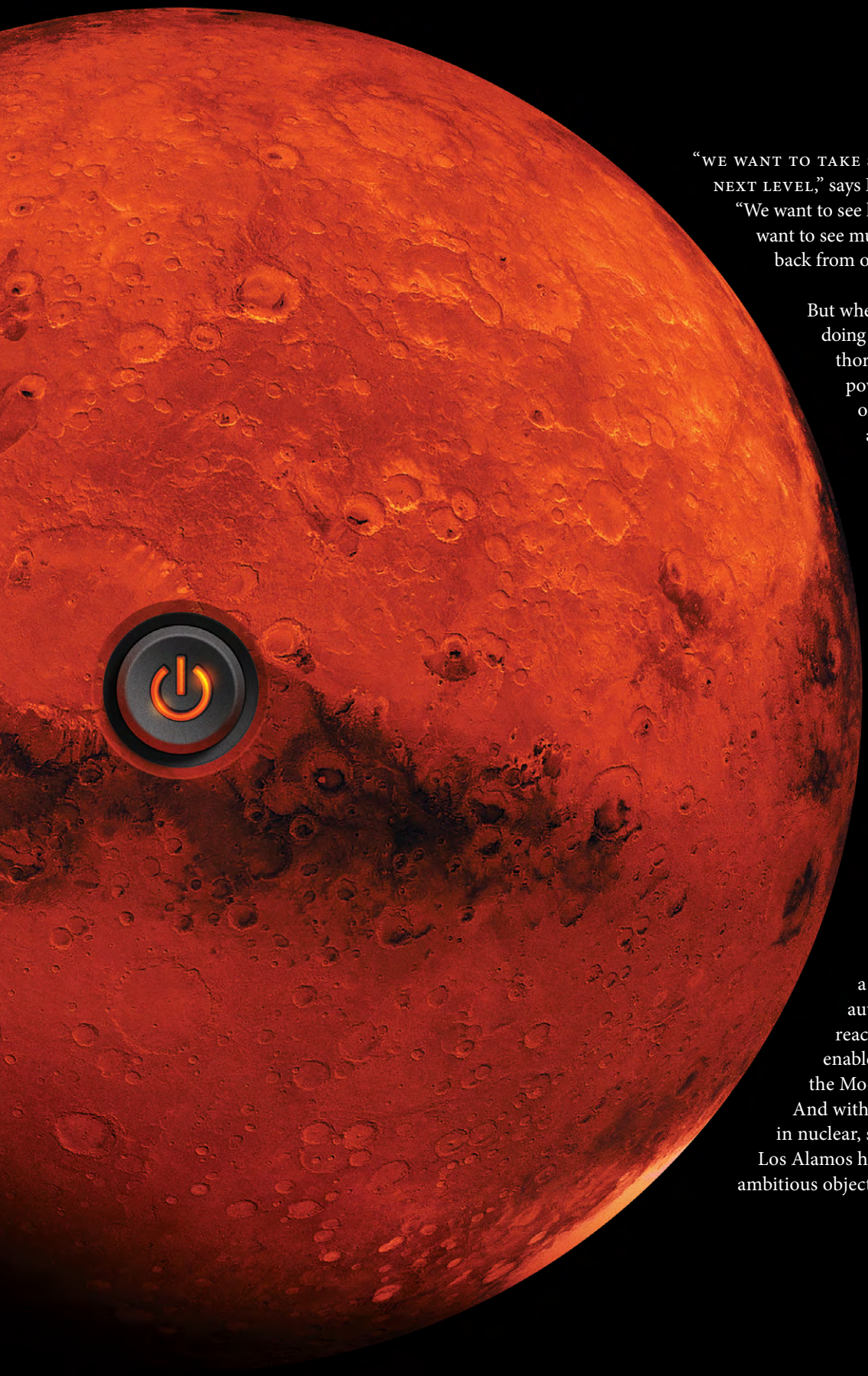
POWER TO THE PLANET

A nuclear reactor the size of a wastebasket could power future operations on **MARS** and beyond.

