Nuclear space technologies: opening the final frontier

Synergies with terrestrial nuclear industry

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Introduction

Nuclear energy use cases in space

Humanity's pursuit of space exploration has always been fuelled by an unrelenting desire to push boundaries, uncover new frontiers, and secure a foothold beyond Earth. While countless innovations have emerged to support this endeavour, few have been as transformative as nuclear energy. From its origins in early space missions to its role in enabling ambitious plans for interplanetary travel, nuclear technology has consistently demonstrated its unparalleled capabilities in addressing the unique challenges of space exploration.

The story of nuclear energy in space is one of continuous evolution. Since the 1960s, nuclear systems have powered and heated spacecraft traveling to the farthest reaches of our solar system. This enduring legacy reflects not only the technical ingenuity behind these systems but also their deep connection to terrestrial nuclear advancements. Innovations in reactor design, materials science, and safety protocols developed on Earth have shaped the development of reliable, efficient nuclear energy systems for space - and vice versa.

As the space industry gains momentum, nuclear energy is poised to play a central role in enabling sustainable exploration and operations on the Moon, Mars, and beyond. This paper explores four critical use cases of nuclear energy in space: **1-heating** electronics, sensors, and actuators; **2-generating electricity** via nuclear radioisotope decay; **3-deploying micro nuclear reactors** for localized power generation; and **4-revolutionizing propulsion systems** for interplanetary travel. Each of these use cases underscores the unique advantages of nuclear energy in addressing the power and propulsion challenges of space.

By examining these applications and the synergies between space and terrestrial technologies, we aim to highlight nuclear energy's indispensable role in the future of space exploration.

Heating for electronics, sensors, and actuators: pioneering reliability in space

The journey of nuclear energy in space began with addressing a simple yet crucial challenge: keeping electronics functional in the harsh vacuum of space.

NASA began experimenting with nuclear-powered heat sources in the 1960s under the Systems Nuclear Auxiliary Power (SNAP) program with **SNAP-19**[(1)]. Some NASA missions e.g., certain Surveyor lunar landers in the late 1960s carried small polonium-210 as heat sources.

Such devises are called Radioisotope Heater Units (RHU). Generally, they are small devices that provide heat to keep a spacecraft's electronic instruments and mechanical systems operational in the cold temperatures of our solar system.

Illustration of Radioisotope Heater Units: Credits NASA (left (SNAP19), middle (1Watt unit)), ESA (right)

The Galileo spacecraft to Jupiter (launched in 1989) is frequently cited as one of the first NASA missions to use multiple, dedicated RHUs. Galileo carried 120[2] RHUs to maintain stable temperatures for instruments and onboard systems in the cold environment around Jupiter.

From the Soviet side, one of the earliest documented uses of dedicated RHU for thermal control was by the Soviet Union's Lunokhod-1 rover, which landed on the Moon in November 1970. Lunokhod-1[3] used polonium-210 capsules as a constant heat source, keeping the rover's internal electronics warm during the two-week-long lunar nights.

Historically, ESA missions (e.g., Rosetta, Mars Express, Venus Express, BepiColombo) have used large solar arrays rather than nuclear technology and RHU, reflecting both Europe's emphasis on solar solutions and regulatory hurdles for nuclear systems.

Today, Europe is actively researching and developing its own RHU units using americium-241[4], a byproduct of civil nuclear reactors.

The United Kingdom's National Nuclear Laboratory (NNL)[5] and university of Leicester with other European partners, in cooperation with ESA, are leading efforts to produce and test americium-based radioisotope heat and power sources.

The technological evolution behind RHU has been closely connected with nuclear innovations on Earth. Improvements in radioisotope containment, driven by high safety standards and reliability requirements in nuclear reactors, directly inform the design and construction of RHU. Conversely, the compact shielding techniques and robust encasements developed for deep-space missions feed back into terrestrial safety protocols, enhancing best practices for handling radioactive materials. This ongoing exchange of expertise continues to advance both space exploration and nuclear applications on Earth.

