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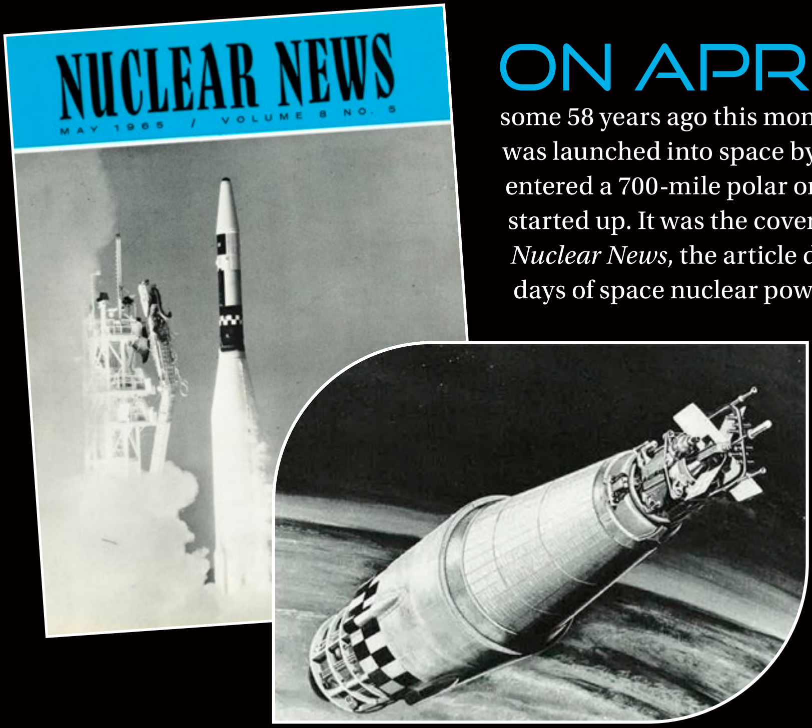
NUCLEAR APPLICATIONS FOR SPACE

SURFACE POWER & NUCLEAR PROPULSION

By Jeremy Hampshire

In this article, we will explore prior NASA programs that incorporated fission technology for space exploration purposes. We also will look at current programs that incorporate fission technology for deep space missions, including missions to the Moon and Mars.



This artist's conception of the SNAP-10A nuclear power system, published in the May 1965 issue of *Nuclear News*, shows the reactor (top right) and the thermoelectric converter-radiator (center) mated to an Agena vehicle at lower left.

ON APRIL 3, 1965,

some 58 years ago this month, the SNAP-10A power reactor was launched into space by an Atlas-Agena D rocket and entered a 700-mile polar orbit, after which it was remotely started up. It was the cover story of the May 1965 issue of *Nuclear News*, the article describing the launch and the early days of space nuclear power systems.

The coverage goes on to describe the Systems for Nuclear Auxiliary Power (SNAP) program. In the article, Glenn T. Seaborg, then chairman of the Atomic Energy Commission, acknowledges that "a nuclear reactor is the only practical device to meet the power requirements of space exploration and travel."

The goal of the SNAP program was to provide a compact reactor that could meet both the demands and restrictions of space travel. The primary contractor, Atomics International, a division of North American Aviation Inc., led many critical aspects of the SNAP program.

SNAP-10A was the first nuclear reactor tested in orbit. Prior to launch, safety systems were heavily vetted through testing at the Rocketdyne Santa Susana Field Laboratory. It consisted of a 34-kW reactor paired with a power conversion unit that could produce upwards of 500 W of electricity.

