SCIENTIFIC AMERICAN

A New Race to the Moon

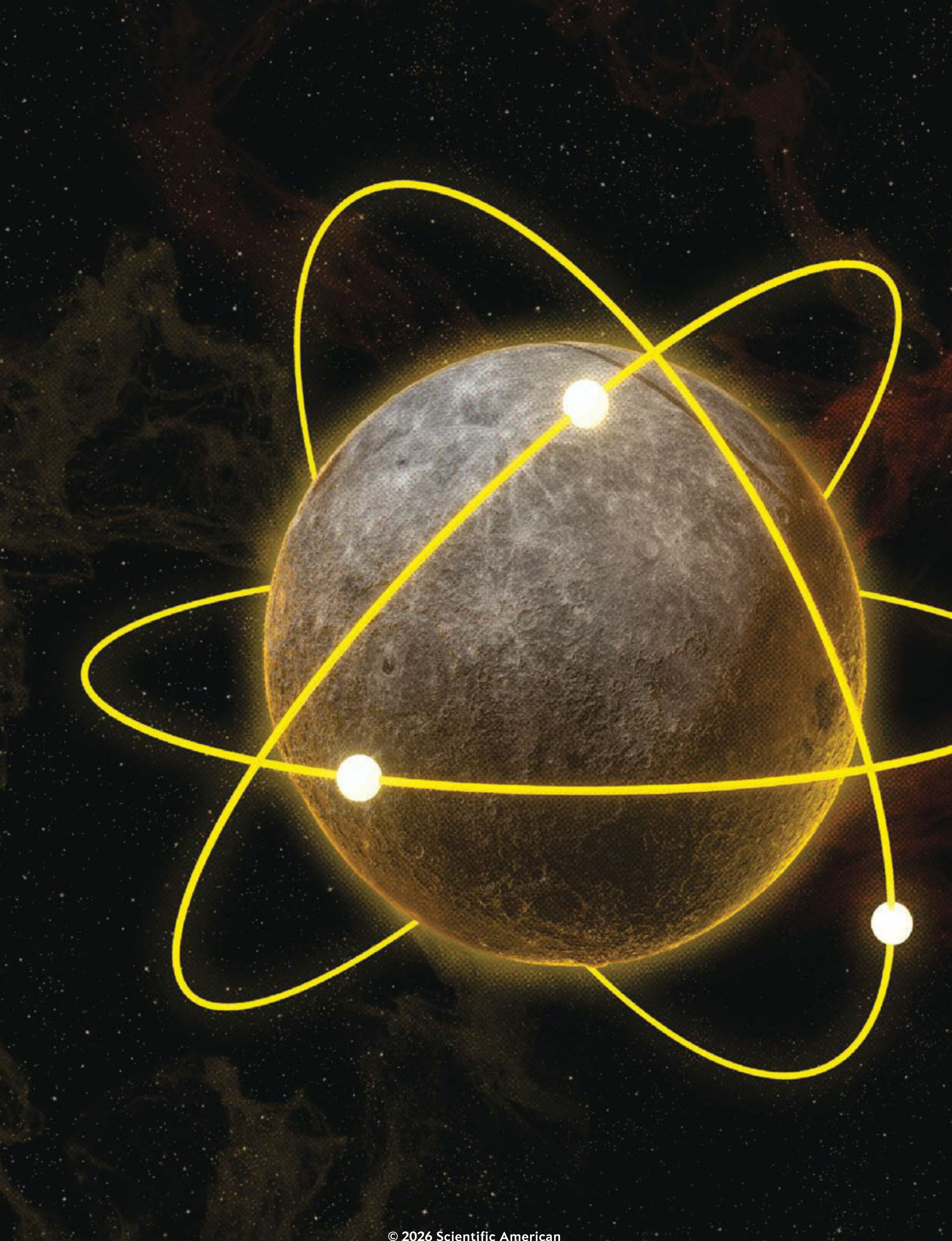
Lost Roads of the Roman Empire

The Scariest Problem in Math

The QUANTUM Revolution

Can the next big thing in computing live up to the hype?