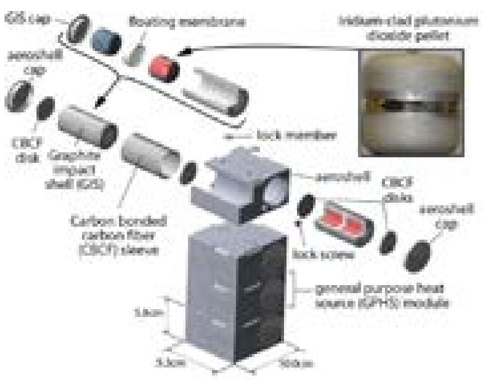
(1) SNAP-19/NIMBUS B INTEGRATION EXPERIENCE, X-450-68-268, August 1968
(2) FINAL Programmatic Environmental Assessment of Launches Involving Radioisotope Heater Units (RHUs), January 2020
(3) A. M. Abdrakhimov, A. T. Basilevsky, « Lunokhod 1: The position of the first soviet rover», sur Planetology.ru
(4) https://nebula.esa.int/content/americium-fuel-pellet-development-and-medium-scale-plant-design
(5) https://uknnl.com/2023/03/new-contract-from-the-european-space-agency-to-accelerate-work-on-americium-241

Electricity generation by nuclear radioisotope decay: enabling long-duration missions

The use of Radioisotope Thermoelectric Generators (RTGs) has revolutionized the ability to sustain long-duration missions in the solar system's most remote regions.

RTGs are a type of Radioisotope Power System (RPS) which provides electrical power to spacecraft using heat from the natural radioactive decay of radioactive isotopes, in the form of an oxide fuel. The large difference in temperature between this hot fuel and the cold environment of space is applied across special solid-state metallic junctions called thermocouples, which generates an electrical current using no moving parts.

The Department of Energy (DOE), in support of NASA, has developed several generations of such space RPS that can be used to supply electricity — and useful excess heat — for a variety of space exploration missions. The current RPS, called a MultiMission Radioisotope Thermoelectric Generator (MMRTG), was designed with the flexibility to operate on planetary bodies with atmospheres, such as at Mars, as well as in the vacuum of space. An MMRTG generates about 110 watts of electrical power at launch, a source of power that can be matched with a variety of potential mission needs.

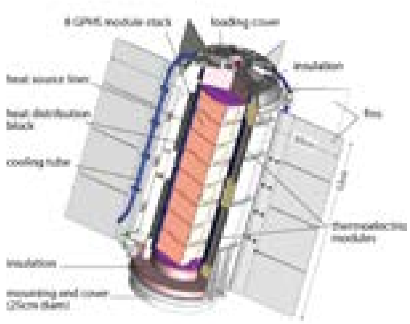


Parts of a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) [6]

Recognizing the strategic importance of RTGs, Europe is actively developing its own capabilities. Today, the **ENDURE**[7] project is primarily driven by the UK's National Nuclear Laboratory (NNL) and the University of Leicester, with industrial support from Orano and Framatome—the latter through its dedicated Framatome Space branch. Their collaboration aims to advance RTG technology and ensure reliable power for future European deep-space endeavours.

In parallel, and on a more limited scale, under the **PULSAR**[8] project, the European Commission Has worked with Tractebel, in collaboration with SCK CEN and the CEA, to develop a roadmap for creating a plutonium-238-based RTG. While Europe has also considered americium-241—an isotope that is more easily obtainable and therefore potentially cheaper, but leading to significantly more massive RTGs (x 4)—, Europe also considers that securing a supply of plutonium-238 remains a critical goal for robust, longer-duration projects[9].

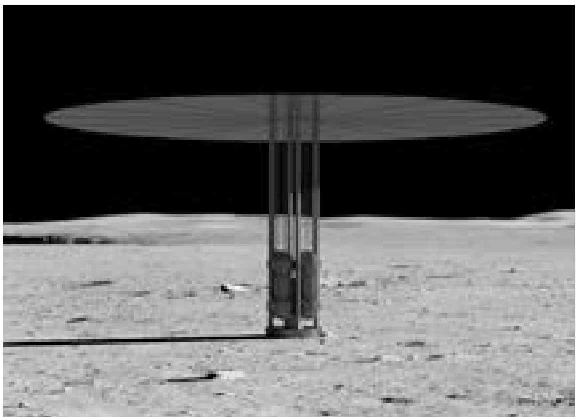
Moving forward, unifying these various initiatives and rallying support from all European nations appears essential to achieving true sovereignty in nuclear-powered space exploration. By pooling resources, expertise, and industrial capabilities, Europe can establish a long-term, independent supply of isotopes for RTGs, bolstering its position in future interplanetary and deep-space missions.