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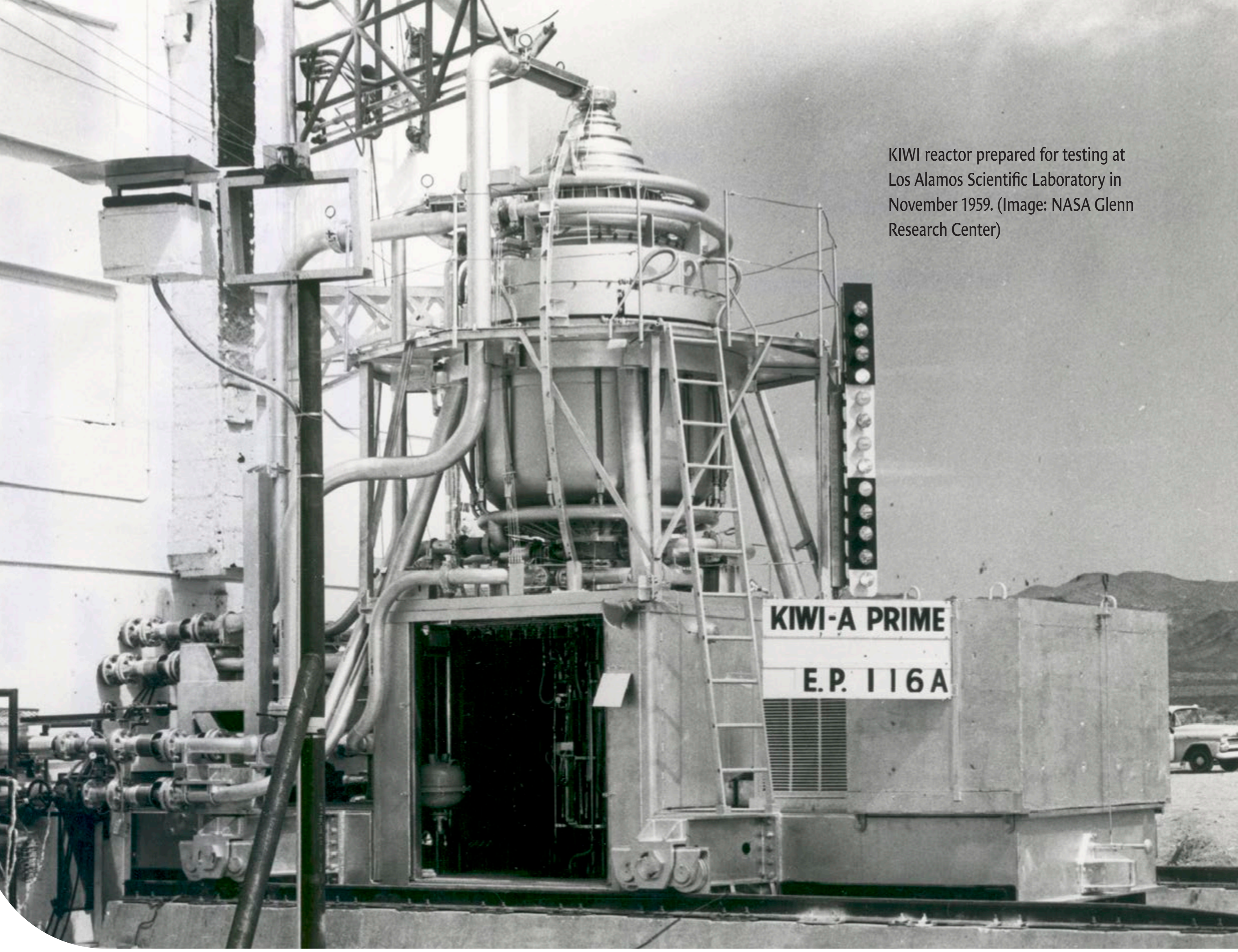


KIWI reactor prepared for testing at Los Alamos Scientific Laboratory in November 1959. (Image: NASA Glenn Research Center)

The reactor core was fueled with 37 fuel rods made of uranium-zirconium hydride. Four control drums in the radial reflector controlled reactivity. The reflector was held to the reactor by a band affixed with an explosive bolt. If there was ever a need to shut down the reactor in an emergency situation, the explosive bolt could be actuated, and the reflector would be ejected from the reactor. Once the reflector was ejected, neutrons would no longer be reflected back into the core, so fission could not be sustained.