JUNE 2026
SCIENTIFICAMERICAN.COM



A Nuclear Moon

NASA wants a nuclear reactor to power a lunar base. It's not as crazy as it sounds

BY ROBIN GEORGE ANDREWS
ILLUSTRATION BY TAVIS COBURN

LAST YEAR, LESS THAN A MONTH AFTER BEING NAMED acting administrator of NASA, U.S. Secretary of Transportation Sean Duffy made an eyebrow-raising announcement to the world: NASA was going to put a nuclear reactor on the moon. As part of strengthening U.S. national security in space, he said, this reactor would be designed, built, flown and delivered to the lunar surface by 2030. To many observers, this declaration sounded wild. Why would you want to put a nuclear reactor on the moon?

The thing is, if America (or any spacefaring nation) wants to establish a permanent presence on the moon—an inhabited station that can operate during the frigid and lengthy lunar night—solar power won't cut it. Through its Artemis program, which just sent four astronauts on a trip around the moon, NASA wants to transform our planet's argent companion into a scientific outpost, a mining site and a rocket launchpad pointed at Mars. To do that, nuclear power is the sole option. "It's the only way we can sustain a lunar base properly long-term," says Simon Middleburgh, co-director of the Nuclear Futures Institute at Bangor University in Wales. It's no wonder, then, that China and Russia are teaming up to put their own nuclear reactor on the moon by 2035 to electrify what they call the International Lunar Research Station—their planned base on the lunar south pole. Sooner or later, from one nation or another, "nuclear power on the moon will happen," Middleburgh says. "It's inevitable."

Nuclear power plants are safer than many suspect. But putting reactors in space is a concept with a checkered history. One notorious reactor caused an international incident in 1978 after it came apart in Earth's atmosphere. And nobody has ever designed a reactor for the moon, a hostile volcanic desert subject to extreme temperature swings, frequent asteroid strikes and protracted quakes.

Experts questioned both the timing and the scale of the nuclear power plant Duffy is proposing. Placing a reactor capable of powering 80 American households on the lunar south pole—an environment no human has yet set foot in—by 2030 sounds rushed, if not impossible. And the last thing anyone wants is for the U.S. to barrel through the conception, construction, launch and landing of a lunar nuclear reactor. "I think the worst-case scenario might be [that] in the quest to be first we skip important design and safety steps," says Bhavya Lal, a professor of space policy at the RAND School of Public Policy and former acting chief technologist and associate administrator for technology, policy and strategy at NASA. "It's good to be first—competition is good—but we need to do it right."

If the U.S. does succeed, its nuclear-powered moon base could become a solar system–exploring foothold among the stars. But mistakes can happen. And whether you've accidentally spray-painted an ancient reserve of water ice with radioactive waste or fatally stranded your astronauts in the lunar darkness without any power, a nuclear disaster on the moon would be, in Middleburgh's words, "a humanity-defining shit show."

KATY HUFF WANTS TO CLEAR something up: uranium, the infamous radioactive element used to power nuclear plants and, with some tweaking, give most nukes their annihilative terror, is dull—at least in a manner of speaking.

Huff, a nuclear engineer at the University of Illinois at Urbana-Champaign, was the assistant secretary for nuclear energy in the Biden administration. Nuclear power is her jam. But it's important to know that unused nuclear fuel is "radiologically very boring," she said during a recent video call. "It's not particularly radioactive." She gestured to an object on her desk. "I have some uranium in that cardboard box right there." The fact that you can hold uranium in your hand without consequence may come as a surprise to many. "You can pick it up. It's toxic more than anything else; it's like lead," Middleburgh says. "So don't eat it."

Uranium becomes dangerous—and helpful—when you chuck it into a nuclear reactor and fire neutrons at it. The impact causes the uranium's unstable atomic nuclei to snap apart and emit more neutrons, which cause more nuclei to rupture—and voilà, you have a heat-emitting nuclear fission reaction. As long as the reaction doesn't spiral out of control, you can use the heat to turn a fluid (often water) into steam. That steam rotates a turbine, which makes electricity.