(6) *Emily Lakdawalla's 2018 book The Design and Engineering of Curiosity Emily Lakdawalla after Woerner et al (2012)*
(7) *https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Tomorrow_s_technology_at_ESA*
(8) *https://www.world-nuclear-news.org/Articles/PULSAR-project-to-research-nuclear-technology-for*
(9) *https://www.world-nuclear-news.org/Articles/PULSAR-project-to-research-nuclear-technology-for*

Electricity generation by micro nuclear reactors: enabling human presence

While both remain in early development, micro nuclear reactors represent the next leap in space power systems. NASA's Kilopower[10] project, currently in a preliminary stage following successful proof-of-concept demonstrations, and the UK's Space Micro-Reactor initiative by Rolls-Royce[11]—still at a more conceptual level—illustrate current efforts to develop compact reactors capable of delivering steady power for lunar and Martian bases. These systems could support human life, in-situ resource utilization, and scientific explorations in environments where solar energy is limited by dust, lengthy night cycles, or weak sunlight.



The expertise driving these projects is rooted in terrestrial nuclear technology. Advanced fuel forms, modular reactor designs, and safety protocols developed for terrestrial reactors are being adapted for space applications. This interplay accelerates innovation, creating a virtuous cycle of knowledge exchange.

Europe, with its robust nuclear sector anchored by Framatome and Orano and supported by the CEA has the potential to take its place in this domain. Italy's national space agency (ASI) has engaged the Selene project with the ENEA, which is a first feasibility study regarding a surface nuclear reactor as a power source for a lunar outpost (SELEN[12]) to power future settlements on the Moon. This initiative, illustrates Europe's collective capabilities, yet maintaining competitiveness requires strategic investment and coordination across all member states. As global players like NASA and the UK Space Agency advance their programs, Europe must harness its strong industrial base in energy advanced technologies to remain at the forefront of advanced space exploration.

(10) https://www.nasa.gov/directorates/stmd/tech-demo-missions-program/kilopower-hmqzw
(11) https://www.rolls-royce.com/innovation/novel-nuclear/micro-reactor.aspx
(12) Nuclear, from ENEA and ASI an energy hub on the Moon, SELENE (Lunar Energy System with Nuclear Energy)