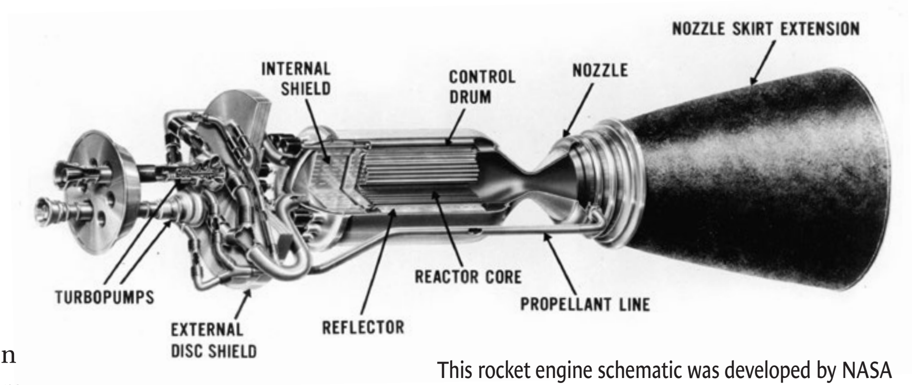
The SNAP-10A reactor was cooled with the liquid metal coolant eutectic sodium-potassium, also known as NaK. The use of a liquid metal coolant allowed higher core temperatures at lower system pressures, which promoted safer operation. A thermoelectric pump was sufficient to circulate the NaK, providing necessary reactor cooling.

SNAP-10A took flight into a circular-polar Earth orbit on an Atlas-Agena D rocket that lifted off from Vandenberg Air Force Base on April 3, 1965. On May 16 that year, the Agena spacecraft suffered an electrical systems failure that resulted in the automatic shutdown of the reactor after just 43 days in orbit. While the reactor operated well, erroneous signal command control of the spacecraft or a failure of one the spacecraft (non-nuclear system) voltage regulators was concluded as the cause of the mission termination. Unfortunately, the automatic shutdown system was designed to eject the main portions of the reactor's external reflector under any off-nominal and accident condition. Therefore, the automatic reflector ejection rendered the system unable to restart, thereby ending the mission.

In hindsight, Seaborg's statement was correct: Nuclear power is, in fact, the only practical means to power space exploration. The future of deep space exploration depends on our ability to fuel both propulsion and electrical systems via nuclear power.

ROVER/NERVA

(1955–1973)



This rocket engine schematic was developed by NASA under the NERVA program and dated 1970. (Image: NASA Glenn Research Center)

Another nuclear thermal propulsion program, Rover/NERVA, spanned from 1955 to 1973. The Rover program started out as a U.S. Air Force project in 1955 and was transferred to NASA in 1958, at which time it became part of the Nuclear Engine for Rocket Vehicle Application (NERVA) project. Rover was primarily focused on development of nuclear rocket reactor design, while NERVA focused on development and deployment of nuclear rocket engines. When the project was first launched, the prevailing idea was for nuclear fission propulsion to be used as backup for intercontinental ballistic missiles. The theories that nuclear propulsion could be used for a lunar flight second stage and Mars missions were also evaluated.

The project was based out of Los Alamos Scientific Laboratory (LASL), as it was then called, and proved that nuclear-powered propulsion systems could be started and shut down frequently without adverse effects. Reactors developed for Rover utilized highly enriched solid uranium fuel with graphite as the moderator and liquid hydrogen as the coolant. Reactors were built at LASL and shipped to the Nuclear Rocket Development Station in Nevada for testing. The Rover/NERVA programs were discontinued in 1972, and in 1973, just as flight engine development was set to begin, the project was cancelled without any reactors ever leaving the ground. Analysis at the time pointed to chemical rockets being more economical. Developments from Rover/NERVA certainly carried through and provided necessary lessons learned for the future use of fission reactors in space. In the end, three reactors for nuclear propulsion, including KIWI-A and -B, PHOEBUS, and PEWEE, were developed and tested.

KIWI-A was designed to produce about 100 MW of power and ultimately was tested at just 70 MW. KIWI-A was a high-temperature, gas-cooled reactor that demonstrated that hydrogen gas could be used for space propulsion after being heated by a nuclear reactor. There were multiple reactor tests in the KIWI-A series, including KIWI-A (July 1, 1959), KIWI-A' (July 8, 1960), and KIWI-A3 (October 19, 1960). The KIWI-A' test reached 88 MW for 6 minutes, and the KIWI-A3 test reached 112.5 MW for over 4 minutes.

