second, a different existing cask may be modified to meet the needs of the fission system. This option may require that the system be transported in several pieces and reassembled after it has arrived at its destination. If nuclear fission reactors for space applications are to be transported fully assembled, including nuclear fuel, they will likely require new cask development to ensure safety and adherence. Cask design considerations include activity, type, and form of the packaged material. Hypothetical accident conditions that must be assessed include the following:

- Free fall from a 9-m distance onto an unyielding surface.
- Crush: 500-kg mass dropped from 9 m.
- Puncture: 3-m free fall onto steel rod 20 cm in diameter.
- Fire: 60-min all-engulfing fire at 800 degrees C.
- Immersion: 8-hr immersion under 0.9 m of water.

Several nuclear fuel and waste management companies provide design and development of transportation casks, as well as end-to-end transportation services including licensing, transport, transferring, and handling of the nuclear material.

Ground operations for fully assembled reactors must prevent unintended criticality throughout all phases including storage, transportation, and launch in a number of contingency scenarios. Particular concern must be given to mishaps that would result in water immersion since water is an effective neutron moderator that can cause inadvertent criticality. Historical fission nuclear systems have used high neutron absorbing, “poison,” wires, and control rods or destruction mechanisms to eject the reflector and scram the reactor, as well as coatings and additives to reduce reactivity in accident scenarios without reducing operational capability [60].

All space nuclear systems must also be housed in nuclear approved buildings: radioisotope-based systems due to their intrinsic activity levels and fission-based systems for their potential for criticality. This requires

additional safety and regulatory considerations. The processes to meet these requirements are well developed and understood but must still be accounted for in project planning.

### 3.1.2. Launch

The primary safety concern associated with the launch of space nuclear systems is radiological release to the environment, which could affect personnel and the public. The Secretary of Energy is required to maintain “the capability and infrastructure to develop, furnish, and conduct safety analyses,” while executive departments and agencies “ensure that safe application of space nuclear systems is a viable option” [5].

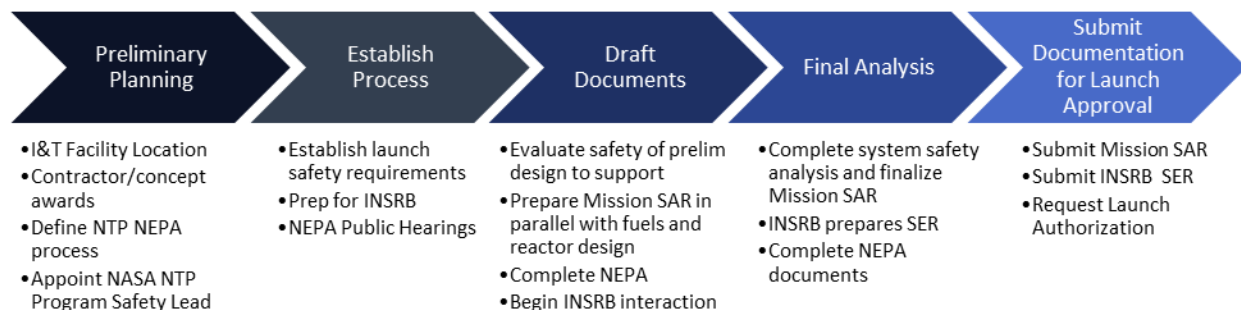
On August 20, 2019, the NSPM-20 was released regarding the launch of spacecraft containing space nuclear systems. As the first major update to the launch approval process for space nuclear systems in over 25 years, NSPM-20 added clarity to existing methods by establishing a three-tiered risk system for launch authorization. These risk tiers are based upon the characteristics of the system, the level of potential hazard, and national security considerations [5]. Table 2, below, describes the three tiers.