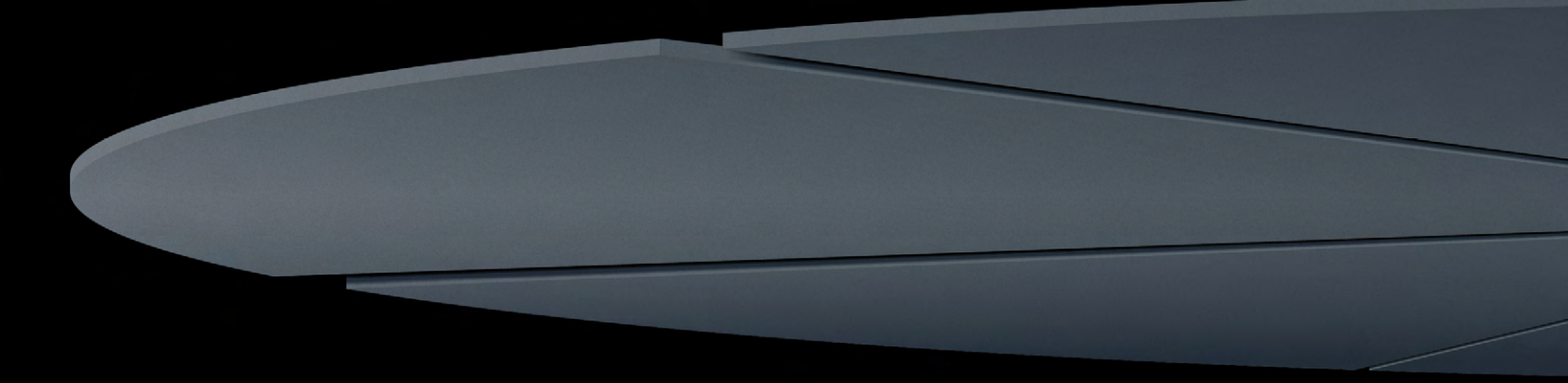


"WE WANT TO TAKE SPACE EXPLORATION TO THE NEXT LEVEL," says Los Alamos engineer David Poston. "We want to see human habitation on Mars, and we want to see much more scientific data coming back from our deep-space probes."

But when it comes to space exploration, doing more always traces back to the thorny problem of generating more power, and for human habitation on Mars or even our own Moon, a *lot* more power. Unfortunately, the intensity of sunlight on Mars is less than half of what it is on Earth, and darkness and dust make solar power a severely limited option. Beyond Jupiter, it's basically not an option at all.

Fortunately, a solution may finally be at hand: the "Kilopower" nuclear fission reactor. It is the present incarnation of an idea that Los Alamos has been considering for decades. Poston, the lead designer, and Patrick McClure, the Los Alamos project lead, have recently returned from the Nevada desert, where they successfully tested their concept: a wastebasket-sized and fully autonomous space-based nuclear reactor. McClure and Poston hope to enable nuclear power stations for Mars, the Moon, and the outer solar system. And with a long history of innovation in nuclear, space, and energy technology, Los Alamos has the pedigree to transform this ambitious objective into reality.

CREDIT: NASA/JPL Caltech/USGS



Two rovers are currently operating on Mars, *Opportunity* and *Curiosity*. *Opportunity* arrived in 2004. It was only expected to last about 90 days, after which the five-month Martian winter would have permitted too little sunlight to reach its solar panels, but NASA was able to tilt the rover sufficiently toward the sun to keep it alive and well eight Martian winters later.

Out of the box, *Opportunity* could recharge its batteries with 900 watt-hours of power per day from its solar panels (enough to put out 100 watts for nine hours, for example). In the winters, this often dropped to about 300 watt-hours—barely more than what the rover needs just to remain "awake" severely limiting what, if anything, the rover could accomplish between solar recharges. Complicating matters, solar panels degrade over time, and dust storms can obscure the sun for weeks or months.* (Poston points out that even in good weather, Matt Damon would have needed about 100 times as many solar panels to provide the power he used in the movie *The Martian*.)