You don't want to hold the uranium fuel after it's been blasted with neutrons. "Then it breaks apart and becomes fission products that are highly radioactive, which is why nuclear waste is dangerous," Huff says. But because that nuclear cascade can continue for a very long time, it's a fabulous power source—particularly in space, where it won't need refueling for years, maybe decades.

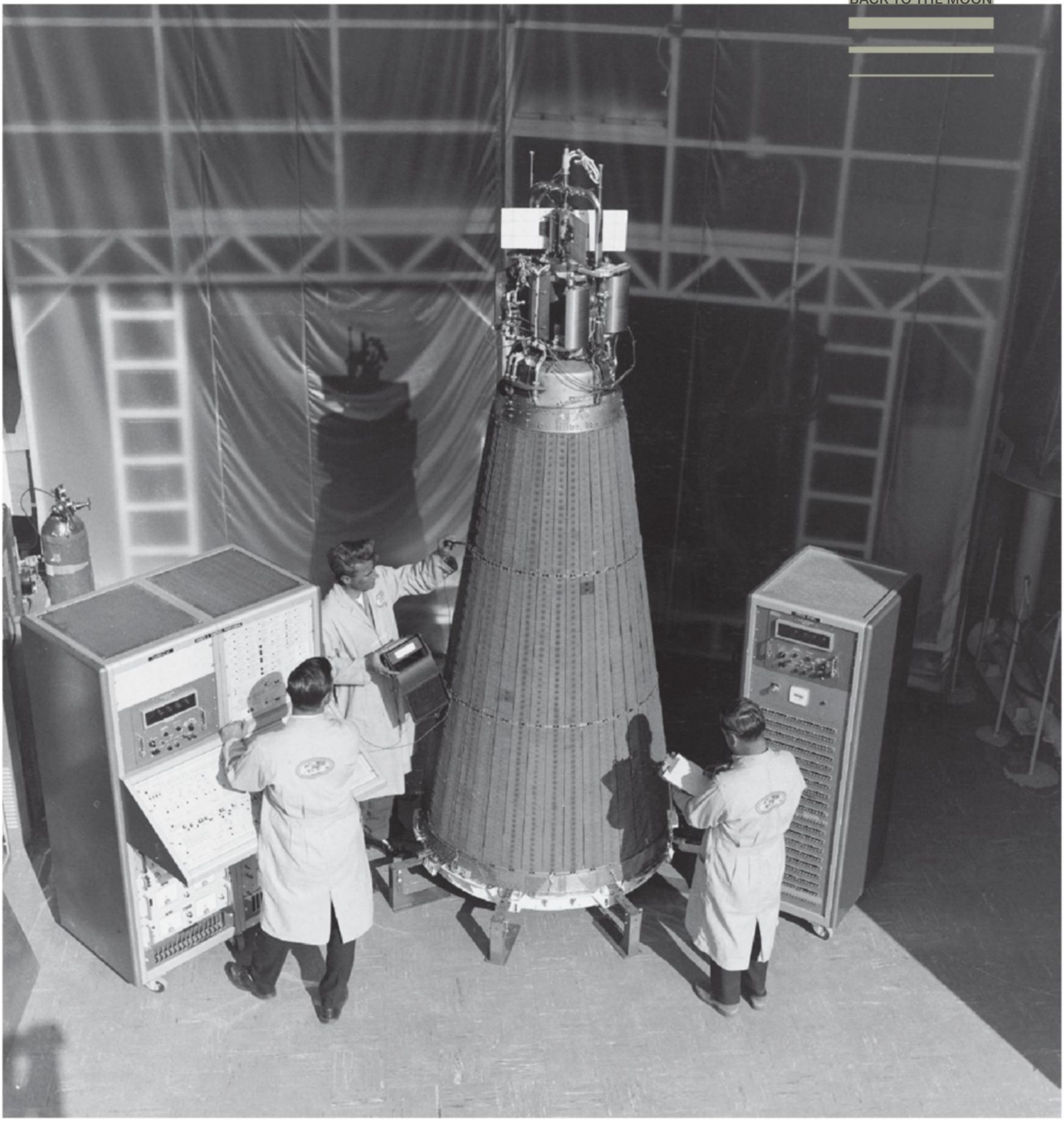
The concept of nuclear power in space isn't new. Starting in the 1960s, both the U.S. and the Soviet Union sent plenty of radioisotope thermoelectric generators, or RTGs, into space to power all kinds of things, from Earth-orbiting satellites and the Apollo-era scientific experiments on the moon to Mars rovers and deep-space probes. Plutonium, uranium's ferocious chemical cousin, was often used in these devices. RTGs, though, are not nuclear reactors. They are more like nuclear batteries: screaming-hot radioactive caches providing a small but lasting source of heat that can produce electricity.