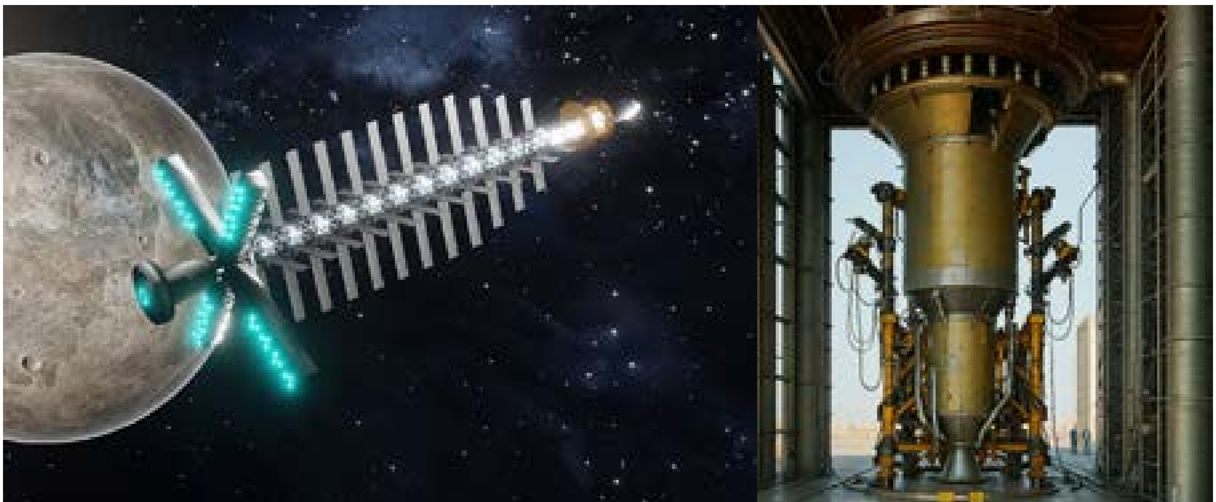
Space propulsion: the next frontier

Nuclear propulsion offers the potential for faster, more efficient travel to destinations like the Moon, Mars, and beyond. Systems such as **Nuclear Thermal Propulsion** (NTP) - in which a reactor heats hydrogen for thrust - and **Nuclear Electric Propulsion** (NEP) - which uses reactor-generated electricity to power ion engines - have undergone preliminary testing and conceptual design since the 1960s. In the United States, the historic NERVA[13] program has carried out ground tests of nuclear engine for crewed missions, laying the groundwork for ongoing research into space propulsion reactors, improved shielding, and advanced thermal management.

In Europe, programs led by the European Space Agency (ESA), alongside industry leaders like ArianeGroup, TAS and Framatome with the support of agency (CEA, CNRS) and university Polimi, are building on this legacy. Projects such as the **RocketRoll[14]**, **Alumni** initiative - conducted under ESA's Future Launchers Preparatory Programme - highlight the continent's emerging commitment to nuclear propulsion. These efforts bring together diverse expertise from universities, space system integrators, and nuclear research institutes, positioning Europe in the wake of major international players like the United States, China and others.

Synergies between terrestrial and space nuclear drive progress in both domains. High-temperature materials, reactor safety measures, and fuel optimizations developed for space propulsion translate into advances for Earth-based reactors example the usage of TRISO type fuel and special ceramic materials. Likewise, the demanding constraints of interplanetary travel encourage innovations that can boost efficiency and sustainability in terrestrial nuclear energy.

To fully realize these benefits, a unified European program under the strategic aegis of ESA, with the participation of aerospace champions like **ArianeGroup**, TAS, ADS and nuclear industry leaders such as **Framatome** and **ORANO**, and the scientific support of National Laboratories such as the **CEA**, and the **ENEA** is essential. By pooling technological resources, aligning policy frameworks, and fostering industrial collaboration across national borders, Europe can accelerate progress towards a first generation of nuclear propulsion systems likely to redefine humanity's reach into space.



NERVA XE in ETS-1 in test facility (Nasa - Left), Artistic illustration of RocketRoll (ASI - right)

(12) https://www1.grc.nasa.gov/wp-content/uploads/NERVA-Nuclear-Rocket-Program-1965.pdf
(13) https://europeanspaceflight.com/esa-study-outlines-2035-launch-of-nuclear-propulsion-demonstrator/

A call for European leadership

The role of nuclear energy in space is not merely an enabler of exploration but a driver of innovation and industry. Its history demonstrates a continuous evolution, deeply intertwined with advancements in terrestrial nuclear technology. Today, as the space economy accelerates, nuclear energy stands at the crossroads of ambition and necessity.

For Europe, the message is clear: act decisively or risk falling behind. With its established industrial leaders, including **Framatome with its brand Framatome Space, Orano, ArianeGroup** and partners across Europe, and under the strategic guidance of ESA, Europe is well-positioned to take its place among the nations mastering nuclear power for space, and to help regulate its use. However, achieving this requires investments, public-private partnerships, and a unified vision to push the boundaries of innovation.

The future of space exploration depends on nuclear energy. Europe must rise to the challenge, asserting itself not just as a participant but also striving to join the global leaders in this exciting frontier.

Deep dive for space propulsion

The history of space exploration

The history of space exploration shows a clear path of ongoing scientific progress and bold experiments.

