State of Play

EMERGING IN-SPACE PROPULSION TECHNOLOGIES

Commercial Technologies and New Programs 2023 Q1 Update

Change is coming to in-space propulsion. This edition of State of Play looks at what's happening with emerging technologies for nuclear, electric, and solar propulsion.

Overview

The marketplace has arrived at a point where multiple companies have advanced technology for nuclear, electric, chemical, and solar propulsion that could dramatically improve Earth-centric space operations and interplanetary exploration in the years and decades to come. Below, we survey technologies and the market's "state of play" for insight into near- and medium-term developments.

Key Technologies and Developments

Nuclear Propulsion—What Is It?

Nuclear propulsion derives from two atomic processes, fission and fusion. In ***fission***, heat is created when energetic neutrons bombard and break apart uranium atoms within a nuclear reactor. Hydrogen propellant is then passed through the reactor for propulsion. The term "Nuclear Thermal Propulsion" (NTP) generally implies a rocket engine with a nuclear fission reactor for heat. For ***fusion***, atoms of deuterium or tritium (isotopes of hydrogen) are forced together to become heavier atoms, which in turn releases tremendous heat. This process creates hot fusion plasma, which either has propellant directed around/through it, or is directly exhausted out a nozzle for propulsion. In either case, these systems must be carefully traded with conventional propulsion methods at a holistic mission architecture level to properly assess the potential benefits, challenges, and investment considerations for meeting mission needs.

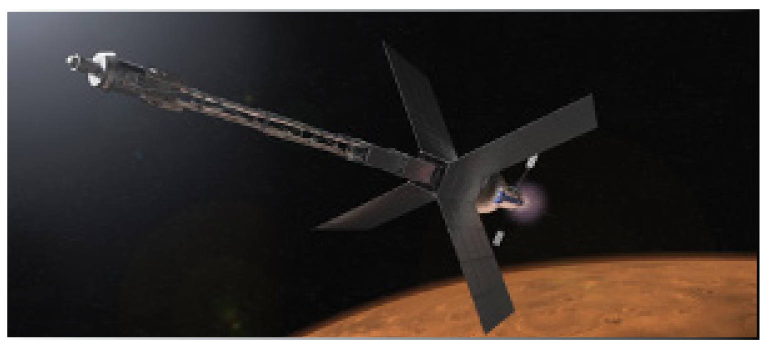
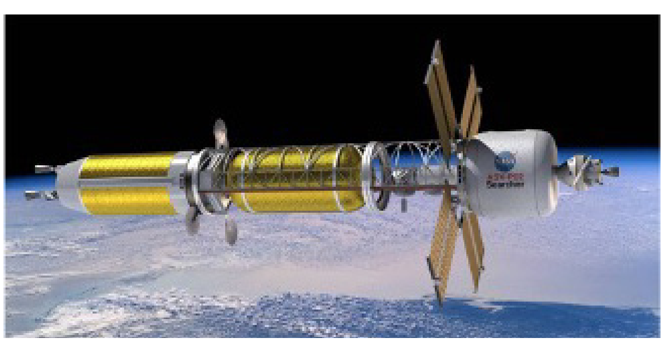


Illustration of a Mars transit habitat and nuclear propulsion system that could one day take astronauts to Mars. Credit: NASA/Advanced Concepts Laboratory.

NASA and the Defense Advanced Research Projects Agency (DARPA) both have projects focused on the development of demonstration NTP systems. The space nuclear propulsion (SNP) project at NASA Marshall Space Flight Center has three industry providers designing concepts for an NTP engine reactor and is entering the second year of the project as the designs mature. The objective is to develop a small-scale NTP engine ready for either ground or flight test within this decade, and which would



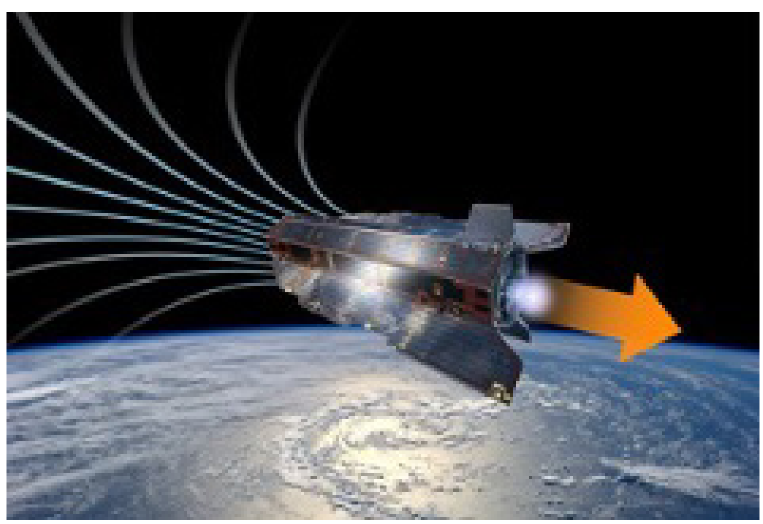
Spacecraft propelled by nuclear fission or fusion are now being researched as a faster means of traveling the solar system. Illustration: NASA.

ideally be extensible to the NTP engine conceptualized for crew/cargo round-trip missions to Mars. Concurrently, DARPA is ready to begin the second phase of their Demonstration Rocket for Agile Cislunar Operations (DRACO) project aimed at flight demonstrating an NTP system in near-Earth space by 2027.