But an RTG would be insufficient to power a moon base. Astronauts need more than just energy to keep the lights on. They need a constant source of heat in the night and a way to vent that heat when the mercury soars during lunar daytime. If they want machines that can extract precious water from the lunar soil—water for hydrating both astronauts and crops and, crucially, to be electrically split into hydrogen and oxygen gas to make rocket fuel—then they'll need oodles of electricity to power them.

It makes sense, then, that for the past several years, across both the first Trump administration and the Biden administration, NASA and its industry partners had been working on designs for a 40-kilowatt lunar reactor. This size would be enough to power an office building, which is about right for a prototypical moon base, experts say.

Under Duffy's brief tenure as NASA's leader, that number jumped to 100 kilowatts. Why? "I have no idea," Huff says. "I found no evidence that they thought about that number beyond it

Robin George Andrews is a volcanologist and science writer based in London. His most recent book is *How to Kill an Asteroid* (W. W. Norton, 2024). Follow him on X @SquigglyVolcano



George Rinhart/Corbis Historical/Getty Images

being bigger." Compared with a standard U.S. nuclear reactor on terra firma, 100 kilowatts is tiny—it's about 10,000 times less powerful, and it would be only the size of a large car. But this capacity is "huge for space," Huff says, noting that 100 kilowatts is a full order of magnitude greater than the output of any other nuclear reactor launched off-world.

Technically, putting a bespoke 100-kilowatt reactor on the moon in just four years is possible. "It is an aggressive but achievable goal," says Sebastian Corbisiero, national technical director for the U.S. Department of Energy's space reactor program.

In January, NASA's current administrator, Jared Isaacman, reaffirmed the plan to put nuclear fission power on the moon. And in March he announced that NASA would launch the first interplanetary spacecraft powered by nuclear electric propulsion—the Space Reactor-1 Freedom—to Mars by the end of 2028. This mission will help test out nuclear fission technology in deep space

The System for Nuclear Auxiliary Power (SNAP) 10A, which launched in 1965, was the first nuclear reactor sent to space. Heat from the reactor (*top*) was converted to electricity by the cone structure.

before the U.S. establishes a nuclear power plant on the lunar surface.

"I am quite confident that no reactor the U.S. launches will have safety concerns," Lal says. Yet "obviously things can always go wrong, and there's no such thing as 100 percent safe anywhere in the world—and anybody who says [they've achieved] that is lying."

TO PUT A NUCLEAR REACTOR on the moon, you must first put it on a rocket. "Keeping it safe for launch is one of the biggest factors," says Lindsey Holmes, an expert in space nuclear technology and vice president of advanced projects at Analytical Mechanics Associates, an aerospace company based in Virginia.

The U.S. launched the first nuclear reactor to space, the experimental Systems for Nuclear Auxiliary Power 10A reactor, back in 1965. This waste-basket-size 600-watt box generated power for just 43 days before a voltage regulator broke. It's still orbiting the planet today and remains America's sole attempt at operating a nuclear reactor off-planet.

Technically, putting a bespoke 100-kilowatt reactor on the moon in four years is possible.