*Table 2: Launch Approval Tiers and Authorities for Federal Government Missions [5]*

Tier	Description	Applicable Systems	NEPA and SAR Guarantor	Reviewer	Approver
I	- Smaller radioactive sources ( $\leq 100,000 \times A2$ )	LWRHU	Agency Head & DOE Secretary	Agency Head	Agency Head
II	- Smaller radioactive sources ( $\leq 100,000 \times A2$ ) with $> 1/1,000,000$ risk of exposure $> 5$ rem - Larger radioactive sources ( $> 100,000 \times A2$ ) - LEU fission systems ( $< 20\%$ enrichment)	RTG DRPS FPS REP NEP NTP	Agency Head & DOE Secretary	INSRB	Agency Head
III	- Any system with $> 1/1,000,000$ risk of exposure $> 25$ rem - Non-LEU fission systems	N/A	Agency Head & DOE Secretary	INSRB	U.S. President

The Interagency Nuclear Safety Review Board (INSRB) is an assembly of representatives from each of the Government agencies that are or could be affected by the launch of nuclear systems into space. Members include the Department of State, DOD, DOE, DOT, Environmental Protection Agency, NASA, and; as appropriate; the NRC. Together the INSRB reviews the Safety Analysis Report (SAR) which is provided by the sponsoring agency. (For NASA missions, this analysis is typically assigned to the DOE.) The SAR is used to aid the INSRB in producing a Safety Evaluation Report (SER) to document any findings prior to the launch of any space nuclear system. Prior to NSPM-20, the Interagency Nuclear Safety Review Panel (INSRP) was an ad-hoc panel that was assembled to support safety reviews, as required. NSPM-20 established that the INSRB would be a full-time board replacing the INSRP. Figure 3-1 presents the documentation process for launch approval.

Figure 3-1: Documentation Process for Launch Approval



### 3.1.3. Exo-Earth

Deployment of a space nuclear system means installation of the system in its area of intended operations, either in-space or on the surface of another celestial body. While guidelines exist for exo-Earth nuclear system transportation, additional and more formal guidelines may be needed to prepare for the anticipated future human and international missions utilizing space nuclear technologies.

Risk of radiation exposure to the astronauts, the public, and the environment is the greatest safety concern for space nuclear systems. The nuclear system designers must account for additional safety measures to keep the astronauts safe and mitigate the risk of radiation exposure. Radiation shielding for in-space operations (e.g., docking and extravehicular activity) must be three-dimensional, and mapping of radiation fields will be required to ensure safe operations and protocol. Nuclear systems should minimize or eliminate any need for the astronauts to move or approach the nuclear system. If maintenance or repairs to the operational system are anticipated, exposure can be mitigated by robotic support, portable shielding, or operations after the system has been shut down for the time needed to achieve safe radiation levels.

Additionally, system and mission designers incorporate risk mitigations to prevent unplanned Earth reentry and to provide an extremely low probability of exposure should reentry occur. NSPM-20 requires that individual systems perform safety analysis to develop unique requirements based on the approved mission risk tier and individual system design. All missions must meet tier dose and probability requirements for all phases of the mission. Security concerns for nuclear technologies operating on other planetary surfaces are not well defined at this time but limits are delineated in Outer Space Treaty statutes.

## 3.2. Space Rating

The launch and space environments produce unique environmental requirements that any space system needs to verify on the ground prior to launch through analysis and testing. The launch environment produces acceleration and acoustic vibration loads that place significant stress on the payload for relatively brief periods of time. The in-space environment's vacuum conditions, with higher concentrations of ultraviolet light, space radiation, and atomic oxygen, impacts material selection and the physical processes, such as heat transfer, that dictate operations. Generally, a nuclear system will follow the same processes and rigor for verifying environmental requirements as any other space system; however, certain aspects of nuclear systems add complexity to the test and certification processes.

Given the radiation produced by space nuclear systems, the test facilities used for ground verification will be regulated by either the DOE or the NRC in order to provide assurances in worker, public, and environmental safety. Some facilities already exist for radioisotope-based systems; however, new facilities will be required to safely house and test the larger fission reactors. Ground testing of fission reactors will be primarily performed on separate qualification or acceptance units rather than the flight system itself in order to not increase the radioactivity levels of the nuclear payload prior to launch. NASA has radiation protection protocols and assigns a radiation safety officer that closely monitors all pre-launch through launch activities of a SNS and who is actively involved in keeping exposure risk to the workforce and public as low as reasonably achievable.