There has also been significant interest in the utilization of ***fission-based nuclear electric power*** as a supplement to solar, battery, or radioisotope systems for spacecraft or planetary surface applications. Nuclear power promises to offer continuous, consistent, and reliable power ranging from tens of kilowatts to megawatt levels, regardless of shadowing or orientation to the sun. Part of NASA's SNP project examined the critical technology elements and maturation needed to enable high-power nuclear electric propulsion options for Mars missions, while **NASA Glenn Research Center** has the fission surface power (FSP) project dedicated to exploring conceptual designs for a planetary power plant serving lunar or Mars bases and infrastructure. Building from NASA's robust heritage with the study and testing of space nuclear power systems, the DOD has a vested interest in evaluating the use of spacecraft nuclear fission power to enable national security missions. **Air Force Research Laboratory (AFRL) (Kirtland AFB)** recently completed a study of nuclear power systems for the **U.S. Office of Management and Budget** and is preparing to begin a project called **Joint Energy Technology Supplying On-Orbit Nuclear Power (JETSON)** to conceptualize such systems with industry.

All of the fission-based projects discussed above are cooperatively and directly supported by the **Department of Energy**, who is bringing to bear their robust capability for space nuclear reactor design. In addition, Aerospace has become a focal point for these projects in our federally funded research and development center (FFRDC) role supporting multiple, cross-agency customers spanning defense, civil, and commercial interests. Aerospace has been a consistent entity among both industry and government participants by continuing to provide technical and programmatic support, along with internally developing new capabilities to meet future needs.

Meanwhile, the Defense Innovation Unit announced in May of 2022 it selected Ultra Safe Nuclear Corporation and Avalanche Energy Designs, LLC, to develop small nuclear-powered spacecraft for in-space demonstrations planned for 2027. In April 2022, startup Zeno Power received $20 million in Series A funding for their "small-scale nuclear batteries that can power spacecraft for years." The substantial interests in space nuclear propulsion and power have also led to a flurry of conference activity. The American Institute of Aeronautics and Astronautics (AIAA) Accelerating Space Commerce, Exploration, and New Discovery (ASCEND) conference held in October of 2022 had seven sessions related to the topic, up from one the prior year, and involved representatives from several DOD, civil, and European projects. The Joint Army-Navy-NASA-Air Force (JANNAF) conference held in November saw five technical paper sessions and two other papers, up from zero the prior year, and drew some of the largest audiences of the event. The most notable technical papers recognized at both events were produced by various authors from the **University of Alabama at Huntsville**, who have been supporting the NASA SNP project with relevant academic research.

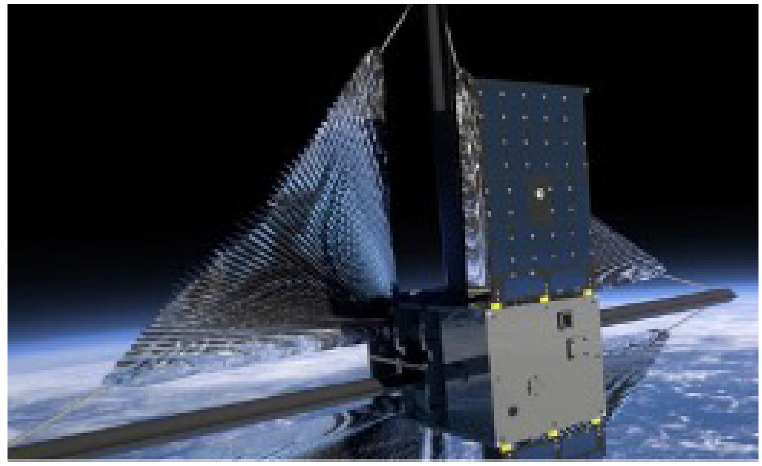


Air-scooping electric propulsion satellite (artist's concept). Image Credit: ESA.