The Soviet Union, in contrast, propelled more than two dozen nuclear reactors beyond Earth's atmosphere. Most of these reactors, which were often used to power radar spy satellites, went up without incident. One, however, "spewed radioactive stuff all over Canada," Holmes says, providing a brutally instructive master class in what not to do.

The spacecraft carrying that reactor, the Kosmos 954, started moving off target about three months after its September 1977 launch. Both the Soviet Union's operators and the U.S. officials noticed it wobbling around, but the Soviets initially kept quiet. Their engineers tried to eject the satellite's active nuclear reactor into space before the vehicle crashed back to Earth, but to no avail. Eventually the Soviets fessed up to their American counterparts—but they claimed Kosmos 954 would incinerate without consequence during its by then unstoppable atmospheric reentry.

U.S. authorities openly wondered what to do about a hot nuclear reactor plunging back to Earth. Gus Weiss, then a special assistant to the secretary of defense, said at the time that "a quick scan of literature showed no textbook answer, nor even a textbook question." Ultimately, in January 1978, Kosmos 954 showered its deadly detritus over a 15,000-square-mile patch of Canada's relatively sparsely inhabited Northern Territories. During a joint Canadian-American operation called Morning Light, hazmat-suited agents scoured the frozen realm for the shattered corpse of Kosmos 954. Some parts of the satellite weren't highly radioactive, but other fragments made the agents' personal radiation dosimeters sound off like "a field of crickets," according to a member of the team. Miraculously this trial by radioactive fire didn't kill a single soul—and the Soviet Union paid Canada $3 million CAD in apology. One clear lesson emerged from the Kosmos 954 kerfuffle: don't start a lunar nuclear reactor until it lands on the moon. "Until you turn it on, there's no nuclear waste inside," Huff says.

Ideally a lunar reactor should launch over the ocean because a splashdown would be a far better outcome than splattering a populous area with a smashed-apart nuclear reactor. The episode also revealed that the choice of reactor fuel is important, and you would want a fuel type that isn't prone to dispersing over a wide area. Tristructural isotropic particle fuel, better known as TRISO fuel, could work wonders here. It consists of pellets that are "basically gobstoppers of fuel," Middleburgh says. Each pellet is essentially a uranium, carbon and oxygen blob imprisoned within an ultraresilient carbon and ceramic shell. Not only can they survive high-velocity impacts fully intact, but you could pour lava over them to no effect. "If your launch were to fail, it'd be a big economic mess," Middleburgh says, but "you'd be able to sweep it all up."

MIDDLEBURGH, LIKE MANY of his colleagues, is enchanted by nuclear power. Unprompted, he waxes lyrical about the first time he saw Cherenkov radiation—an eerie blue glow—in a reactor pool: "TVs and pictures on the Internet don't do it justice. It's opalescent, magical; it's like the northern lights." But he's under no illusion that trying to put a working nuclear reactor on the moon, though entirely plausible, will be simple.

Let's start with the bad news: it's a lot easier to operate a nuclear power plant on Earth. The moon, quite frankly, is an awful place. It's a low-gravity world with essentially no atmosphere, which means its surface temperatures regularly swing from 250 degrees Fahrenheit during the day to –208 degrees F at night. It also has moonquakes, which resemble Earth's tectonic tremors but are weirder, and frequent small asteroid impacts create hefty craters on the surface at random times and locations.

The good news is that nuclear reactors aren't as prone to cataclysmic explosions as you might think. If the machine gets too hot and can't cool down, it will melt. But meltdowns are not explosions. Modern reactors are designed so that if nuclear fuel liquefies, they contain it within the plant.

Nuclear power plants are not particularly fragile, either. "When we think of nuclear, we think of Fukushima, we think of Chernobyl," Middleburgh says. But along with the virtually countless nuclear power plants around the world that have been operating normally for decades, "we don't think of the ones that have been floating in our oceans." Nuclear submarines are also plentiful; they exist in a fairly extreme environment, get knocked around all the time and are designed to withstand combat scenarios. "These things can be seriously robust," he says. There's no reason they can't withstand the moon, too.