All nuclear systems will be designed with robust structural and material implementation decreasing their susceptibility to the launch and in-space environments. The heavy metals and ceramics required for the neutronics and temperature requirements of fission systems lead to compact structures with direct load paths and high material strength. Despite being fairly heavy, this provides a relatively easy approach to design the system to withstand the launch environment. In addition, the metallic and ceramic structures are also naturally robust to outgassing due to ultraviolet or atomic oxygen degradation. Therefore, no preconditioning of the materials such as “bake-out” will likely be required. Finally, space nuclear fission and radioisotope systems, are already designed to withstand source-radiation which is expected to reduce additional requirements for space radiation when compared with non-nuclear systems. The primary area of concern for space rating with nuclear technologies would be ensuring the instrumentation and electronics for the spacecraft’s other, nonnuclear subsystems are able to withstand being within close proximity of a concentrated radiation source. Radiation hardened electronics capable of long-duration spaceflight with a fission radiation source is a design challenge. For outlying radiation design considerations, standard mitigation techniques such as geometric design, spot shielding, and use of radiation-hardened parts will be employed.

Space nuclear systems will need to operate in reduced- or zero-gravity conditions. This could impact the characteristics of fluid flow, especially where there might be convection-driven effects in gravity. In most cases, gasses and fluids are held under pressurized conditions and/or are flow driven where reduced or zero gravity is not an issue.

NASA is in the process of reviewing the specific environmental test requirements for space nuclear systems and revising Agency procedural requirements needed for launch approval. Close coordination of these requirements and procedures with the DOE will be essential.

### **3.3. Human Rating**

Safety of crew is a top priority for NASA. Thus, any technology intended for a crewed mission must undergo rigorous evaluation to meet the elevated standards encompassed in a human rating certification. Today’s human rating certification process is detailed in NASA Procedural Requirements (NPR) 8705.2, “Human-Rating Requirements for Space Systems,” and encompasses the process and standards for design, verification, and validation of capabilities and performance; flight test; and operation of all human-rated systems.

The mandatory technical capabilities are categorized as system safety, human control of the system, and crew survival and aborts. Human rating for space systems, particularly nuclear space systems, may require additional safety standards; however, the same Probabilistic Risk Assessment processes can be followed for nuclear missions.

The fundamental safety issue for human rating nuclear systems is exposure to radiation for the crew. However, naturally occurring radiation from space is just as much a concern for astronauts as radiation from the space nuclear system. Methods that may be utilized to minimize exposure to both space and nuclear radiation include distance from radiation source, active management of exposure time, and shielding.

For in-space applications placing crew modules as far as practical from the nuclear source and shielding of the source and/or crew modules will be the major design considerations. Strategic placement of other spacecraft elements, such as propellant tanks, between the reactor and crew can also be an effective means to reduce crew exposure. For surface applications, nuclear heat and power sources should be placed a significant distance from crew operations and habitat. The sources may be shielded, placed behind hills, or buried in the ground to further reduce radiation exposure to the astronauts and equipment on the surface. Space nuclear systems will be designed to avoid the need for maintenance or other activities near the nuclear system. However, if space or surface operations must be performed in close proximity to the nuclear source, the time periods should be as short as possible to minimize exposure and robotics or other remote handling operations should be used whenever practical. Radioisotope power systems have an advantage that their radiation is less and more easily shielded; that may allow astronauts to be in closer proximity for longer periods. Additional safety and mitigation strategies involve radioprotectants,

pharmaceuticals, and individual risk assessments for each astronaut. The current certification process, along with these radiation exposure mitigation strategies, will enable nuclear systems to be prepared and qualified for human-rating certification.

### 3.4. Fluid Transfer and Cryogenic Fluid Management

Cryogenic fluids are often used as coolants, working fluids, and propellants for both nuclear and nonnuclear space systems. Cryogenic fluids are prevalent on Earth as well space, but terrestrial designs for cryocoolers needed to maintain cryogenic temperatures are massive and unrealistic for space applications. Cryogenic Fluid Management is critical for nuclear propulsion systems, especially NTP, where large amounts of hydrogen are required to be preserved at cryogenic temperatures for years, with minimal losses. CFM development also has broad benefits to other cislunar space and lunar surface operations. Liquid oxygen and liquid methane are common choices for ascent and descent chemical propulsion.