There also were multiple reactor designs in the KIWI-B test series. KIWI-B1A was the reactor test in December 1961. The test only reached a maximum power of 225 MW (i.e., not a hoped-for 1,125 MW), and it had to be terminated after 36 seconds of operation. The KIWI-B4A test was run on November 30, 1962 (reaching a maximum power of 450 MW), the KIWI-B4D test was run on May 13, 1964 (reaching a maximum power of 990 MW), and the KIWI-B4E test was run on August 28, 1964, and rerun on September 10, 1964. The August 1964 test reached a maximum power of 937 MW, and the September 1964 test reached a power of 882 MW. Two KIWI reactors were also placed next to one another in September 1964 to verify that the reactors could be safely operated in clusters.

PHOEBUS was designed to produce 5,000 MW and was tested at 4,082 MW during the PHOEBUS-2A full-power run on June 26, 1968. The test was terminated at this power because the reactor's clamp-band temperature reached its limit of 417 K (i.e., the issue wasn't overheating of the pressure vessel). Control drum reactivity discrepancies, hydrogen flow oscillations, and core temperature scaling inconsistencies were also noted during the test.

PEWEE was designed to have an output of 500 MW and demonstrated that a small reactor could operate in the high temperatures experienced in the rocket engine environment.

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KILOPOWER PROJECT (2015–2018)

The purpose of the Kilopower Project, which started in October 2015, was to power both planetary missions and deep space travel. Kilopower was utilized to demonstrate potential uses for nuclear reactors including nuclear electric propulsion and mission electrical supply.

The prototype reactor known as Kilopower Reactor Using Stirling TechnologY, or KRUSTY, was a 5-kW (thermal) solid fuel uranium-235 reactor that used boron carbide control rods. KRUSTY had a core the size of a paper towel roll. The reactor was cooled by liquid sodium that ultimately transferred heat to Stirling engines.

KRUSTY testing was conducted in phases from November 2017 to March 2018. The phases included the following:

- Component criticals: reactor fuel, the neutron reflector shield, and the start-up rod were assembled in different configurations and total reactivity was measured.
- Cold criticals: zero-power critical testing was performed when the heat pipes, clamps, insulation, and vacuum vessel were added.
- Warm criticals: the core was heated incrementally using fission power.

The testing showed that the system operated as expected and that the reactor was highly tolerant of possible failure conditions and transients. The key feature demonstrated was the ability of the reactor to load-follow the demand of the power conversion system. The thermal power of the test ranged from 1.5 to 5.0 kW(thermal), with a fuel temperature up to 880°C. Each 80-W(electric)–rated Stirling converter produced about 90 W(electric) at a component efficiency of about 35 percent and an overall system efficiency of about 25 percent.

In 2018, NASA and NNSA engineers lower the wall of the vacuum chamber around the Kilowatt Reactor Using Stirling TechnologY (KRUSTY) system. The vacuum chamber was later evacuated to simulate space conditions. (Photo: LANL)