A nuclear disaster on the moon is possible, though. Let's say a nuclear reactor does overheat and creates the first-ever nuclear meltdown on the moon. That would be a truly ignoble achievement, but at least most of the melted fuel would be contained at the site. It would, however, mean that "there would be a large, radioactive hunk of metal sitting there on the lunar surface," Huff says. Nobody could approach it, perhaps for generations. And if it oozed into a precious reserve of water ice nearby, that game-changing resource—the entire reason astronauts would be based there—would be permanently contaminated. "Yikes," Huff says. "It would be terrible. It would be very hard to forgive a nation willing to do that to the moon." But at least the astronauts would be fine, right?

Well, not really. Radiation from the reactor—even what might be unleashed during a meltdown—wouldn't be a huge worry (in fact, the solar and cosmic radiation on the moon is much more of a concern for astronaut health). The failure of the plant would be the bigger problem. Say the lunar base relying on it loses electricity during the two weeks when any given spot on the moon is cloaked in darkness. In such cold conditions, battery systems may hold only a modicum of juice before they run dry. Then the astronauts are in deep trouble "because their entire life-support system goes down," says Nicholas Schmerr, a planetary seismologist and geophysicist at the University of Maryland, College Park. "They're not going to be able to survive."

But experts don't anticipate that we'll see a lunar Chernobyl in our lifetime. And a spokesperson at NASA says "the fission surface power system will be designed with safety in mind." That's a relief. A more realistic worst-case scenario for a 100-kilowatt nuclear reactor is that the moon simply breaks it, and it stops working when the astronauts need it most. So the real question is, "How long can we design all the sensors and electronics and all those components to last in a fairly hostile environment?" Corbisiero asks.

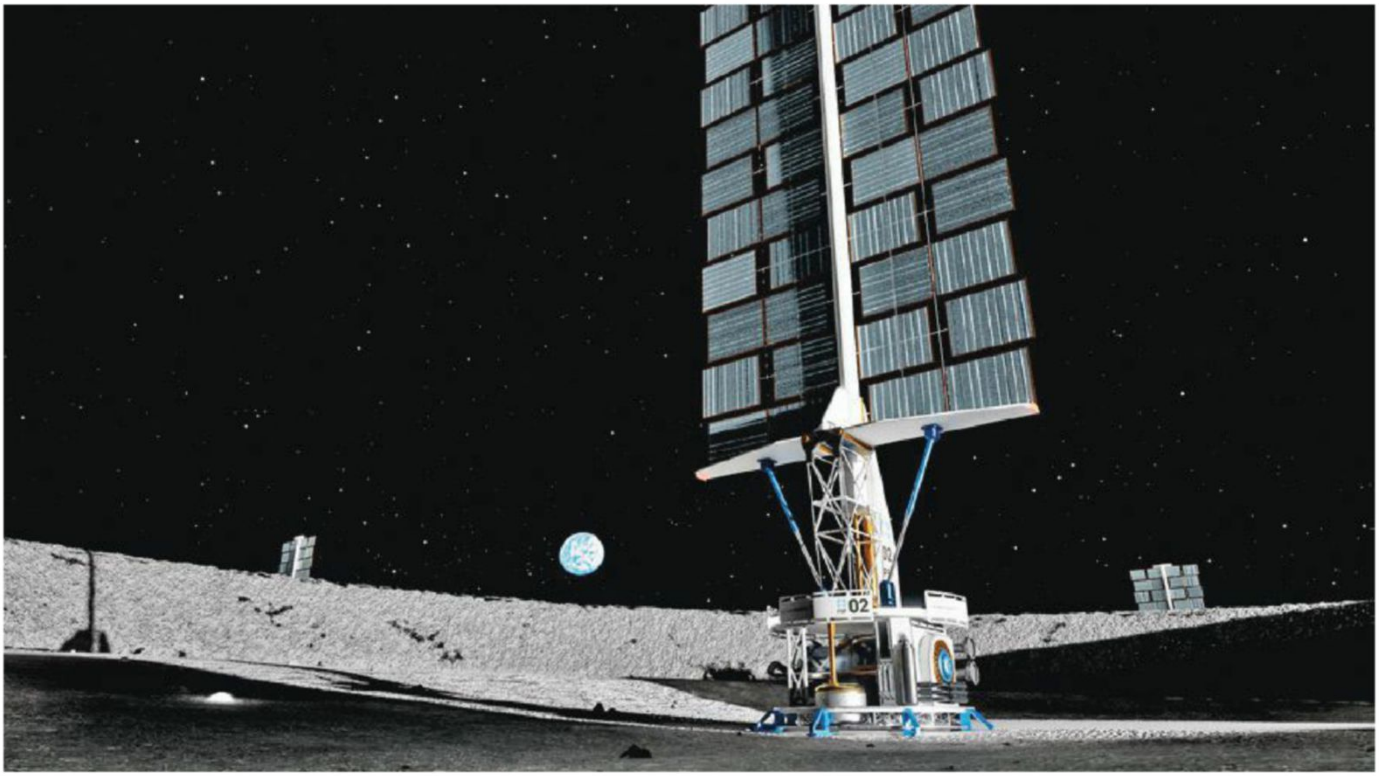
A LUNAR REACTOR WILL HAVE to function differently than those on Earth. It probably won't be able to use water either as a coolant or as the heat-absorbing, steam-making substance that turns a turbine to make electricity. "Water has a lot of problems in space," Huff says. It doesn't flow properly under low gravity, and the maddening temperature swings on the moon could cause the steam to violently expand or the water to freeze, breaking pipes in the process. Instead the reactor would probably use air brought from Earth to take on the heat and move it to the turbine. That's more difficult to design for, but it's possible.

