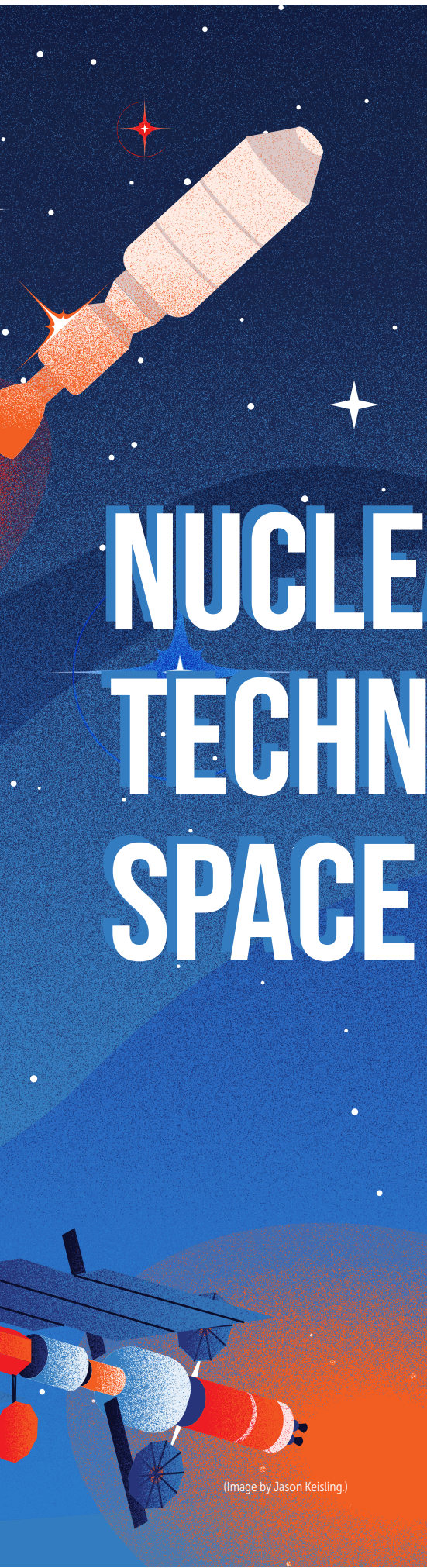






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NUCLEAR FISSION TECHNOLOGIES FOR SPACE EXPLORATION

Anthony M. Calomino, Kurt Polzin, Venkateswara Rao Dasari,
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NASA is developing multiple technologies for space nuclear power and propulsion to enable a sustained lunar presence and to propel a crewed mission to Mars.

(Image by Jason Keisling.)

NUCLEAR FISSION TECHNOLOGIES

Humans have been captivated by Mars for centuries. People dream of one day having a colony on our neighboring planet, but that future is fraught with many challenges. Although we have sent rockets carrying rovers to the surface, carrying humans will place additional demands: a larger spacecraft with different propulsion systems, more power during the stay, and resources to make a return journey.

Additionally, human health is of the utmost concern. Exposure to cosmic radiation and microgravity during a long flight to Mars poses many biological challenges, including decreased muscle mass and bone density, visual impairment, and an increased risk for degenerative diseases and cancers. Not to mention the potential for psychological stress because being in isolation with only the other crew members affects mental health.

Space nuclear technology isn't new. As early as the 1950s, propulsion systems based on the fission of uranium atoms were being designed for rockets. Nuclear fission propulsion systems harness the heat released when uranium atoms split. The energy then is used either to produce electricity or to directly heat a propellant such as hydrogen. To date, only one US-built nuclear reactor for space has successfully reached orbit; the country's other rockets remain reliant on chemical reactions for propulsion.

The technological limits of what chemical propulsion can provide have been reached. Human exploration cannot go much beyond the Moon without a new type of engine. Although chemical propulsion will still be used to escape

Earth's gravity well, nuclear propulsion can expel propellant faster and allow a rocket to travel farther using less fuel. On the surface of another planet, nuclear systems may be the best way to power any permanent space bases, especially when greater power is needed and when solar power won't suffice. New nuclear efforts are currently being funded to facilitate missions to the Moon, Mars, and beyond.

Fission propulsion

Nuclear fission systems possess a high energy density: They deliver significant total impulse in a compact package. Applications for in-space propulsion include nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP). An NTP system, like that illustrated in figure 1, uses the heat generated in a fission reactor core to convert a liquid propellant into a gas, which is then expanded through a nozzle to provide thrust. Much like a terrestrial nuclear power plant, an NEP system, like that shown in figure 2, uses fission to generate electricity, which then ionizes and accelerates a gaseous propellant.