By contrast, the *Curiosity* rover, which landed in 2012, runs on nuclear power via a device known as a radioisotope thermoelectric generator (RTG). It uses the prolific radioactivity of plutonium-238 from Los Alamos to produce heat, which is then converted to electricity by a low-efficiency but long-lived and reliable thermoelectric device. Since plutonium's half-life is 88 years, the RTG will continue to function for a long time, although its power decreases each year as the plutonium decays. But it's no simple matter to manufacture and launch large quantities of plutonium, and *Curiosity's* RTG, even when new, was limited to only 110 watts. Indeed, interplanetary spacecraft are typically limited to only a few hundred watts of RTG-supplied power.

THE REACT R WILL PUT OUT AS MUCH HEAT AS IS ASKED OF IT

Whether for a rover or a spacecraft, making the most of such limited power is a serious challenge. *Opportunity* and *Curiosity*—extraordinary successes by any measure—have traveled 28 and 12 miles, respectively, in all the years they have been operating. But what if NASA wanted to explore significantly farther afield or do more energy-intensive science each day? Realistically, existing power systems for robotic exploration are already pretty close to maxed out.

Then what about a human habitat on Mars? How much power would that require? At its peak, a typical U.S. household might consume 5000 watts (or 5 kilowatts, kW) just by running the lights and appliances and maintaining a temperature slightly more comfortable than the natural temperature range on Earth. But a Mars habitat would have to provide heat against a –55°C average surface temperature; recharge rovers capable of carrying astronauts and their gear over large distances; and manufacture air, water, and rocket fuel from native resources. Experts estimate that a habitat on Mars would need a reliable source of 40 kW or more. To accomplish this with solar power, for example, would require an extremely large mass of solar panels and batteries and would be limited to locations close to the Martian equator. By contrast, fission power is lighter and would be reliable in any geographical location, day or night, in clear skies or even massive dust storms.