Replacing water as the nuclear reactor's coolant is much more problematic. Most of the heat produced by the fissioning uranium would be used to make electricity, but some of it would be excess. This "waste heat" will need to escape into the environment, but without any atmosphere there won't be any airlike sink to easily soak it up. Stopping the nuclear reactor from overheating is "going to be hard in a vacuum," Huff says. She and Middleburgh suggest the same solution: sails—giant finlike adornments that can use their large surface area to eject heat into space.

Sounds good. But don't forget about those pesky micrometeorites—pebble-size rocks that move like hypersonic bullets. "The moon is constantly being bombarded by extraterrestrial material," Schmerr says, and there's no atmospheric shield to stop them. If several of these meteorites puncture the radiator fins, the plant will be unable to cool down properly.

You also could get supremely unlucky, and an asteroid a dozen or so feet across could smash into the ground nearby. "We saw new craters that formed during Apollo that were 70, 80 meters [230 to 260 feet] wide," Schmerr says. "If you happen to be at ground zero for one of those impacts, you're having a really bad day."

Astronauts cannot defend their base against any of these rarer, larger asteroid strikes. But they can mitigate the threat of the more frequent but



diminutive space bullets by burying their power plant underground. They wouldn't even need to dig—they could simply use one of the moon's multitude of hollowed-out lava tubes.

Moonquakes are another challenge. They are nowhere near as powerful as Earth's tectonic convulsions: the largest spotted by seismometers placed during the Apollo era were between magnitudes 3 and 4. Still, a nuclear power plant shouldn't go right next to a potentially active fault, because even a modest tremor could knock over taller structures and break things.

> "We don't want to *not* be the first to have a nuclear reactor on the moon."
> —BHAVYA LAL *RAND SCHOOL OF PUBLIC POLICY*

But the moon's geological makeup gives moonquakes a surprising persistence compared with earthquakes; the tremors can last for several hours. "Not only is your system shaking, it's shaking a lot for a long time," Schmerr says. "This is not something we normally think about with structural construction here on Earth."

If the reactor isn't properly fortified against the moon's seismic dangers, three things could happen: the reactor could break and stop working; the fuel might be jiggled around and put into a weird arrangement that slows down the fission reaction; or the fuel could shift in a way that speeds up the reaction—and makes the power plant overheat until it requires a shutdown before it turns into a lethal, incandescent soup.