Compared with chemical propulsion systems, both NTP and NEP provide significantly higher specific impulse I_{sp} , defined as the momentum transferred to the rocket per unit weight of propellant flow and expressed in seconds. The greater I_{sp} means that less propellant is needed for a given mission. Nuclear propulsion systems could reduce trip times to Mars by 25% or more and deliver payloads of considerably greater mass, thereby supporting a human presence while still accommodating enough propellant for the return trip to Earth. The systems also provide significantly extended capabilities for aborting missions and flexibility in mission planning, including broader departure windows.

For a human Mars mission, the target I_{sp} is approximately 900 seconds, roughly twice as much as is achievable with conventional chemical systems. For hydrogen propellant—the leading option for a Mars mission because of its low molecular weight—that I_{sp} corresponds to a temperature of approximately 2700 K when the propellant exits the reactor.

The largest technological challenge involved in NTP is the development of robust fuel and reactor components that can withstand the extreme thermal, chemical, and mechanical environments associated with the process of rapidly heating cryogenic liquid hydrogen to 2700 K. The reactor increases to maximum power and temperature in as little as a minute. The engine then operates at maximum power for roughly 30 minutes per maneuver, of which there will likely be six to eight for a human Mars mission. The engine is needed to leave the Earth–Moon system and make midflight course adjustments.

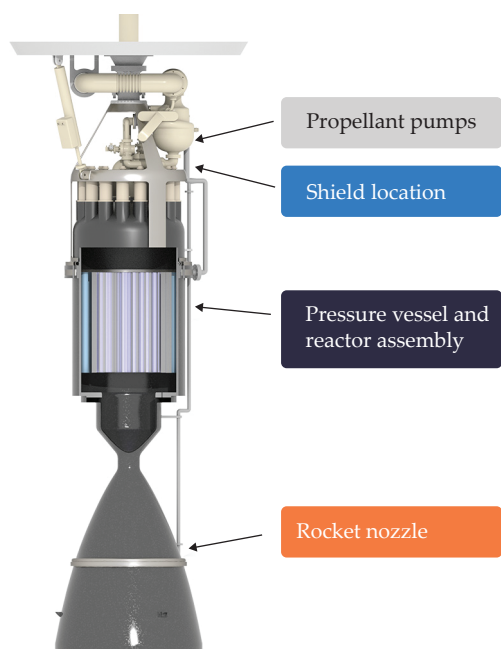


FIGURE 1. IN A NUCLEAR THERMAL PROPULSION SYSTEM, the combustion chamber of a conventional rocket is replaced by a nuclear reactor. Fission heat is directly transferred to a propellant that flows through the reactor. The hot propellant is then expanded through a nozzle to generate thrust. (Image adapted from Analytical Mechanics Associates.)

