

NASA sees a future with nuclear power

The space agency views reactors as options both for propulsion to Mars and as a power source for life on the red planet.

When astronauts travel to Mars, they may well get there under nuclear power. Once on the red planet, they may live for a time on nuclear power while they produce propellant for their trip back to Earth.

NASA is developing reactors for spacecraft propulsion and for a planetary power source, with the goal of having both available for a crewed mission to Mars sometime in the 2030s. But although the agency is advancing a reactor technology that uses low-enriched uranium (LEU), containing less than 20% of ^{235}U for propulsion, its planetary power source, known as Kilopower, utilizes weapons-grade uranium enriched to 90% or more ^{235}U . Nonproliferation advocacy organizations have objected to the use of highly enriched uranium (HEU, material containing 20% or more ^{235}U); they say an LEU design, although it would require more time to develop, would be feasible and consistent with US policy.

Testing of a 1 kW prototype Kilopower reactor began last month at the Nevada National Security Site (formerly the Nevada Test Site), capping a three-year development program. Kilopower is vying with solar power to provide electric power on Mars, says Lee Mason, NASA's principal technologist for power and energy storage, and the agency is pursuing both avenues. Solar energy's attractiveness is reduced because the solar flux reaching Mars is much less than Earth's and varies greatly depending on the season and geographic position. In addition, Martian dust storms can last for months. Nuclear systems would likely offer weight and operational advantages over an equivalent solar array and energy storage system, Mason says.

The Kilopower reactor might also



compete with solar as a power source for human habitation on the Moon, says Mason, should the Trump administration decide to return there. Although solar flux on the Moon is comparable to that received on Earth, nonpolar missions would experience a long lunar night period of half a month, which would require massive energy storage to supply continuous power. Mason says nuclear would offer uninterrupted power at any location, including permanently shadowed craters where lunar ice may be located.

Nuclear propulsion R&D

In a separate program, NASA's Marshall Space Flight Center is leading the development of nuclear-thermal propulsion (NTP), with the idea of transporting humans to Mars, says Jeffrey Sheehy, chief engineer for NASA's space technology mission directorate. After pursuing NTP for more than a decade, the agency abandoned it in 1973 when space funding fell in the post-Apollo era.

In NTP, heat generated by the reactor

is transferred to hydrogen fuel in rocket engines. It produces thrust similar to that of today's conventional liquid-fuel rockets but with the potential to double the fuel-utilization efficiency. That makes it attractive for long-duration missions.

In addition to the possibility of reducing travel times to Mars, NTP could provide more mission flexibility. If short trip time is an important requirement, the mass, and hence the number of heavy launches required to put an NTP system in place, would be significantly less than for a conventional propulsion system, Sheehy says. Reducing travel time for a conventional rocket-powered spacecraft would require much more propellant and much more mass than would NTP.

An NTP system could double the launch window for a trip to Mars from the "few tens of days" available with today's rockets, says Sheehy. That's particularly important when the optimal launch windows are 26 months apart. Moreover, the greatly improved fuel utilization of NTP would allow a spacecraft to return safely to Earth up to three

months into the seven-month journey should anything go wrong with the craft or crew. That capability would be just a few days with conventional rockets, he says.

NASA continues to explore conventional and solar-electric propulsion for Mars travel. In the solar-electric system, electricity generated from solar arrays is used to create and accelerate a plasma in specially designed thrusters. Exhaust velocity can be up to 10 times higher than in conventional rockets, but the quantity of exhaust, proportional to the thrust force, is only a few kilograms, compared with a potential 34 000 kg from NTP, says Sheehy. That could make solar-electric a good choice for a slow-moving cargo vessel to Mars.

In Nevada during the 1960s, NASA and the Atomic Energy Commission tested several NTP reactors, and the program was “on the right track” technically, says Sheehy. Although much of the R&D from those years is still applicable, new materials, improvements in computing, and other advances have come along in the intervening years.

One NTP program goal for fiscal year 2018 is the design of a system to mitigate environmental concerns by capturing exhaust gases during the testing of the rocket engines. Small amounts of radioactive material would be emitted in the exhaust. Another program objective this year will be to test fuel elements fashioned from a uranium surrogate material to see how they withstand reactor operating temperatures anticipated to be up to 2500 K.