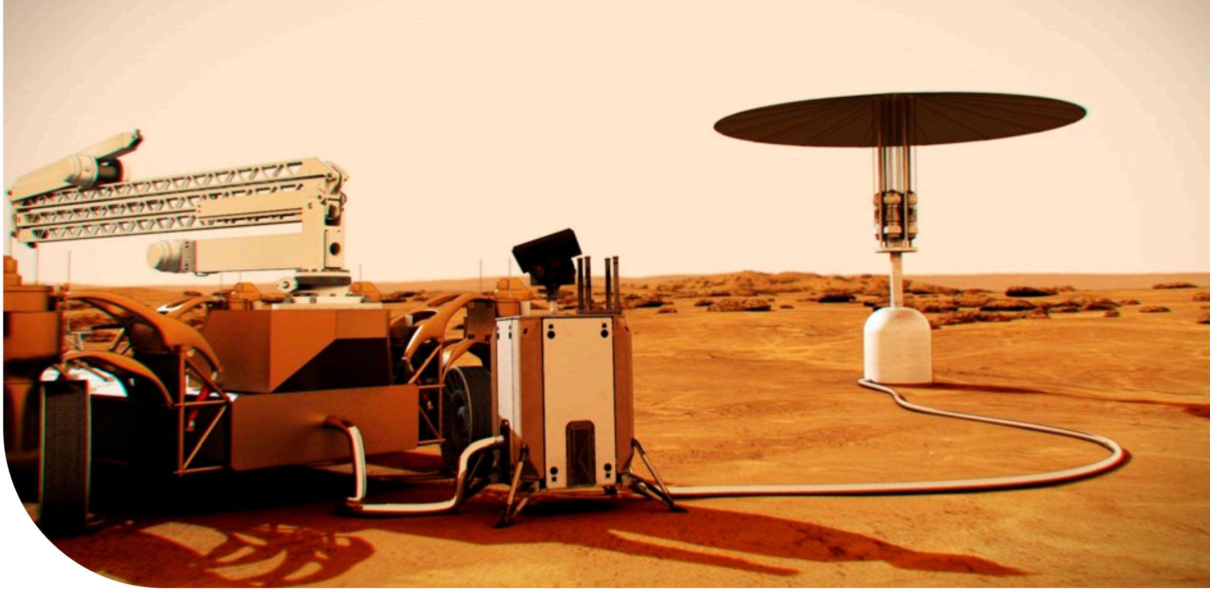

Illustration of a nuclear fission power system on Mars. (Image: NASA)

The Kilopower Project and the resulting KRUSTY reactor proved that a new reactor could be designed, built, and successfully tested. In 2018, the project was deemed a success and paved the way for the next project: fission power surface power.

NASA FISSION POWER PROJECTS TODAY

There are currently two projects underway that address using nuclear fission technology in space. The first project is the design of fission surface power (FSP). The second is the development of a nuclear thermal propulsion (NTP) system. These two projects could provide the power and propulsion necessary to make deep space exploration possible.

Fission surface power

Currently, NASA is working with the Department of Energy and industrial partners to design and build a reactor power system capable of generating 40 kW of electricity for a minimum duration of 10 years. FSP will enable missions to both the Moon and Mars to be powered without interruption from the harsh environmental conditions characteristic of both locations. The end goal is to have a flight-ready FSP available for shipment to the launch site by the end of 2029.

A few key parameters for the FSP project include the following: 40-kW(electric) output at 120-V direct current, 6,000-kg weight limit, ability for FSP to fit on a lander, and ease of transportation away from the lander for optimal use. In addition to these requirements, there are strict radiation protection requirements that must be accommodated. According to the FSP request for proposals, “The FSP shall be designed to limit radiation exposure at a user interface location 1 km away to a baseline value of 5 rem per year above lunar background.”

According to NASA, this project will be carried out in a two-phase process. During Phase 1, NASA and the DOE reached out to three industry partners seeking preliminary design concepts for the FSP system. INL is leading the efforts and will review each design to provide feedback to NASA. The industry partners for Phase 1 are IX, a joint venture between Intuitive Machines and X-energy, partnering with Maxar and Boeing; Lockheed Martin, partnering with BWX Technologies and Creare; and Westinghouse, partnering with Aerojet Rocketdyne.

Phase 2 will primarily be handled by INL with the participation of NASA and includes “an independent proposal solicitation, evaluation, and selection process to cover DDT&E [Design Development Test and Evaluation], a separate nuclear ground test unit and payload delivery by December 2029” and “culminates in a flight system delivered to the launch site,” according to NASA.

Nuclear thermal propulsion

NASA has a long history of developing NTP systems, including the design, construction, and testing that took place for Rover/NERVA from 1955 to 1973. The program produced numerous reactor propulsion systems; however, none of them were ever brought to the launchpad. The NTP systems developed for Rover/NERVA nonetheless provided the backbone for the NTP systems currently in development.