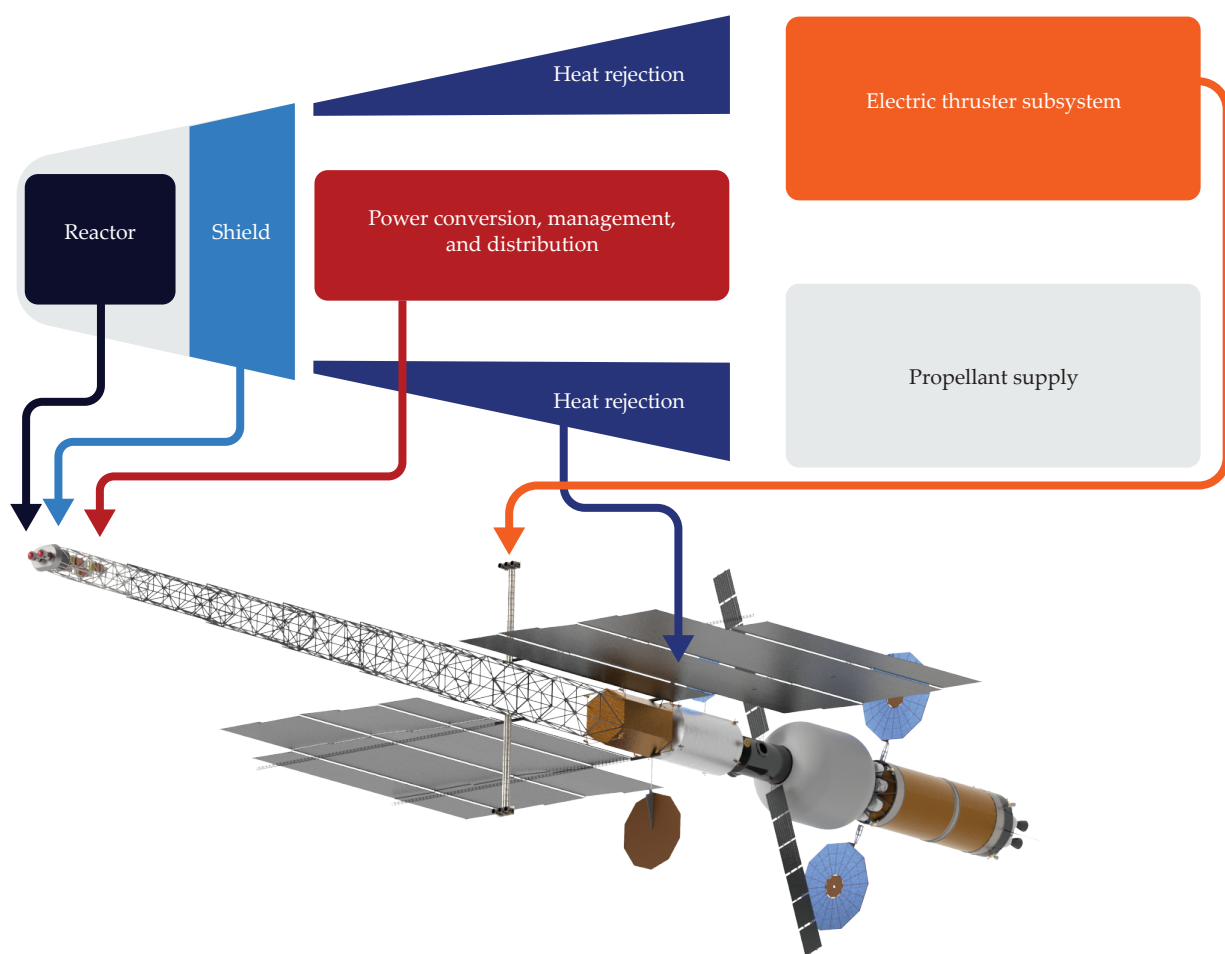


FIGURE 2. A NUCLEAR ELECTRIC PROPULSION SPACECRAFT is still conceptual, but work is being performed to develop the technology. An engineering rendering of one such design is shown alongside a simplified schematic of the components required to generate and distribute electrical power. The electricity accelerates an ionized gas to provide thrust. (Image adapted from Analytical Mechanics Associates.)

Another challenge is the long-duration storage of cryogenic hydrogen. A large quantity of hydrogen is needed for both the trip to Mars and the return, and an advanced cryogenic fluid management system is required to prevent boiloff. NASA is developing those systems alongside other technologies needed for a human Mars mission.

In NEP, the heat from the reactor core is converted through a closed thermodynamic cycle into mechanical energy, which drives a generator to produce electricity. An NEP system achieves and sustains considerably higher I_{sp} (2000–8000 seconds) compared with an NTP system but at much lower thrust, although thrust does increase with additional reactor power.

Although not as hot as NTP, NEP still requires a high-temperature reactor (above 1200 K) to reduce the power system specific mass—the mass per unit power produced—to the level at which a nuclear power source is a value-added design choice. For high-power missions, the

radiators used for heat rejection will be large and will likely require in-space servicing, assembly, and manufacturing technologies. Those technologies, however, need to be developed. Ground testing a full-scale, fully integrated NEP system for a Mars mission is challenging because of its size and because it will need to operate for several years. Alternative ground-testing strategies may include independent subsystem tests combined with robust system modeling, testing for durations shorter than the full operational duration, and scaling to extend subscale test results to the full-scale system.