The requirement to refrigerate extremely low-temperature fluids, such as liquid oxygen and liquid hydrogen, translates to a high refrigeration system efficiency due to the extreme conditions of the space environment. Proper CFM involves cooling and temperature maintenance of the fluid, insulation to minimize thermal conduction, pressure containment to limit loss, and low-conductivity structures to limit thermal shorts as seen in Figure 3-2. A refrigeration cycle is incorporated with the storage tanks to remove any absorbed heat from solar or planetary radiation effects and maintain adequate temperature conditions. Acquisition and distribution of the cryogenic fluids is also important, which requires low leakage valves and disconnects with cryogenic seals. Cryogenic hydrogen offers a particular challenge due to the extreme 20°C temperature and because hydrogen can pass through the smallest gaps and certain materials.

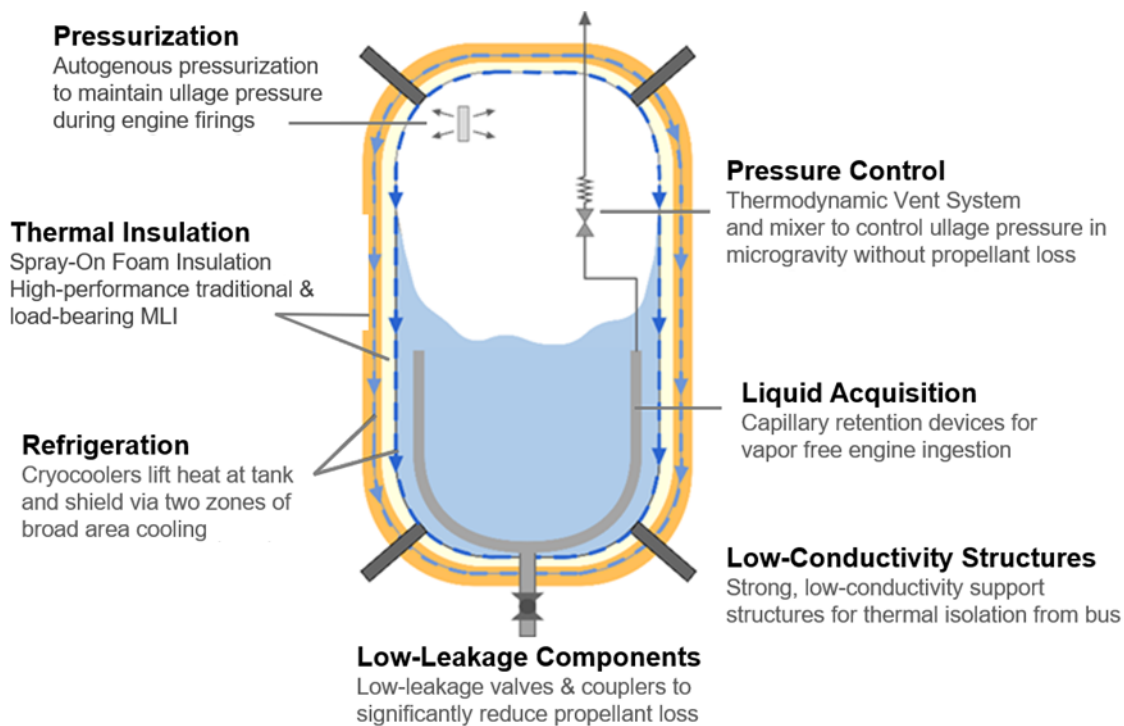


Figure 3-2: Generic NTP liquid hydrogen propellant tank with CFM subcomponents.

While cryogenic fluids have been utilized for in-space missions in the past, the current SoA is insufficient to meet the long-duration requirements for space nuclear propulsion and power missions. Most current uses of cryogenic fluids in space rely on venting a portion of the fluid to maintain the temperature and pressure of the storage tank. This is not practical for long missions where propellant mass carries a high currency. For envisioned NTP and NEP missions, cryogenic storage tanks must be capable of near-zero loss of propellant for years, while maintaining tank pressure, preventing cases of over pressurization, and providing the engine system with the required mass flow rates and conditions. The current method to

minimize the loss of propellant is to approach zero boil-off in prototypic microgravity conditions. This is particularly important for NTP given the larger amount of propellant mass needed compared to NEP.

