Innovations in Space:

Nuclear and fusion power for deep space exploration

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A Series on Innovation and Space

Innovative technologies are reshaping every industry, presenting new business cases and changing our daily lives. These technologies are hyper-connecting the world and offering new ways to interact. Particularly in the Space and Satellite arena, technology is ever-evolving, expanding, and combining in ways never before contemplated.

At the same time, these innovations bring many legal, regulatory, and contractual challenges and considerations that need to be kept in mind to support the successful launch of a new business. Along with new business models and technologies (some fully or partially still on the drawing board), often come new hurdles, paradigms, and new approaches to partnering and capital raising.

Among the new innovations that are changing the face of space—"NewSpace"—are those that improve satellite and spacecraft functionality and better utilize their capabilities: e.g., big data analytics, radar and optical technologies, 3D robotics, geolocation, earth observation and remote sensing, intersatellite links, and other laser/ light technologies. But there are other innovations that can improve where those same vehicles can go and what they can carry, such as nuclear and electric propulsion, in-orbit repair and fueling of space missions, and other life extension technologies. Combined, these latter innovations can enable a whole new set of opportunities that will change how humanity understands and interacts with space, including commercial space travel; more ambitious and human-led deep space exploration; commercial asteroid and deep space mining; planetary defense against comets and asteroids; and orbital debris detection, avoidance, and removal. One area of development that is enjoying increased focus and attention is the use of nuclear and fusion.

New technologies bring with them many new considerations, many of them quite fundamental. Innovative and disruptive technologies change and improve how we see and interface with the world. They bring great benefits and often a paradigm shift in how the industry develops and the benefits it can deliver. But these new innovations also often raise new issues as to space sustainability, the setting not only of national standards but also global expectations, coordination and cooperation, and the recognition of new risks and safeguards to put into place when technologies are deployed in space.

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Nuclear and fusion power – Powering a new deep space race

Nuclear power has always been essential to mankind's ambitions in space. From the Mars rover Perseverance, to the New Horizons and Cassini programs, and the early Voyager probes (which are the furthest man-made objects from Earth) nuclear power has been the primary power and heat source for many of the most complex and critical space missions. With high fuel energy density and 99%+ availability over long periods of time, this technology has been essential for any activity that is distant from the Sun or requires significant, long-term power or heat on a planet itself.

Looking forward, nuclear and fusion technologies are well-positioned to deliver the performance— including sustained power levels, longevity, and reliability—required to compete in the new space race. This includes taking humans and cargo astronomically long distances and supporting the power requirements for long-term colonies far removed from the safety net of Earth. To this end, China is reportedly making investments in the advanced propulsion sector, including in fission and fusion contexts, that dwarfs current U.S. efforts. For the U.S. and Europe/the UK to remain competitive and win what some are calling the new "Deep Space Race," they must double down on investment in nuclear fission and fusion technologies.

The new proposal to support fusion propulsion innovation

In a paper (Fusion Propulsion Report[1]) the Fusion Industry Association—an association of 24 member companies working to commercialize fusion power—has recommended a US$40 million fusion propulsion funding program using an Advanced Research Projects Agency (ARPA)-style structure to accelerate the use of fusion for space travel. This is examined here in the context of recent efforts by the Department of Energy (DOE), National Aeronautics and Space Administration (NASA), and Defense Advanced Research Projects Agency (DARPA) to work together to accelerate the use of nuclear and fusion power in space.

The Fusion Propulsion Report explains that there is a Deep Space Race developing as the U.S. and other world powers have set their sights beyond just on returning humans to orbit and stepping foot on the Moon. Many are seeking to establish permanent colonies on the Moon and Mars, mine asteroids for their wealth of resources, secure planetary defense against asteroid and comet impacts, promote space transport for passengers and cargo to and from space stations or the Moon, and send astronauts to search for life in the outer solar system.

There are compelling reasons to believe that taking the lead in exploration of deep space (beyond the near-Earth orbit) can bring tremendous returns. This is not just in the form of national pride and scientific progress, but also financial benefits. Some, including Goldman Sachs, have predicted that the world's first trillionaire will be the person that successfully mines asteroids and their tremendous amounts of mineral wealth.

As outlined in the Fusion Propulsion Report, chemical-propelled rockets do not have the fuel efficiency to support this far-reaching agenda. Fusion propulsion can be up to 100 times more fuel-efficient than chemical propulsion, while still maintaining large thrusts—making it a prime option for transporting large payloads to distant destinations or ferrying cargo to and from the Moon. Many designs could potentially compress travel times to the Moon and Mars to hours and months respectively and even get to Saturn in as little as two years. In particular, the Fusion Propulsion Report posits that fusion carries the following advantages for Deep Space Race missions over incumbent technologies:

1. See Fusion Industry Association "Fusion Energy for Space Propulsion: Making Fusion Space Propulsion A Reality by 2030" (June 2021).