NASA's experienced industry partners, its own deep expertise and its cutting-edge testing facilities will certainly help to make any reactor disaster-resistant. But it's impossible to perfectly recreate the lunar environment on Earth. Reproducing lunar gravity in a laboratory would require an act of witchcraft, and although vacuum chambers can simulate the moon's extreme temperatures and lack of atmosphere, "the U.S. does not have a facility where you can operate a reactor inside a vacuum chamber," Corbisiero says.

Despite the hurdles that must be overcome, many experts are pretty jazzed about the possibility of a lunar nuclear reactor. "I'm enthusiastic about it," Middleburgh says. But the only way to know for sure that one will work, and work safely, is to go to the moon and switch it on.

LAL AT RAND is also excited about the prospect of the U.S. operating the first nuclear reactor on the moon. But she spends a lot of time thinking about "all the things NASA could do wrong" in the process. Those pitfalls include its interactions with China, a spacefaring nation also keen to establish a nuclear-powered foothold on the lunar south pole.

In one possible future scenario, China and the U.S. have their own spacious patches of the lunar south pole. They coordinate certain operations

Lockheed Martin illustrations show a potential future lunar fission power plant (*left*) and a nuclear-powered Artemis moon base (*right*).

Lockheed Martin

and share a bevy of scientific discoveries, all while keeping a respectful distance from each other. "That's the best-case scenario," Lal says. But it's not the most realistic. China and the U.S. are geopolitical rivals and competitors in the new race to claim the moon. "There's new land, and it belongs to no one," Lal says. "Whoever gets there first makes the rules."

The United Nations Outer Space Treaty, which was signed in 1967, states that "outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." Nobody can legally own territory on the moon (yet). But in his August 2025 declaration, Duffy noted that nuclear power plants could be used to define a "keep-out zone" to other parties: *Hey, this is sensitive, dangerous equipment—stay away!*

Establishing a base would also grant a nation de facto control over a given patch of the moon. But nuclear power plants can be put anywhere for any purpose, far from any astronauts, so both China and the U.S. could place them like radioactive flags. Nations could quickly stake not quite legal claims on any land they deemed valuable—including any swaths rich in water.

For that reason, "we don't want to *not* be the first to have a nuclear reactor on the moon," Lal says. "The U.S. should be the first to land, to set the norms." Preferably, these norms would include the nonaggressive placement of safely designed nuclear reactors. The deployment of each reactor should also be clearly communicated ahead of time to our neighbors on the lunar surface. "We need to be able to talk to our friends *and* adversaries," she says.

But in the current political climate, clandestine behaviors could win out. Suspicion is a breeding ground for unforced errors. And if things get confrontational, nuclear power plants may not be the only territorial markers spacefaring nations put down. "If they want to put a nuclear weapon on the moon, they will just do it," Lal says. Putting nukes in space is illegal under the Outer Space Treaty. Nevertheless, Russia is thought to be developing one for this very purpose. And the treaty isn't legally enforceable; it's more like a guideline. "If somebody wants to be nefarious, there is no way [to force] them not to be," she adds.

For a moment, though, let's envision a future in which someone sets up a lunar base that's safely powered by the first-ever nuclear reactor on the moon. Forget a cramped shoebox; they can now create and sustain a small village for their moonwalkers. In time, this base becomes an engineering hub and a fuel depot—a springboard for astronauts to reach the ocher-hued planet farther afield.

America wants to realize this dream first. So does China. Let's hope that in their scramble to win, they unfurl their nuclear ambitions carefully. "Some overconservatism at the very beginning of the lunar nuclear endeavor is required," Middleburgh says. No matter how exciting the prospect is and what it may enable, one question should be on everyone's mind throughout: "What happens if it goes wrong?" ●

FROM OUR ARCHIVES
Back to the Moon. Sarah Scoles; October 2024. ScientificAmerican.com/archive