In August NASA awarded a \$19 million contract to BWX Technologies for R&D on an NTP reactor and fuel elements. The company said its design would use low-enriched fuel. Other contractors on the NTP program include Aerojet Rocketdyne and Analytical Mechanics Associates.

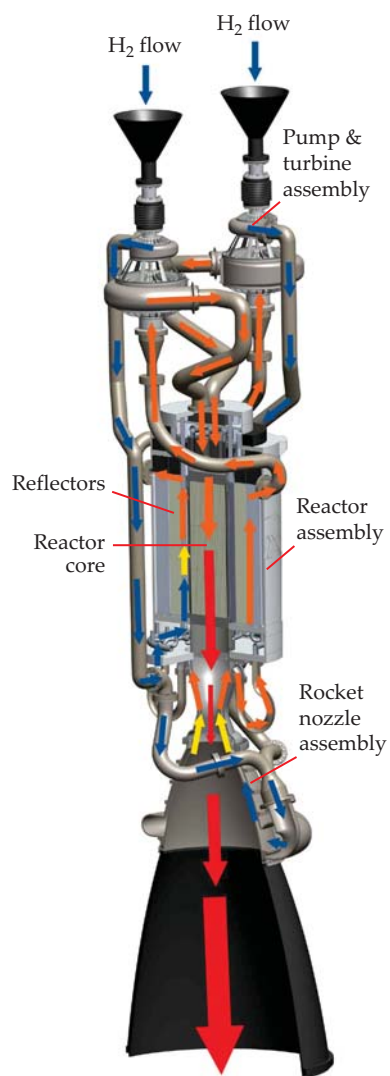
Concerns with HEU

The Union of Concerned Scientists and the Nuclear Proliferation Prevention Project have objected to the use of HEU for space missions; they say the US should set an example for the world in removing HEU from all civilian applications. They note that the 1 kW Kilopower reactor being tested uses about 30 kg of weapons-grade uranium, which is more than enough to fashion a nuclear explo-

sive device. NASA says a 10 kW version of the reactor, the largest size planned, would contain 50 kg of weapons-grade material.

“What is the time scale on which we really may need these reactors, and do we have the time to invest in the R&D to make sure that HEU isn’t needed?” says Edwin Lyman of the Union of Concerned Scientists. “There’s no real rush.”

The Obama administration set a mid 2030s goal for human travel to Mars. The Trump administration has not changed



A NUCLEAR-THERMAL PROPULSION REACTOR design being developed by BWX Technologies for NASA would use a low-enriched uranium core. The arrows show the flow path of the hydrogen gas propellant, with colors representing its relative temperature, from cold (blue) to red (hottest).

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that timetable, but officials have indicated the president may reverse Barack Obama's decision to forgo returning humans to the Moon.

Lyman notes that it has taken the US decades to convert research reactors at home and abroad from HEU to LEU in fuels and in medical-isotope production (see PHYSICS TODAY, April 2016, page 28). That process is still incomplete. NASA should rework the Kilopower program to use LEU fuels from the outset, he says, "instead of getting to the point where one day we need to get a handle on this when many countries enter the market and want to develop their own [space] reactors with HEU."

In a statement, a spokesperson for NASA and DOE said they "take the threat of terrorism very seriously." Various measures are taken to protect personnel and the public, and the transportation and storage of nuclear materials occurs under tight security. Those measures would continue to apply to any flight development activity that may ensue from the Kilopower tests, the statement said. The principle of whether the US

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THE CORE OF THE KILOPOWER REACTOR is composed of highly enriched uranium metal. One of the three segments that form the core is pictured here.

ought to use HEU in nonmilitary applications was not addressed.

Whether NASA uses HEU or LEU will depend on the application, Mason says. "In the case of Kilopower, the favored

approach is to use HEU because it gives us our most compact reactor, which makes it the best option for landing power systems on planetary bodies," he says. "For NTP, because the requirements are so different, it appears LEU is the favored option."