Sample Mission	Estimates – Chemical Propulsion	Estimates – Fusion Propulsion
Colonizing Mars	• 7-9 months • Very limited flight windows • Small payloads	• 3 months • Fly nearly anytime, there and back • Colony-level payloads
Mining the Asteroid Belt	• 10+ years • Visits and sample extraction only	• ~4 years • Return trip with commercial payloads
Planetary Defense	• Not usable for deflecting comets or reaching distant objects	• Able to deflect asteroids and comets, even within limited time windows • Able to reach unknown passing objects
Exploring the Moons of Jupiter and Saturn	• 3.5 - 7 years • Small probes only	• 0.5 - 2 years • Round trips, bringing back samples • Human trips eventually possible

Figure 1: Potential advantages of fusion propulsion in sample Deep Space Race missions

However, fusion and other technologies can and should be used together. Fusion propulsion systems need the thrust and power of chemical rockets to get into space in the first place, and many such systems rely on the power provided by other systems, such as nuclear fission or solar, to provide input power.

This report comes at a turning point for fusion propulsion, which is far closer to commercialization than people realize. U.S.-based startup Helion Energy's reached fusion-relevant temperatures of 100 million degrees in its 6th generation device, and DOE's Lawrence Livermore National Laboratory achieved fusion ignition in 2022.[2] Several other companies are planning to demonstrate fusion energy technologies in the near future. Alongside, a host of private funding-backed entities are deploying novel new propulsion designs—many of which they argue are easier to commercialize than terrestrial fusion energy systems, including the UK's Pulsar Fusion, which focuses only on delivering fusion-based space propulsion with an orbital demonstrator of its "Sunbird" concept targeted for 2027.[3]

To bring fusion propulsion technologies to the next level, the Fusion Propulsion Report advocates for an ARPA-style, milestone-based funding program to accelerate the development of critical fusion propulsion technologies and enable designs to start being testing. ARPA programs have a demonstrated track record of moving promising technologies on a track towards commercial deployment by the private sector. The Fusion Propulsion Report recommends a fusion propulsion program that would synthesize best practices from the DARPA and Advanced Research Projects Agency-Energy (ARPA-E) programs and apply it to deep space.

The Fusion Propulsion Report concludes that the US$40 million program "has the potential to transform the way we look at the universe and ourselves, unlock potentially trillions of dollars in scientific and economic innovation, and secure American interests for this century and the next."

2. See Businesswire "Helion Energy Achieves 100 Million Degrees Celsius Fusion Fuel Temperature and Confirms 16-Month Continuous Operation of Its Fusion Generator Prototype" (22 June 2021); DOE, "DOE National Laboratory Makes History by Achieving Fusion Ignition" (13 December 2022).
3. See World Nuclear News, "Pulsar Fusion unveils nuclear fusion rocket concept for space travel" (11 March 2025).

Agencies aligning on use of advanced nuclear systems

In the U.S., the DOE and NASA have a long history of collaboration on the use of nuclear power in space. Over the past 50 years, the DOE enabled space exploration on over twenty NASA missions in deep space and on Mars by providing safe and reliable radioisotope power systems and radioisotope heater units.

This relationship has now accelerated in scope, with a goal to enable much larger uses of nuclear power in space. In 2018, NASA and the DOE launched an effort to develop the Kilopower Reactor, with a hope to demonstrate a fission surface power system on the moon by the end of the decade. Toward the end of the last Trump administration, former Secretary of Energy Dan Brouillette and former NASA Administrator Jim Bridenstine also signed a memorandum of understanding (MOU) to expand the DOE-NASA partnership on space exploration.[4] Nuclear power and propulsion were among the key areas of interest listed in the MOU. This was followed up with Space Policy Directive 6[5], which sought to implement a "National Strategy for Space Nuclear Power and Propulsion," and Executive Order 13972, which recognized the role small modular reactors could play in space exploration.[6]

Currently NASA is examining the possibility of utilizing two nuclear systems in space exploration. The first is a nuclear electric propulsion system, which is highly efficient and allows a spacecraft to travel for longer periods than currently used technologies although at lower thrust. The second type of system is a nuclear thermal propulsion (NTP) system, which is a higher thrust system but still far more efficient than a traditional rocket. (There are fusion analogs of both these systems as well).