Portable power plant

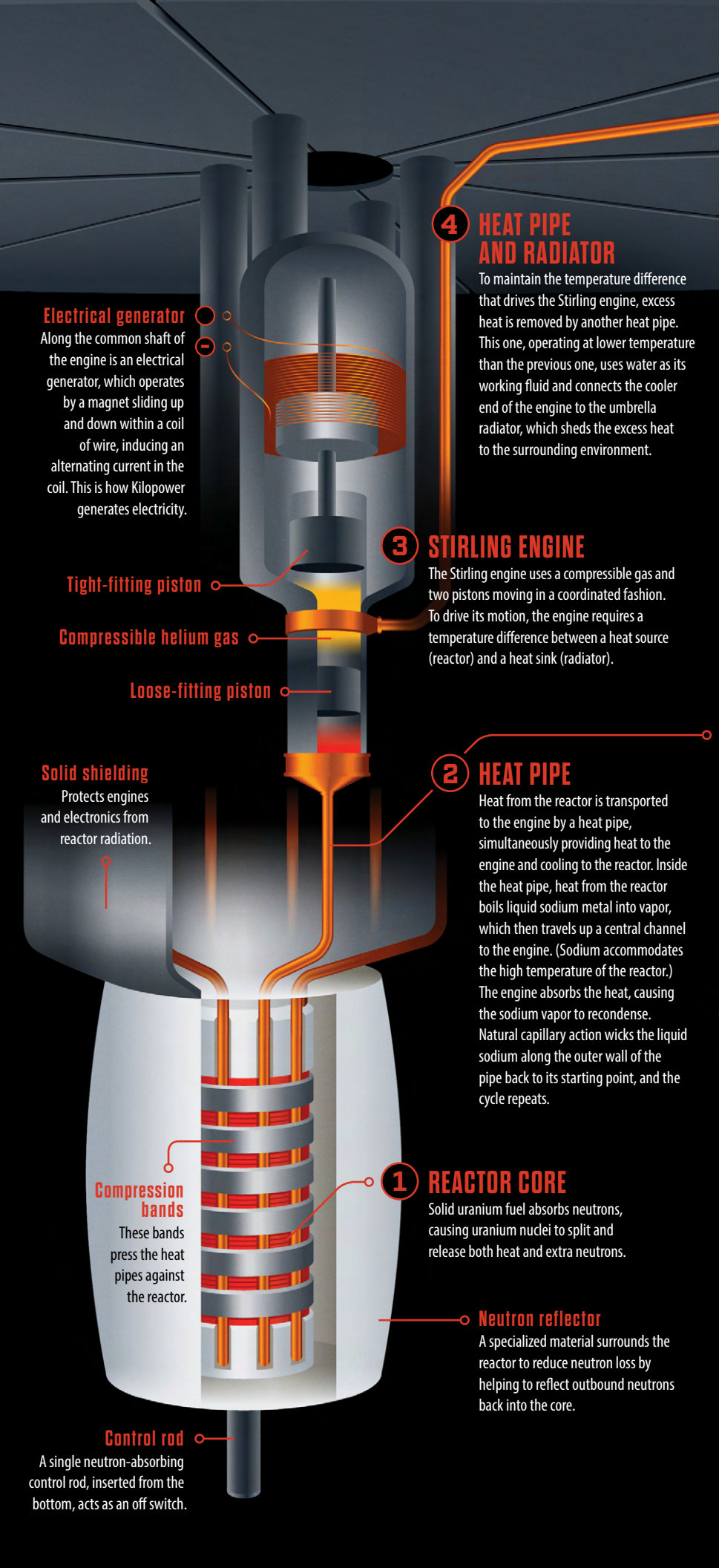
McClure and Poston's reactor recently demonstrated what five decades of research and experimentation had yet to do successfully: operate a nuclear fission power plant—think giant cooling towers—that's lightweight, reliable, and efficient enough to run fully automated without refueling for a decade or more in a hostile environment. Instead of producing about a gigawatt (a billion watts) like a nuclear power plant on Earth, two Kilopower designs produce either 1 or 10 kW. A single 1-kW unit would greatly outclass existing RTG power systems on large, unmanned, interplanetary spacecraft like *Galileo* or *Cassini*. And a human habitat on Mars, as currently envisioned, would run four of the 10-kW variety and keep a fifth one in reserve.

A nuclear power plant basically has four components. (1) A nuclear reactor generates heat by fission, or "splitting the atom." (2) A heat exchanger, which is effectively a plumbing system, carries the heat away from the reactor and delivers it to an engine, simultaneously powering the engine and cooling the reactor. (3) The engine uses the heat to boil a liquid, as in a steam engine, or expand a gas, as in a jet engine, to turn a turbine or move a piston. That motion drives a generator to produce electricity. (4) Another heat exchanger then carries residual heat away from the engine and offloads it to the surrounding environment. For Kilopower, steps (1) and (2) pertain to the Los Alamos reactor design; the others pertain to the NASA power conversion system, which NASA engineers successfully designed and integrated with the reactor.

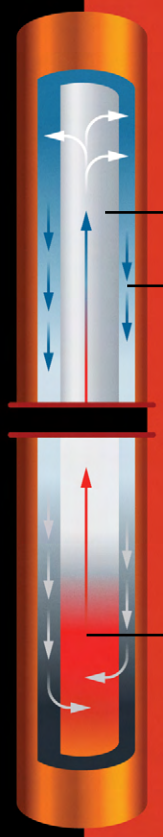
Counting backwards, cooling technology (4) is relatively straightforward, and for Kilopower, it is accomplished by

*As this publication goes to press, the *Opportunity* rover s fate is uncertain because a massive, planet-wide dust storm—raging for seven straight weeks as of mid-July—is severely limiting the available solar power.

HEAT CONTROL FROM THE COLD WAR



With the emergence of the Cold War, the Laboratory s postwar future began to solidify. In the 1950s, Los Alamos conducted the world s first full-scale thermonuclear test, and as a means of delivering such large, first generation thermonuclear weapons, it started developing nuclear rocket engines to propel missiles. The need for nuclear-propelled missiles quickly faded as the Laboratory miniaturized nuclear weapons so that they could be delivered with chemical rockets, but the nuclear rocket program lived on. Rebranded as a space technology, the Rover Program ultimately produced the most powerful reactor of all time, intended to be capable of



carrying astronauts far beyond the moon to destinations such as Mars.