Starting with the first steps in rocket technology and moving through the Space Shuttle era, each part of space travel's history has faced its own technical challenges and has led to important scientific discoveries. As we explore deeper into space, the limitations of old propulsion methods are becoming more obvious. This article explores how nuclear propulsion could change the way we travel through the space.

Space exploration has always chased advancements in more efficient technology to achieve propulsion function. Early rockets, revolutionary for their time, faced limitations in thrust and fuel efficiency. Today, companies like SpaceX pushed the boundaries with their advanced rockets, improving upon these aspects. However, even with these improvements, deep space exploration remained a challenge. This is where the potential of nuclear propulsion becomes critical. Offering a significant jump over conventional methods, nuclear propulsion **promises greater efficiency, extended mission durations, and the capability to reach previously inaccessible destinations in space.**

Today's non-nuclear propulsion systems, while advanced, face significant limitations. They are constrained by the rocket equation physical limitation, a mathematical law that governs the relationship between fuel, velocity, and mass. Moreover, design requirements can be contradictory depending on the stages of a space mission for example regarding the specific impulse (Isp) and thrust.

Specific Impulse (ISP)

This is a measure of how effectively a rocket uses its fuel, essentially indicating the efficiency of a propulsion system. It's defined as the amount of thrust produced per unit of propellant consumed over time, typically expressed in seconds. A higher Isp means the engine is more efficient, as it generates more thrust for a given amount of fuel. This is particularly important for long-duration missions where carrying large amounts of fuel is impractical.

Thrust

This is the force exerted by the engine to propel the rocket through space, measured in newtons or pounds. It's a direct measure of the power of the engine. Higher thrust allows a rocket to accelerate more quickly and is crucial during liftoff when overcoming Earth's gravity is a priority.

The contradiction between Isp and thrust result from the fact that optimizing for one can often led to compromises in the other:

- High Isp engines, like those used for deep space missions, often have lower thrust. They are efficient and ideal for long-duration missions where carrying a lot of fuel isn't feasible. However, their lower thrust makes them unsuitable for the initial phase of a mission, where high thrust is needed to escape Earth's gravity.

- Conversely, high-thrust engines, ideal for liftoff and escaping Earth's gravity, tend to have lower Isp. They consume fuel more rapidly, providing powerful thrust for short durations. This makes them less efficient for long-duration space travel.

The table below summarize the challenges in each of the 3 phases of a trans planetary mission, focusing on the balance between Specific Impulse (ISP) and thrust. It shows how important the dilemmas are and how complex the design of an optimal propulsion system can be.

Phase[15]	Specific Impulse (Isp) Challenge	Thrust Challenge	Dilemma
Gravity Extraction to Orbit (Liftoff and Earth Departure)	Lower Isp due to high-thrust requirement.	High thrust required for liftoff and breaking free from Earth's gravity	Using a higher Isp system would be more fuel-efficient but might not provide the necessary thrust to achieve orbit.
Trans-planetary Travel (Cruise Phase from Earth Orbit to destination planet Orbit)	High Isp desired for fuel efficiency over prolonged space travel.	Lower thrust as no immediate large accelerations is necessary.	Higher thrust could shorten travel time but consume more fuel, while high-ISP, low-thrust is more fuel-efficient but results in longer durations.
Orbit Insertion and Descent and Landing	Lower Isp due to high-thrust requirement for rapid deceleration.	High thrust beneficial for rapid adjustments and descent.	Using a high-ISP propulsion system could be more fuel-efficient but might not provide rapid deceleration needed for safe landing.

Now let's look at some order of magnitude of the performance of some mature and non-mature non-nuclear technologies in terms of Ips and thrust. One can remark that the only performing and mature technology for Gravity Extraction to Orbit is the chemical propulsion however it has a relatively poor ISP. In the other part of the technology landscape, we have the Solar Sails technology that is impossible to use for Gravity Extraction to Orbit but has a theoretically unlimited ISP.