Additionally, NASA's Fission Surface Power Project is exploring concepts for an electricity-generating fission reactor on the Moon, in collaboration with DOE and private companies Lockheed Martin, Westinghouse, Intuitive Machines, and X-Energy.[7]

The efforts by NASA and DOE complement a program by DARPA, called Demonstration Rocket for Agile Cislunar Operations (DRACO), to demonstrate a NTP system in orbit, under which Lockheed Martin will develop a spacecraft and BWXT will provide the nuclear reactor and fuel.[8] As DARPA explains, "[t]he space domain is essential to modern commerce, scientific discovery, and national defense. Maintaining space domain awareness in cislunar space—the volume of space between the Earth and the Moon—will require a leap-ahead in propulsion technology."[9] These efforts complement private sector efforts, such as an exciting proposal by Zeno Power Systems to launch radioisotope power systems made from recycled nuclear waste. And to the same end, all three federal agencies have taken interest in the use of fusion to achieve similar goals.

In Europe, following NASA's AEPS thruster program and the UK's Pulsar Fusion, the ESA has commissioned two feasibility studies under the agency's Future Launchers Preparatory Programme in partnership with France's Atomic Energy Commission (CEA). The two programs, RocketRoll and Alumni, focus on alternative technologies (RocketRoll on electric thrusters powered by a nuclear power source and Alumni on a nuclear-thermal propulsion engine), both with the ultimate objective of launching a successful design by 2035.

4. See NASA "Memorandum of Understanding Between National Aeronautics and Space Administration and U.S. Department of Energy Regarding Energy-Related Civil Space Activities" (19 October 2021).
5. See Federal Register "Presidential Policy Directive 6 (Space Policy), "National Strategy for Space Nuclear Power and Propulsion" (23 December 2021).
6. Exec. Order No. 13972, Promoting Small Modular Reactors for National Defense and Space Exploration (12 January 2021).
7. NASA, "NASA's Fission Surface Power Project Energizes Lunar Exploration" (31 January 2024).
8. DARPA, "DARPA Kicks Off Design, Fabrication for DRACO Experimental NTR Vehicle" (26 July 2023).
9. See Defense Advanced Research Projects Agency "Demonstration Rocket for Agile Cislunar Operations (DRACO)" (Accessed 16 April 2025).

Resolving the challenges ahead

As the technology develops, regulatory and other issues are starting to rise to the fore.

First on the list is who will regulate, and how will they regulate, the launch of commercial nuclear systems. A key Presidential memorandum, NSPM-20: Launch of Spacecraft Containing Space Nuclear Systems[10], has started to move the ball forward by setting forth a framework for how the U.S. government can approve launches of radioactive material and nuclear systems in space. In Europe, the ESA has initiated the development of a European space nuclear safety framework (ENSaF), with all previous missions (e.g., Ulysses and Cassini/Huygens) being cooperative missions with NASA, conducted entirely under the U.S. frameworks. Additional guidance is needed to expand on these frameworks, but a start has been made.

Second is the question of regulation of these systems on the ground and after launch in space – in particular where these are not operated entirely by a single government agency. In Europe, where space missions may be undertaken by an international intergovernmental organization, multilateral approval may be required and/or more than one State or international organization may be approving for authorizing a space NPS mission. Furthermore, licenses by the NRC in the U.S., or equivalent body in other jurisdictions, may be required to manufacture, test, export, and otherwise possess these systems on Earth. The NRC and other nuclear regulators are currently debating the regulatory framework for both advanced nuclear systems and fusion energy, which could have implications on how fusion systems and their fuels are regulated on their way to the launchpad or after launch.

Third, the commercial development of space, and the role of nuclear power in space, are both potentially subject to international treaties and norms. This will require conversations between the commercial sector, regulatory experts, and world leaders (and perhaps new treaties) to adapt expected norms to growing commercial interests and capabilities.

What's next?

To successfully compete with China and Russia in the new Deep Space Race, the 'Western World' (i.e. Europe, the UK, and the U.S.) need to accelerate investment in these mission-critical areas and form public-private partnerships to accelerate technology development. There are numerous private companies, including the ventures listed in the Fusion Propulsion Report, pursuing innovative and advanced nuclear space propulsion concepts. And as evidenced in recent events and programs hosted by the DOE, NASA, DARPA, and the ESA, a number of companies stand ready to support the development of nuclear and fusion space propulsion technologies.

However, beyond possibly the DARPA DRACO effort, these initiatives generally lack a significant and long-term dedicated funding program to support their commercialization. Continued investment in nuclear and fusion propulsion concepts, through the establishment of long-term programs with the clear end goal of demonstrating multiple advanced propulsion technologies in space (including but not limited to an ARPA-like program recommended in the Fusion Propulsion Report), can have a tremendous impact on whether the U.S. or another NATO member will "win" the next space race, compared to countries like Russia and China who are making these programs national priorities.

As the technology and funding issues start to be resolved, aligning the regulatory and legal frameworks to enable these new innovative technologies to come to market will be increasingly important. Resolving the manufacturing and testing challenges, and use of these systems on Earth and in space, will be necessary for paving the way for what is effectively a new industry—one which has the potential to change our understanding of space and humanity's role in it.

10. See NASA "Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems" (4 September 2019).

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