Though a manned deep-space mission failed to materialize, Rover succeeded in producing working prototype engines and world-changing spinoff technologies. Among these was the heat pipe, invented by Los Alamos scientist George Grover in 1963 for space based nuclear-reactor applications. A sealed metal tube with no moving parts, the heat pipe rapidly and reliably conveys heat from one end to the other without an external power source.

—Alan Carr

delivering excess heat to a thin metal "umbrella," which radiates the heat away. Step (3) requires a lightweight, maintenance-free engine system to operate on Mars, rather than the likes of a massive, pressurized steam engine, as on Earth. For this, McClure, Poston, and their collaborators at NASA prefer Stirling-engine technology, which NASA has been developing for decades because of its simplicity and efficiency. An engine converts energy from heat (from burning coal, a solar concen trator, nuclear fission, etc.) into motion, and the Stirling variety uses a loosely fitted piston surrounded by a compressible gas in a sealed cylinder—requiring fewer moving parts than, for example, a car engine, in which valves must repeatedly open and close to intake fuel and air and discharge exhaust gas.

A KILOWATT UNIT WOULD GREATLY OUTCLASS EXISTING P ' WER SYSTEMS ON LARGE INTERPLANETARY SPACECRAFT LIKE GALILEO OR CASSINI

A key innovation that allows nuclear fission to become spaceworthy is the heat exchanger (2) between the reactor and the Stirling engine. Rather than using conventional plumbing—susceptible to corrosion and requiring fluids (which could leak) propelled by power-consuming pumps (which could fail)—it uses something called a heat pipe. Invented in 1963 for space-based reactor applications by Los Alamos scientist George Grover, with experimental work carried out by his Laboratory colleagues Ted Cotter and George Erickson, the heat pipe is a sealed metal tube with no moving parts. A liquid—molten sodium in the case of Kilopower—is boiled into vapor at the hot reactor end of the pipe and then travels to the comparatively cold end, where it provides the heat source for the Stirling engine. There it re-condenses and, through natural capillary action, flows back to the hot end. Such heat pipes are reliably long-lasting and consume no power to operate.

Fission fired and fully fail-safe

Finally, there's the fission reactor (1). Kilopower's fuel, like that of Earth-bound nuclear plants, is uranium-235. Fission of uranium-235 happens when the nucleus absorbs a neutron, causing it to split into two smaller atomic nuclei, plus a few more neutrons. Poston's design uses a solid, cast uranium core the size and shape of a coffee can. Wrapped around it is a layer of beryllium oxide to help reflect outbound neutrons back into the core, where they can induce more fissions. There is also a control rod made of boron carbide, which absorbs neutrons, inhibiting the chain reaction. It acts as a power switch: when the rod is withdrawn, the reactor turns on; when the rod is inserted, the reactor shuts down.

The reactor is designed to be fully autonomous. Unlike nuclear power plants on Earth, with control rooms staffed with nuclear engineers, Kilopower adjusts power on its own as conditions require. Importantly, it does this entirely through passive responses, meaning that it is controlled directly by the laws of physics, rather than by a computerized control system, which could malfunction.

For instance, for Kilopower's equivalent of a loss-of-coolant accident (a serious failure for a nuclear power plant on Earth), the rising temperature in the reactor core causes the fuel to expand. This, in turn, reduces the core's density, thereby allowing more neutrons to escape and correspondingly decreasing the fission rate. Essentially, the reactor senses—without relying on sensors—that it is overheating and immediately cuts power. Conversely, if power is being consumed too quickly, the heat draw of the Stirling engine increases, so the reactor core cools, becomes denser, and therefore produces more fissions to adjust to the increased power draw.