Propulsion Technology[16]	Approx. Specific Impulse (Isp)	Approx. Relative Thrust	Technology Readiness Level (TRL)
Chemical Propulsion	250-450 s	High	9 (Mature)
Electric Propulsion	500-5000 s	Low	8-9
Electric Propulsion Resist jet	300-500 s	Low	8
Electric Propulsion Arc jet	500-800 s	Low	7-8
Electromagnetic Propulsion	1000-6000 s	Low	6-8
Electrostatic Propulsion (Ion Thrusters)	2000-5000 s	Very Low	8-9
Solar Sails	possibly infinite	Very Low	6-7
Magnetic Sails	(Depends on solar wind)	Very Low	4-5
Tether Propulsion	(Depends on usage)	Low	6-7
Pulse Detonation Engines	600-1000 s	High	5-6

Now first question, can nuclear technology do better? Let's test this idea for the Gravity Extraction to Orbit for a known missions like Apollo and its famous Saturn V. The Saturn V had a mass of 2950 tons. Its fuel-to-payload ratio was approximately 50:1, meaning for every ton of payload, it carried 50 tons of fuel. It generated a massive thrust of 3402 tons with a power output of its first stage was around 120 million kilowatts. To put this in perspective, the first stage's power, at is maximum level, is equivalent to about 22 times the output of France's most powerful nuclear power plant: Gravelines. This is roughly the same as the electrical power of about 132 nuclear reactors with Gen 3+ 3 loops Pressurized Water Reactor (PWR) technology. This is huge! We cannot therefore picture replacing the Saturn V engines with PWR technology reactors many another technology.

(15) The return mission is made of the 3 elementary phases played in the reversed order.
(16) Many technologies classification is possible to evaluate the existing non-nuclear technologies. These classification does not claim to be exhaustive and the order of magnitudes of ISP are estimations based on different public sources.

Hence, what are the available nuclear technology that can be used for space propulsion?

Nuclear propulsion options come in various forms, each with unique characteristics and potential applications. From thermal to electric nuclear systems, the possibilities are as varied as they are promising. However, these technologies don't come without challenges.

The table below provides a classification of possible nuclear technologies for space missions. Some of these technologies, reached prototype testing level before being abandoned[17].

From the performance perspective, we can remark that some of nuclear technologies are able to solve the ISP and Thrust Dilemma. For example, Nuclear Salt-water Rocket and Magnetized Target Fusion.

Set apart from the Magnetized Target Fusion technology, the main concern for all these technologies is the challenge of mitigating risks related to the release of radioactive material during normal operation or in the event of an accident. This way the use of nuclear technologies for the gravity extraction to orbit is excluded today. However, the use of these nuclear technologies in the other phases of the space mission still presents some advantages especially because of the high ISP.

Category / Subcategory	Example Projects / Proposals	Core Principle	Key Advantages	Typical Isp	Typical Thrust	TRL
NTP (Reactor heats a working fluid)	• **NERVA** (NASA, 1960s–1970s) • **Timberwind** (USAF, 1980s–1990s) • **DRACO** (DARPA/ NASA, ongoing) • **RD-0410** (Soviet/ Russian)	A fission reactor heats a propellant (often hydrogen), which expands and is expelled through a nozzle to produce thrust.	• Higher specific impulse (~800–900 s) compared to chemical rockets • Faster transit times for deep-space missions	~800–900 s	Moderate	5–6
NEP (Reactor generates electricity for electric propulsion)	• **Prometheus/JIMO** (NASA, early 2000s) • **TEM / Nuclon** (Roscosmos, ongoing)	A fission reactor produces electricity, which powers electric thrusters (ion or Hall-effect), expelling ions for thrust.	• Very high Isp (1,500–10,000 s) • More efficient than chemical rockets • Ideal for long-duration missions	~1,500–10,000 s	Very Low	4–6
Advanced Fission Concepts Pulsed (Orion-like)	• **Project Orion** (USA/ UK, 1950s–1960s)	Series of discrete nuclear explosions (fission bombs) behind the spacecraft, pushing it forward via a massive "pusher plate."	• Extremely high theoretical thrust and specific impulse • Potentially rapid interplanetary or interstellar travel	Variable	Extremely High	2–3
Advanced Fission Concepts Continuous/Direct	• Various **Fission-Fragment Rocket** designs (theoretical) • **Nuclear Salt-Water Rocket** (Zubrin concept, 1990s)	Continuously (or quasi-continuously) expel nuclear reaction products to generate thrust. Salt-water rocket mixes fissile salts in water; fission-fragment rockets eject high-energy fission products directly.	• Potentially very high Isp (thousands to millions of seconds) • Eliminates or reduces need for separate propellant • Could achieve extremely high thrust (in salt-water designs)	High to Very High	Moderate to Very High	1–2
Fusion Concepts Pulsed (Daedalus-style)	**Project Daedalus** (British Interplanetary Society, 1970s)	Series of fusion micro-explosions (inertial confinement) providing thrust in pulses for interplanetary or interstellar travel.	• Potential for extremely high performance (Isp and thrust) • Could enable interstellar missions	Variable (Very High)	High to Extremely High	2–3
Fusion Concepts Continuous (magnetic / inertial confinement)	• **Experimental MagLIF** research at Sandia Labs (USA) • Various tokamak-based direct-exhaust concepts	Magnetic or inertial confinement of a fusion plasma, with energy used to heat and expel a working fluid (or plasma exhaust) continuously.	• Potentially high thrust • Very high Isp • Reduced long-lived radioactive waste compared to fission	Very High	High	2–3