Minimization of propellant leakage and boil-off rates due to solar and planetary heating loads are achievable through advanced tank materials and proper refrigeration [61, 62]. As a fluid is warmed from external heat sources, the fluid boils to gas, and gaseous fluid increases pressure unless released from the tank vessel through venting. The lack of natural convection heat transfer in microgravity complicates the storage of cryogenic propellants in space. On Earth, cryogenic fluid storage relies on free convection to mix the cryogenic fluid and prevent any heat leaks into the system from causing localized boiling. Without free convection, the cryogenic fluid is much more likely to have localized cold and hot spots because there is no mixing from free convections. This can lead to thermal stratification in the cryogenic fluid and result in boiling and venting of the fluid or damage to the system. The length of any crewed interplanetary mission accentuates the potential impacts of these limitations which necessitates CFM design maturation and future in-space operational testing. A few areas identified for maturation efforts for a future operational or demonstration mission include [63]:

- High-capacity, high-efficiency cryocoolers at both 20 K (liquid hydrogen) and 90 K (liquid oxygen and methane).
- Integration of the cryocoolers with tanks and structure through dual-zone broad area cooling.
- Reduced-gravity cryogenic transfer operations.
- Cryogenic valves, actuators, and couplers with minimized leakage.

While there are numerous design challenges for in-flight CFM, the challenges can be overcome through technology maturation and engineering development, which is currently being performed by Government and commercial entities. Ultimately, CFM capabilities will have to be proven through in-flight testing to eliminate the uncertainties of gravity effects.

## 4. Conclusion

Higher power, high energy density, higher efficiency solutions to power, and propulsion are enabling NASA's future mission goals and the Nation's ability to compete with growing international interests for global space access, exploration, and sustained human presence. Space nuclear power and propulsion offers a revolution in the design of satellites and deep space vehicles that can operate in harsh environments with increased mission flexibility. Space nuclear systems are enabling for lunar and Mars human exploration missions and a key capability needed to establish a sustained human presence in space. Advanced space nuclear systems, including fission power and propulsion and radioisotope power, offer greater capabilities to explore the far reaches and harsh environments of the solar system with robotic probes. NASA's current nuclear fission technology interests and investments are targeting power for surface operations and in-space propulsion systems for cislunar operations and deep space missions. Space nuclear systems development and application plans over the next 15 to 20 years will enable a new generation of space exploration. Exploration capabilities powered by highly reliable nuclear systems will improve the flexibility and extend the lifetime of a mission without the need for system repair or refueling. NASA's goals, enabled by nuclear technologies, usher in a new age of exploration for humans and robotics which will advance scientific objectives and expand our understanding of other planetary bodies, and eventually support long-term human presence in the solar system.

## Appendix A Acronym List

Acronym	Meaning
$\Delta V$	"Delta-V" – a change in velocity
A2	See glossary
ASRG	Advanced Stirling radioisotope generator
C	Celsius
CFM	Cryogenic fluid management
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DRPS	Dynamic radioisotope power system
EO	Executive Order
EOL	End of life
F	Fahrenheit
FPS	Fission power system
GPHS	General purpose heat source
HA-LEU	High Assay Low Enriched Uranium
HET	Hall-effect thruster
HEU	Highly enriched uranium
hr.	Hour
INSRB	Interagency Nuclear Safety Review Board
INSRP	Interagency Nuclear Safety Review Panel
$I_{sp}$	Specific impulse
ISRU	In-situ resource utilization
K	Kelvin
kg	Kilogram(s)
kbf	Kilo-pound-force
km	Kilometer(s)
kW	Kilowatt(s)
LEU	Low Enriched Uranium
LGN	Lunar Geophysical Network
LWRHU	Lightweight Radioisotope Heater Unit
lb.	Pound(s)
lbf	Pound-force
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MPD	Magnetoplasmadynamic
m	Meter(s)
min	Minute(s)
m/s	Meter(s) per second
MW	Megawatt(s)
N/A	Not applicable
NASA	National Aeronautics and Space Administration
NEP	Nuclear electric propulsion