Some missions will likely use a spacecraft with a dual propulsion system. An NEP system's low-thrust, high- I_{sp} electric thrusters can pair well with a high-thrust system, such as chemical propulsion or NTP. The high-thrust system allows for fast escapes from and insertions into planetary gravity wells, while the high- I_{sp} NEP system can continuously accelerate the vehicle and significantly change its

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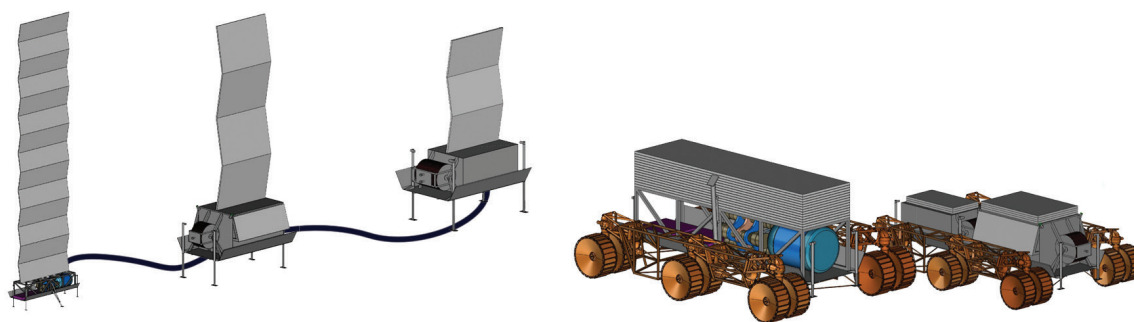


FIGURE 3. A FISSION SURFACE POWER CONCEPT developed by NASA. The design has three connected components that generate electricity, convert it to a usable voltage, and serve as a control unit. The system would supply 40 kW of electrical power on the lunar surface. Each of the components could be compactly stowed for transportation. (Illustration adapted from NASA.)

momentum as the thrust is integrated over the entire deep-space flight path.

Fission power

Rovers on the Moon and Mars currently rely on solar or radio-isotope power to keep their systems running, but a human space base will need much more power. The power-rich environment provided by nuclear fission systems may enable the development of a robust lunar economy and permit human exploration on the surface of Mars and beyond. Conceptually, a fission surface power (FSP) system is modular and extensible to a wide range of electric power levels, from tens to thousands of kilowatts. When humans reach a new planet, they could unload FSP modules that could generate electricity for a variety of applications. Figure 3 shows one concept for a three-pallet system that can be stowed on rovers for easy transport.

The power-system mass is more of a constraint for FSP systems than for propulsion reactor systems because FSP systems must fit on a vehicle that lands on the surface of another planetary body rather than one that remains in space. Once on the surface, they can operate continuously in harsh environments for long durations without the need to refuel or rely on outside energy sources, such as the Sun. And unlike solar arrays, FSP systems don't have their output diminished by factors like dust accumulation.

NTP, NEP, and FSP reactors share some commonalities. Their core contains nuclear fuel, into which fissioning atoms deposit immense quantities of heat. An intricate network of channels incorporated into the reactor core is used to cool the fuel and extract heat. At peak operation, an NTP engine, for example, would deposit 500 MW of thermal power or more into the fuel. Failure to adequately remove that heat could cause the fuel to melt within seconds.

NEP and FSP power densities are two orders of magnitude lower than the power density of NTP, so the peak stress on the fuel elements is less. But power reactors operate for a long time, often many years, and the fuel elements in NEP and FSP

systems receive a lifetime neutron dose that is at least an order of magnitude higher than what NTP elements receive. Although NEP and FSP power reactors operate at lower temperatures than NTP systems, the large total neutron dose, additional nuclear fuel burnup, and fission product buildup are likely to result in significant swelling and deformation of both nuclear fuels and structural materials. In some ways, that makes developing an NEP or FSP reactor just as challenging as an NTP reactor.

Historical efforts

Multiple NTP programs have been initiated over the past seven decades, including programs in the Soviet Union, the US, and, more recently, China. The only US programs to date to build and test NTP reactors and engines were Project Rover, active from 1955 to 1973, and the Nuclear Engine for Rocket Vehicle Applications (NERVA) program, which ran from 1961 to 1973. Rover and NERVA tested numerous reactors and engines, all using hydrogen propellant, in open air at the Nevada Test Site (now the Nevada National Security Site); one such test is shown in figure 4. Among the programs' achievements were an NTP-produced thrust of 250 000 pounds of force (lb_f), or approximately 1100 meganewtons; continuous operation of a reactor for 62 minutes; and a peak reactor temperature of 2750 K.¹

There have been several NTP programs since Rover and NERVA, but none have successfully reached the point of producing integrated nuclear rocket systems that could be assembled, tested, and launched. That is partially because of challenges in testing an NTP engine on the ground. Increased regulatory and safety constraints now require performing extensive analysis, processing and scrubbing of the nozzle flow before exhausting byproducts into the environment, and building robust reactor-containment shielding, all of which increase test costs.