An NTP system will play a critical role in future

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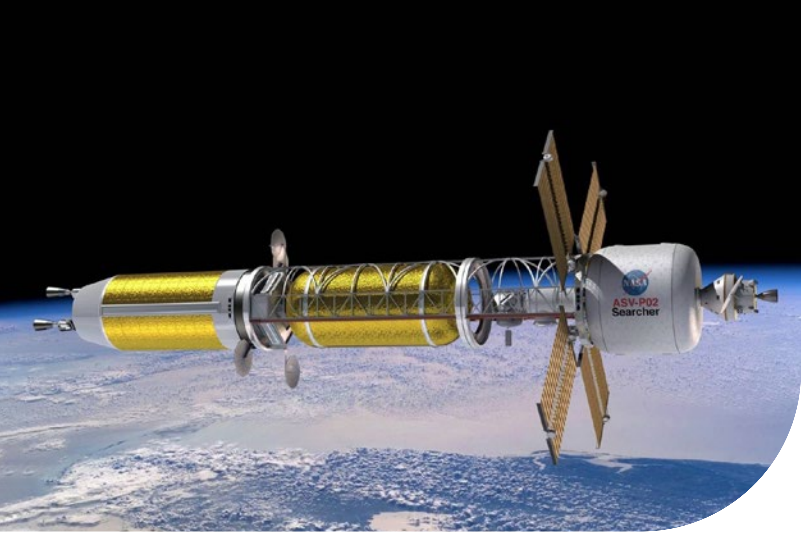

Illustration of a conceptual spacecraft enabled by nuclear thermal propulsion. (Image: NASA)

deep space missions including the journey to Mars. NTP offers a more efficient means to provide propulsion for space missions than traditional chemical propulsion systems. Current NTP systems are not designed with the capability to produce the amount of thrust required for launch. A more traditional chemical rocket propulsion system will be used for launch; thereafter, the flight crew will begin using NTP.

The use of an NTP system will also allow NASA to shorten the round-trip time to Mars. As it is a more efficient way to propel astronauts, it could effectively reduce a flight crew's cosmic radiation exposure by shortening the flight time by nearly 25 percent. An arguably more important benefit is the ability to abort missions and return the astronauts to Earth before they reach Mars. Chemical rocket systems would need to burn their fuel to leave Earth orbit and pick up more fuel at Mars to return to Earth. There would be no feasible way to turn around mid-mission without staging more fuel somewhere between Earth and Mars. NTP systems carry their fuel with them, and so they aren't limited in their ability to maneuver as long as they don't run out of hydrogen propellant.

NASA is working with the Defense Advanced Research Projects Agency (DARPA) on an NTP system known as the Demonstration Rocket for Agile Cislunar Operations (DRACO) (see "Leading DRACO to launch" on p. 20 of this issue), with anticipated project completion in Fiscal Year 2027.

NTP systems are being designed to be fueled by low-enriched uranium. In collaboration with INL, new NTP fuels are being developed in multiple places including INL, Oak Ridge National Laboratory, Los Alamos National Laboratory, the NASA Marshall Space Flight Center, BWXT, Ultra Safe Nuclear Corporation, and X-energy. Irradiation testing of fuels is being performed in the Transient Reactor Test Facility (TREAT), although TREAT is not technically being used to develop fuels. Important testing is also being performed at all the above locations as well as at the Massachusetts Institute of Technology.

NTP works by using fission to produce heat, by way of the reactor core heating up a low-molecular-mass propellant such as hydrogen as it passes through the core. After the hydrogen is heated, it is the expansion of the hot hydrogen as it moves through the nozzle that actually produces thrust in NTP systems.

The DOE has awarded design contracts for three reactor design proposals supporting the NTP program. INL issued the design contracts on behalf of NASA, but there are many organizations including INL, LANL, ORNL, MSFC, NASA headquarters, and Glenn Research Center that are involved in reviewing the designs produced under the contracts.

The three industry partners are BWXT, partnering with Lockheed Martin; General Atomics, partnering with X-energy and Aerojet Rocketdyne; and Ultra Safe Nuclear Technologies, partnering with Ultra Safe Nuclear Corporation, Blue Origin, GE Hitachi Nuclear Energy, GE Research, Framatome, and Materion.

The history of using fission power in space was significantly directed by the SNAP, Rover/NERVA, and Kilopower programs. NASA, the DOE, and industry partners have much to look back on to guide engineers and designers in creating both fission-powered propulsion systems and fission power systems. These systems will be critical for journeys to the Moon, Mars, and even future deep space exploration. The fuel reliability and lifespan these missions will require are well within reach.

Jeremy Hampshire is an ANS member whose avocation is writing about nuclear science and technology's history. His experience includes time as a lead nuclear quality assurance auditor and a senior nuclear technical advisor.