NEPA	National Environmental Policy Act
NERVA	Nuclear Engine for Rocket Vehicle Application
NGRTG	Next generation radioisotope thermoelectric generator
NPR	NASA Procedural Requirement
NRC	Nuclear Regulatory Commission
NSPM	National Security Presidential Memorandum
NTP	Nuclear thermal propulsion
PMAD	Power management and distribution
PPU	Power processing unit
Pu	Plutonium
REP	Radioisotope electric propulsion
RHU	Radioisotope heater unit
RPS	Radioisotope power system
RTG	Radioisotope thermoelectric generator
SAR	Safety Analysis Report
sCO <sub>2</sub>	Supercritical carbon dioxide
SER	Safety Evaluation Report
SESAME	Scientific Exploration Subsurface Access Mechanism for Europa
SiGe	Silicon-Germanium
SNAP-10A	Systems for Nuclear Auxiliary Power
SNAPSHOT	Space Nuclear Auxiliary Power Shot
SNPP	Space Nuclear Power and Propulsion
SNS	Space Nuclear Systems
SoA	State of the art
SPD	Space Policy Directive
s	second(s)
TRL	Technology readiness level
U	Uranium
U.S.	United States
W	Watt(s)
W <sub>e</sub>	Watt(s) electric
W <sub>t</sub>	Watt(s) thermal
W/m	Watt(s) per meter

## Appendix B Glossary of Terms

**A2:** A measure of the amount of radioactive “material at-risk,” relative to an IAEA standard used for land, sea, and air transport defined in the “IAEA’s Specific Safety Requirements No. SSR–6, Regulations for the Safe Transport of Radioactive Material.” For reference, the amount of Pu-238 in an MMRTG is  $1.3 \times 10^7$  times the A2 value and the amount of Pu-238 in a RHU is 6,840 times the A2 value” [64].

**Cask:** A containment structure for transporting new or used reactors or reactor fuel. Federal and state regulations dictate the amount of radiation shielding required given the use case of the radioactive material.

**Closed loop:** A loop option that does not allow the fluid to escape the control volume. NEP, NFPS, and Earth-based reactor concepts rely on closed fluid loops to remove nuclear heat and generate electrical power. A closed loop is different from an open loop system in that an open loop is a loop option that allows the fluid to escape from the control volume of the system. A common example in space nuclear technologies is the hydrogen propellant used in NTP designs to cool the reactor and provide thrust.

**Cryogenic fluid:** Typically, gaseous elements/mixtures that are cooled beyond the condensation point (gas to liquid phase change). Cryogenic temperatures approach absolute zero, or 0 K.

**Dynamic radioisotope power system (DRPS):** DRPSs incorporate moving parts to achieve a higher electrical current from the heat source. This dynamic system achieves three to four times higher efficiency than traditional RPS concepts.

**Exo-Earth:** Outside of Earth, or “nonterrestrial,” operations (e.g., planetary orbit, Martian/lunar surface, free space, etc.).

**Fission:** A neutron-induced reaction with a radioactive nucleus, typically one with high atomic mass, that causes the nucleus to split into smaller nuclei. Besides the fission product nuclei, gamma rays, neutrons, and large quantities of energy are released from this reaction. Nuclear reactors rely on self-sustaining fission reactions to generate heat continuously which can be used to create electrical power.

**Fission power system (FPS):** Fission reactor concept capable of providing electric power output for planetary/lunar surfaces or low-power NEP missions. Most future applications of FPS will focus on power sources for surface habitats, rovers, and in-situ resource utilization. Key system components include a reactor, advanced power conversion systems, and heat rejection through radiator paneling.

**High-assay, low-enriched uranium (HA-LEU):** Following the same explanation in the LEU definition, HA-LEU is the next level of regulatory classification of fuel based on the U-235 quantity. HA-LEU fuel is limited to 5 to 20 percent U-235, which improves the nuclear performance of the reactor.