Numerous NEP and FSP programs have also been initiated over the years, with the most notable being the Systems for

Nuclear Auxiliary Power (SNAP) program, which ran from 1955 to 1973. It aimed to develop lightweight, compact nuclear electric systems for space, sea, and land use. Several reactors were developed and tested at the Santa Susana Field Laboratory, including the SNAP 10A system shown in figure 5.

On 3 April 1965, SNAP 10A became the first and so far only nuclear reactor launched by the US. Following launch, it produced more than 600 W of electrical power and operated for 43 days before an electrical system failure on the host spacecraft ended the mission. SNAP 10A remains safely in a high orbit to this day.²

Current US space nuclear activities

Several of today's efforts are aimed at developing the technologies that will enable NTP, NEP, and FSP for fast-transit missions to the Moon, Mars, and the outer planets and for power production to support permanent outposts on their surfaces. Current efforts are focused on utilizing high-assay low-enriched uranium (HALEU) nuclear fuels, which have ²³⁵U enrichment below 20%. (For more on NASA's uranium fuel-based developments, see *PHYSICS TODAY*, December 2017, page 26.) Using HALEU fuel reduces proliferation concerns, enables university and commercial-sector participation in the development of space nuclear systems, and is in line with President Trump's Space Policy Directive-6. Issued on 16 December 2020, the presidential memorandum states that "the use of highly enriched uranium in SNPP [space nuclear power and propulsion] systems should be limited to applications for which the mission would not be viable with other nuclear fuels or non-nuclear power sources."

Because space nuclear system designs and enrichment levels differ from the designs and fuels used in the past, it is harder to extrapolate from historical test data. The scope of the current projects covers the spectrum from technology advancement and maturation to preliminary design and analysis that support flight demonstration missions.

NASA's space nuclear propulsion project is responsible for all the agency's work related to NTP and NEP. Those efforts have focused on design and op-

erational testing of components and subsystems at prototypical conditions. The test results are used to develop predictive modeling and simulation tools to guide additional R&D for the design and execution of future flight missions.

A program initiated under the space nuclear propulsion project is the investigation of multiple fuel and moderator types and various composite structures for containment and insulation. In 2021, the US Department of Energy, on behalf of NASA, selected three companies to design a HALEU-fueled NTP reactor that could operate at temperatures commensurate with a 900-second specific impulse, an engine thrust of 12 500 lb_f, and a reactor mass under 3500 kg. Two companies received additional funding in 2023 to focus on manufacturing demonstrations and the evaluation of hardware under various engine conditions, including high temperatures while exposed to hydrogen gas.

The space nuclear propulsion project is also partnering with the US Department of Defense, US Department of Energy, and commercial entities to develop and fly one or more NTP demonstration engines. That work will be a valuable operational, regulatory, and safety pathfinder and will establish precedent for mission planners contemplating the use of nuclear technologies.

NEP work is currently focused on maturing technologies that can be used both for lower-power science and robotic



FIGURE 4. ONE EARLY TEST of a nuclear thermal propulsion reactor as part of Project Rover, which ran from the mid 1950s to the early 1970s. Here, fission-heated hydrogen propellant is exhausted into the open air of the Nevada Test Site. (Photo courtesy of the National Security Research Center at Los Alamos National Laboratory.)