Artist s conception of Kilopower on Mars with umbrella-style radiators fully deployed.
CREDIT: NASA Langley

"Whether during normal operation or some kind of fault, the reactor will put out as much heat as is being asked of it," says Poston. "Even if the Stirling engines stop completely, the reactor will not overheat. It will wait in warm standby, ready to produce full power if the engines restart." The robust design eliminates the potential hazard of a meltdown, although Poston notes that, for an astronaut, loss of power may be a bigger concern than any potential radiation release.

There is also minimal danger on Earth. Unlike RTG plutonium, which is highly radioactive, uranium-235 has comparatively little radioactivity. So even if a rocket intended to carry a Kilopower unit into space were to explode during takeoff, spreading uranium across land or sea, the radiation hazard would be essentially negligible—hundreds of times less than what the average American receives in a year from natural sources.

Once the reactor is up and running, the uranium splits into other isotopes with greater radioactivity, but that takes place in space or on Mars, not here on Earth. And while constructing anything with the potential for sustained fission obviously demands that significant safety and security protocols be observed, it doesn't carry the kind of risk already sufficiently minimized to be approved for RTGs.

THERE'S VERY LITTLE SUNLIGHT DURING THE LONG MARTIAN WINTER—OR DURING MONTH-LONG DUST ST ' RMS

Los Alamos legacy

The heart of Kilopower's technology is quite old: the Stirling engine was invented in 1816, the first nuclear reactor was built in 1942, and the heat pipe, in its Los Alamos conception, was patented in 1963. But successful integration at small scale and with spaceworthy technology and autonomy has proven elusive for decades. An American experimental fission-powered satellite was launched in 1965, but its active-control system failed within a month and a half, and that was that for American fission power in space for decades thereafter.

Recent presidential administrations have indicated the desire to send humans back to the Moon and subsequently to Mars, putting fission power in space back on the table. (Nearly everywhere on the Moon is in shadow for weeks at a time, making solar power impractical, despite the solar flux being about as strong there as it is on Earth.) Still, NASA remained leery of pursuing fission power because of the expensive failed programs of the past, giving McClure and Poston the chance to seize an opportunity.

"In 2012, we came up with the idea of a very simple reactor demonstration to prove to NASA—and frankly to ourselves—that we could test a small-reactor concept quickly and affordably," says McClure. "We leveraged an existing experiment and the expertise of the Los Alamos team at NCERC," he says, referring to the National Criticality Experiments Research Center at the Nevada National Security Site (NNSS). The NNSS, which has the facilities and security measures in place to accom modate work involving enriched nuclear fuels, is also where Los Alamos researchers perform subcritical experiments on key nuclear-weapons components.

The success of the 2012 demonstration convinced NASA to test something much closer to a prototype reactor. That full-temperature test took place earlier this year at the NNSS, with the reactor behaving as predicted and meeting all major test objectives. It convincingly proved—for the first time since their conceptualization in the 1960s—that heat-pipe-cooled reactors offer predictable and robust performance. (Poston called the 2012 demonstration "demonstration using Flattop fissions," or DUFF, and the 2018 one "Kilopower reactor using Stirling technology," or KRUSTY; he readily admits to a bit of *Simpsons* fandom.)

"DUFF and KRUSTY were the first heat-pipe reactors ever built," says McClure. "And we at Los Alamos have the unique history that helped bring it all together. From our fundamental research on nuclear technology in the Manhattan Project to our subsequent research on nuclear rockets and satellites and heat pipes and RTG fuel, we are now working to enable a new era in space."

"But it's more than just our history," Poston adds. "This work would not have been possible without the unparalleled nuclear-computation codes, physics data, and experimental capabilities that the Laboratory maintains today."

Following on the successful KRUSTY experiments, Kilopower stands ready for a spaceflight demonstration and subsequent full-scale deployment. But the technology admits even grander, longer-term possibilities, too. Kilopower could someday become megapower.

"We could ultimately scale up to millions of watts, and who knows what that would do for humanity's future in space?" ponders McClure. "In many respects, scaling fission *down* is the harder thing to do." LDRD

—Craig Tyler

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