**Half Life:** A half life in nuclear applications is defined as the amount of time it takes for half of a radioisotope to decay away and reach a stable state. For example, after 87.7 years, 1 gram of Pu-238 would become 0.5 grams of Pu-238. Through the natural day process, Pu-238 will decay to U-234.

**High-enriched uranium (HEU):** HEU fuel is any U-235 enrichment level about 20 percent. Some regulatory bodies have further distinctions between 20 to 100 percent, but HEU will cover the entire range for this report. Most HEU reactor concepts push the U-235 content to 90 to 95 percent to maximize the amount of fission reactions given the same amount of material.

**Interagency Nuclear Safety Review Board:** A committee of regulatory agencies that reviews the program safety analysis and delivers a Safety Evaluation Report (SER) to the launch authority before the launch of any space nuclear system is approved.

**Low-enriched uranium (LEU):** Uranium has numerous natural isotopes (varying number of neutrons given the same number of protons), including the prevalent U-238 and U-235. U-235 is the predominant fissionable material in Uranium, but it comes in a much smaller quantity in comparison to U-238 (99.3-percent U-238, 0.7-percent U-235). “Enrichment” is the process of increasing the percentage of U-235 to increase the amount of fission reactions in the reactor. LEU is a regulatory limit that limits the U-235 percentage to 5 percent.

**Neutronics:** (Physics) Of or relating to a neutron or neutrons; consisting of neutrons. Also: specifically concerned with or employing neutrons in nuclear reactions.

**Radioisotope decay:** A probabilistic phenomenon that emits particles and energy from unstable nuclei based on the half life of the material. Three common types of radioactive decay include alpha, beta, and gamma decay. Alpha decay releases two protons and two neutrons (a helium nucleus), beta decay releases a high-energy electron, and gamma decay releases high-energy electromagnetic waves (gamma rays). Radioisotopes used in space nuclear applications, such as Plutonium-238, are predominately alpha decaying isotopes.

**Radioisotope electric propulsion (REP):** Propulsion system that relies on an RPS (either RTG or DRTG) for electric power. Power generated from the RPS will be used to power electric thrusters to provide system propulsion. Several missions, including the Persephone orbiter to Pluto and the Kuiper Belt, have been outlined for the next several decades.

**Radioisotope power system (RPS):** RPS designs rely on decay from a long-lived radioisotope, such as Pu-238. These systems convert the decay heat from the radioisotope source to electrical energy.

**Radioisotope thermoelectric generator (RTG):** Radioisotope power source, usually loaded with unstable Pu-238, used to generate electric power through thermoelectric generators. These designs are rigid and low mass to provide a reliable power source for extended mission lifetimes.

**Seebeck effect:** A thermophysical phenomenon where the temperature difference between two thermoelectric materials naturally produces an electrical current and voltage.

**Specific impulse:** A measure of efficiency to show how well a propulsion engine uses its available propellant. Specific impulse of a spacecraft is comparable to the miles per gallon of a car.

**Specific mass:** Commonly denoted with the Greek letter  $\alpha$ , this ratio relates the total mass of a system or subcomponent to the total electrical power output, resulting in kg/kWe units. Specific mass is typically used for large mass power and propulsion systems, NEP in particular.

**Specific power:** This relation is the ratio between the total electrical power and mass of the system and is commonly used for lower mass and power systems. This term is also the inverse of the specific mass term described previously. Units for specific power varies between W-e/kg (RTG, DRTG) and kWe /kg (FPS) depending on the use case.

**Solar irradiance:** Power per unit area received from the Sun in the form of electromagnetic radiation as measured in the wavelength range of the measuring instrument. Magnitude of solar irradiance is heavily dependent on the distance from the Sun and can directly impact mission decisions for solar energy options.

**Thermoelectric generator:** A type of static power conversion system that builds upon the fundamental principle called the Seebeck effect.

**Thrust:** The force that moves an object through air and/or space and is produced through a propulsion system. The propulsion system accelerates a heated working fluid and exhausts it through a nozzle to provide thrust. NTP, NEP, and REP systems use thrust as a main performance metric to reach mission objectives.

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