Two key Kilopower scientists at Los Alamos National Laboratory (LANL) discussed the trade-offs between LEU- and HEU-fueled reactors in an 11 August white paper. Project manager Patrick McClure and chief reactor designer David Poston say that the major disadvantage of an LEU-fueled Mars surface reactor is that it would be two to three times as heavy as an HEU version. But the extra cost of developing an LEU reactor would mostly be offset by the high security costs, an estimated \$10 million per month, inherent to working with HEU.

Due to its much greater concentration of ^{235}U , an HEU-fueled reactor will last longer than an LEU version, they add.

McClure says that allowable mass and required lifetime "may necessitate the use of HEU, and it should not be ruled out on cost alone."



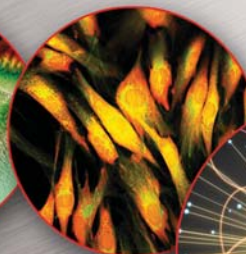
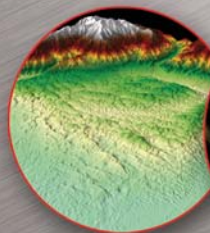
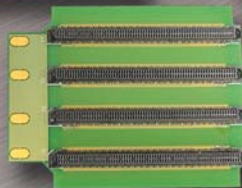
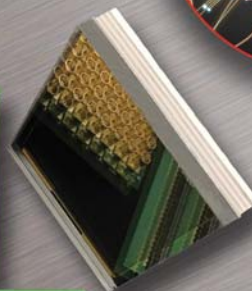
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An LEU reactor would eliminate concerns of fissile material falling into the wrong hands in the event of a launch failure or an abort, McClure and Poston say. The HEU-fueled reactor is simple to build and test, with a core consisting of three solid chunks of HEU metal (see the photo on page 28). But they acknowledge that an LEU-fueled reactor of similar design also could be built.

Minimal hazards

NASA engineers have estimated that 40 kW is needed for a crewed Mars surface base. One possible mission approach would be to send five of the 10 kW Kilopower reactors to Mars to provide a spare unit for increased reliability.

Even the smallest Kilopower reactor would produce considerably more electricity than the radioisotope thermoelectric generators (RTGs) that have powered more than two dozen NASA spacecraft since the 1960s. The largest RTGs, whose deployments have included *Cassini*, *Galileo*, and *New Horizons*, produced 300 watts, and the RTG on the *Curiosity* Mars rover makes 110 watts. The human health hazards, however small, that come with the potential launch failure of an RTG-fueled spacecraft aren't an issue with uranium fuels. Unlike the highly radioactive plutonium-238 that fuels RTGs, ^{235}U emits only tiny amounts of radiation, and Kilopower reactors wouldn't begin generating fission products until they are turned on after landing.

The Kilopower design being tested in Nevada has eight Stirling engines to convert heat from the reactor to electricity. They produce mechanical energy by using the temperature difference between their hot and cold ends to alternately heat and expand, and then cool and compress, a gas. To save on costs, only two Stirlings, borrowed from another NASA development program, will be included in the Nevada tests. Other options being considered for converting reactor heat to electricity include thermoelectric devices and small turbines. But the Stirling route is attractive for its efficiency, which allows for a simple reactor design, says McClure.

Although the earlier US program to develop NTP produced multiple prototypes that were ground-tested, the only space reactor ever deployed by the US was the thermoelectric HEU-fueled

SNAP-10A satellite, launched in 1965. The reactor was designed to produce around 500 watts of electric power for early military reconnaissance satellites. The spacecraft failed after 43 days in space due to an electrical fault, but it continues in orbit.

The Soviet Union launched 33 nuclear-reactor-powered radar ocean reconnaissance satellites from 1970 to 1988. The military satellites were deployed to low-Earth orbit and boosted into a

disposal orbit at the end of their lives.

The last US effort on nuclear-powered low-Earth orbit satellites was the SP-100 program to develop a thermoelectric reactor. The program, which aimed to produce reactors up to the megawatt range, ran from 1983 to 1994. It was terminated after the Department of Defense's Strategic Defense Initiative and NASA scaled back their projected space power needs.

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