Nuclear fusion propulsion development companies have received significant venture capital funding to pursue this "green" technology. Due to the temperatures achieved, fusion propulsion has a very high efficiency compared to chemical and fission systems. For example, the space shuttle has 440 sec specific impulse (I_{sp}), whereas nuclear fusion propulsion may enable an I_{sp} in the high thousands of seconds.

The downside is that fusion propulsion does not produce as high thrusts and accelerations as fission or chemical concepts, thus potentially increasing travel time.

Nuclear electric propulsion (NEP) is being researched as a viable alternative for solar- or battery-powered electric propulsion. Instead of solar or battery systems providing direct electrical energy to a conventional electric propulsion system, NEP uses a nuclear fission- or fusion-based reactor to heat a working fluid to produce electricity. The electricity then directly powers the EP system. A February 2021 study by the National Academy of Sciences notes that nuclear electric and NTP both need to overcome technical hurdles on the path to a crewed mission to Mars in the 2030s.



Solar Sail. Image credit: NANOAVIONICS/NASA.

Electric propulsion uses electrical energy to accelerate ions to produce a low thrust. For specific applications, electric propulsion provides excellent in-space capabilities. In December 2020, French startup ThrustMe performed the first on-orbit tests of an **iodine-fueled electric propulsion** system, proving its ability to change a CubeSat's orbit. According to the company, the system was tested during two 90-minute burns and resulted in a total altitude change of 700 meters. ThrustMe claims that iodine propellant allows propulsion systems to be "delivered completely prefilled to customers and allows for a simpler satellite integration process." Iodine-fueled electric propulsion uses a Hall thruster with iodine as the propellant. Another novel approach is taken by Momentus, developing a microwave electrothermal system using water as the propellent. Should there be supplies of water on celestial bodies, this could be significant.

Air-scooping electric propulsion (ASEP) is a cutting-edge concept for spacecraft propulsion that does not require any propellant at all. An ASEP ingests scarce air molecules from the upper atmosphere for propellant. This extends the lifetime of satellites in very low Earth orbits by providing periodic reboosting to maintain orbital altitudes. Although an ASEP spacecraft has not yet flown, recent **Japan Aerospace Exploration Agency (JAXA)** and **European Space Agency** experiments have demonstrated that electric propulsion can effectively counter atmospheric drag, including this recent ground test. **The Aerospace Corporation** recently extended the state of play with this paper focused on ASEP design and atmospheric challenges, as well as new applications and mission opportunities.

Solar sailing is a method of spacecraft propulsion using mechanical pressure exerted by sunlight on large mirrors, similar to wind pushing a sailboat. High-energy laser beams could be an alternative light source to exert greater force than sunlight (known as "beam sailing"). A solar sail-propelled spacecraft could reach distant planets and star systems much more quickly than a rocket-propelled spacecraft because of the continual acceleration that solar sailing provides. In 2010, Japan's Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS) was the first spacecraft to successfully demonstrate solar sail technology with a Venus flyby. In 2019, The Planetary Society's LightSail 2 launched a solar sail spacecraft that uses sunlight to change its orbit. In November 2022, NASA launched Near-Earth Asteroid (NEA) Scout, a low-cost, solar sail CubeSat that was designed to unfurl a large solar sail and demonstrate the capability of a small spacecraft in cislunar space to perform reconnaissance of an asteroid. Advances in electric and chemical propulsion are expected to move at a slower rate than nuclear propulsion, while for niche missions, solar sailing is slowly being mainstreamed by virtue of its JAXA and Planetary Society space heritage, the French Gama Alpha 6U solar sail Cubesat launched in January 2023, and other upcoming U.S. and international initiatives.

Future Outlook

We expect the pace of change to accelerate, and the number of new commercial space technology companies to continue to grow for at least the next 3–5 years. This is due to increasing government and commercial demand for propulsion technologies; new, low-cost, rapid methods of developing and testing emerging technologies; and continuing availability of investment capital, both from the private sector and U.S. government agencies. Overall, we are likely to see new market entrants in virtually all of these in-space propulsion technologies. In particular, we expect to see an increase in efforts to find a breakthrough case for nuclear fusion propulsion, and we expect increasing coordination among the U.S. government spacefaring organizations of NASA, United States Space Force (USSF), and others where it comes to funding technologies with overlapping mission benefits. Advances in electric and chemical propulsion are expected to move at a slower rate than nuclear propulsion, while for niche missions, solar sailing is slowly being mainstreamed by virtue of its JAXA and Planetary Society space heritage, and NASA's NEA Scout program.

By Laura Speckman with Aerospace Corporation Contributors:

Andrew Cortopassi
Andre Doumitt
Tom Heinsheimer
Andrea Hsu
Greg Meholic
Julie Reiss

The Aerospace Corporation | 2310 East El Segundo Boulevard, El Segundo, California 90245-4609 USA | www.aerospace.org