(17) US National Archives. Nuclear Propulsion in Space. On ground testing: https://www.youtube.com/watch?v=eDNX65d-FBY&t=1033s

It's clear that there isn't a miraculous solution or a single technology (nuclear and non-nuclear) capable of providing the ideal balance of specific impulse and thrust without compromising safety. The solution could lie in "hybrid" or "multi-modal" propulsion, which combine nuclear and non-nuclear technologies.

Hybrid propulsion approach involves using two or more types of propulsion systems, each operating independently and not sharing the same propellant or fuel. This setup allows for separate and independent propulsion systems within the same spacecraft.

On the other hand, multi-modal propulsion represents the convergence of multiple propulsion methods using a common propellant or fuel source in a single spacecraft system. This technology is gaining attention as it promises to significantly enhance the capabilities of spacecraft and future space missions. By using shared propellant, multi-modal propulsion offers exceptional flexibility and adaptability for spacecraft, potentially leading to weight reductions and increased efficiency for certain types of missions.

Based on the elements presented before, we defined 3 scenarios: realistic, prospective, and futuristic presented in the table below.

<table>
<tr><th>Scenario</th><th>Propulsion Combination</th><th>Gravity Extraction to Orbit (Liftoff and Earth Departure)</th><th>Trans-planetary Travel (Cruise Phase)</th><th>Orbit Insertion</th><th>Descent and Landing</th></tr>
<tr><td>Realistic</td><td>Hybrid/multi-modal Chemical + Nuclear Electric</td><td rowspan="2">Chemical Propulsion</td><td>Nuclear Electric Propulsion</td><td>Nuclear Electric Propulsion
Variant: Chemical Propulsion</td><td>Chemical Propulsion</td></tr>
<tr><td>Prospective</td><td>Hybrid/multi-modal: Pulsed Nuclear Thermal + Chemical</td><td>Nuclear Thermal Propulsion</td><td>Nuclear Thermal Propulsion
Variant: Chemical Propulsion</td><td>Nuclear Thermal Propulsion</td></tr>
<tr><td>Futuristic</td><td>Magnetized Target Fusion</td><td colspan="4">Magnetized Target Fusion</td></tr>
</table>

The realistic scenario has been studied from the engineering decision perspective and led to the following high level design principles:

- Modular architecture with standardized physical interfaces for the system.
- Modules will be assembled and commissioned in different orbits.
- Modules will be in-orbit re-configured to accommodate different missions' objectives.
- High temperature, high fuel density, fast neutron spectrum reactor for the nuclear modules.
- Heat pipe technology for heat extraction from the reactor module.

Beyond the definition of these scenarios, the adoption of nuclear propulsion is not just a technological decision; it's a geopolitical, market and ethical one. International regulations, public perception, and ethical considerations play a significant role in shaping the future of nuclear propulsion in space exploration.

expert

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