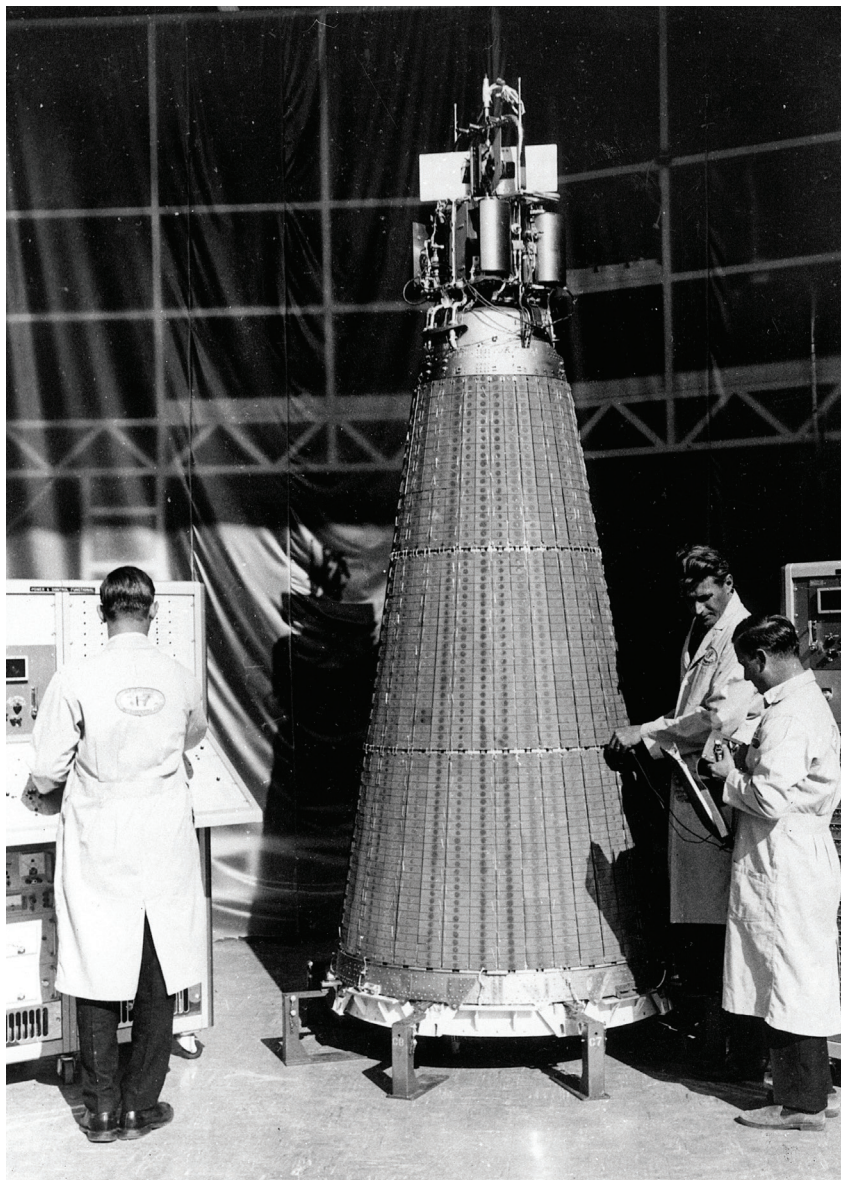


FIGURE 5. THE SNAP 10A OPERATIONAL SPACE POWER REACTOR SYSTEM is the only US nuclear reactor to reach orbit. Launched in 1965, it operated for 43 days before its nonnuclear components failed. (Photo from the US Department of Energy.)

missions requiring on the order of tens to hundreds of kilowatts of electric power (kW_e) and for megawatt-power missions that could support human exploration. The effort, formulated in response to a consensus report by the National Academies of Sciences, Engineering, and Medicine,³ aims to fabricate and extensively test NEP subsystem hardware at scale. That requires assembling a database of measured hardware performance, mass, and wear mechanisms to quantify component and subsystem lifetimes. Through the effort, NASA will gain experience to support the assembly, launch, and operation of NEP systems.

The fission surface power (FSP) project is responsible for all NASA work related to the development and operation of

a space nuclear power system that can be landed on the surface of a moon or other planetary body. The requirements for the recently completed phase-1 effort were a HALEU-fueled 40 kW_e reactor that had a mass of less than 6000 kg and could operate continuously for 10 years.

Outside of NASA, the US Space Force Joint Emergent Technology Supplying On-Orbit Nuclear Power (JETSON) program is funding space fission-reactor development to power conventional—and presently existing—xenon-fed Hall or ion thrusters at $6\text{--}15 \text{ kW}_e$. The JETSON phase-1 effort is scheduled for completion at the end of 2025.

Like many NASA programs of the past, nuclear technology designed for space has synergies with terrestrial applications and developments. Numerous companies are creating microreactors capable of producing tens of megawatts of electric power for commercial, residential, and military applications. Because mass is always a key consideration for space technologies, the push to reduce space-reactor sizes also supports terrestrial microreactor-sized activities. In addition, as space reactors overcome various design challenges, the solutions may result in improved terrestrial reactors. Developing space and terrestrial nuclear technologies in concert with each other will drive the refinement of nuclear policies, improvement of the regulatory process, and growth in the number of skilled technicians and engineers, all of which result in a safer and more reliable nuclear field.

NASA is investing in NTP, NEP, and FSP technologies to establish a sustained lunar presence, send the first humans to Mars, and enable a new era of interplan-

etary science missions. Nuclear power has the potential to usher in a new space age that will make our ancestors' dreams of living on the red planet a reality and pave the way for new and even bigger dreams.

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