Most of what humanity knows about the outer planets came back to Earth on plutonium power. Cassini's ongoing exploration of Saturn, Galileo's trip to Jupiter, Curiosity's exploration of the surface of Mars, and the 2015 flyby of Pluto by the ...

NASA's Plutonium Problem Could End Deep-Space Exploration

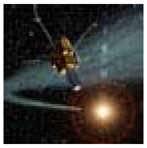
- By Dave Mosher
- 09.19.13
- 6:30 AM

The Voyager probe's three radioisotope thermoelectric generators (RTGs) can be seen mounted end-to-end on the left-extending boom. (*NASA*)

In 1977, the Voyager 1 spacecraft left Earth on a five-year mission to explore Jupiter and Saturn. Thirty-six years later, the car-size probe is still exploring, still sending its findings home. It has now put more than 19 billion kilometers between itself and the sun. Last week NASA announced that

Voyager 1 had become the first man-made object to reach interstellar space.
More on Plutonium-238:

How the U.S. Tested the Safety of Nuclear Batteries



The Best Plutonium-Powered Space Missions

Timeline: Plutonium-238′s Hot and Twisted History

The distance this craft has covered is almost incomprehensible. It's so far away that it takes more than 17 hours for its signals to reach Earth. Along the way, Voyager 1 gave scientists their first close-up looks at Saturn, took the first images of Jupiter's rings, discovered many of the moons circling those planets and revealed that Jupiter's moon Io has active volcanoes. Now the spacecraft is discovering what the edge of the solar system is like, piercing the heliosheath where the last vestiges of the sun's influence are felt and traversing the heliopause where cosmic currents overcome the solar wind. Voyager 1 is expected to keep working until 2025 when it will finally run out of power.

None of this would be possible without the spacecraft's three batteries filled with plutonium-238. In fact, Most of what humanity knows about the outer planets came back to Earth on plutonium power. Cassini's ongoing exploration of Saturn, Galileo's trip to Jupiter, Curiosity's exploration of the surface of Mars, and the 2015 flyby of Pluto by the New Horizons spacecraft are all fueled by the stuff. The characteristics of this metal's radioactive decay make it a super-fuel. More importantly, there is no other viable option. Solar power is too weak, chemical batteries don't last, nuclear fission systems are too heavy. So, we depend on plutonium-238, a fuel largely acquired as by-product of making nuclear weapons.

But there's a problem: We've almost run out.

"We've got enough to last to the end of this decade. That's it," said Steve Johnson, a nuclear chemist at Idaho National Laboratory. And it's not just the U.S. reserves that are in jeopardy. The entire planet's stores are nearly depleted.

The country's scientific stockpile has dwindled to around 36 pounds. To put that in perspective, the battery that powers NASA's Curiosity rover, which is currently studying the surface of Mars, contains roughly 10 pounds of plutonium, and what's left has already been spoken for and then some. The implications for space exploration are dire: No more plutonium-238 means not exploring perhaps 99 percent of the solar system. In effect, much of NASA's $1.5 billion-a-year (and shrinking) planetary science program is running out of time. The nuclear crisis is so bad that affected researchers know it simply as "The Problem."

But it doesn't have to be that way. The required materials, reactors, and infrastructure are all in place to create plutonium-238 (which, unlike plutonium-239, is practically impossible to use for a nuclear bomb). In fact, the U.S. government recently approved spending about $10 million a year to reconstitute production capabilities the nation shuttered almost two decades ago. In March, the

DOE even produced a tiny amount of fresh plutonium inside a nuclear reactor in Tennessee.

It's a good start, but the crisis is far from solved. Political ignorance and shortsighted squabbling, along with false promises from Russia, and penny-wise management of NASA's ever-thinning budget still stand in the way of a robust plutonium-238 production system. The result: Meaningful exploration of the solar system has been pushed to a cliff's edge. One ambitious space mission could deplete remaining plutonium stockpiles, and any hiccup in a future supply chain could undermine future missions.

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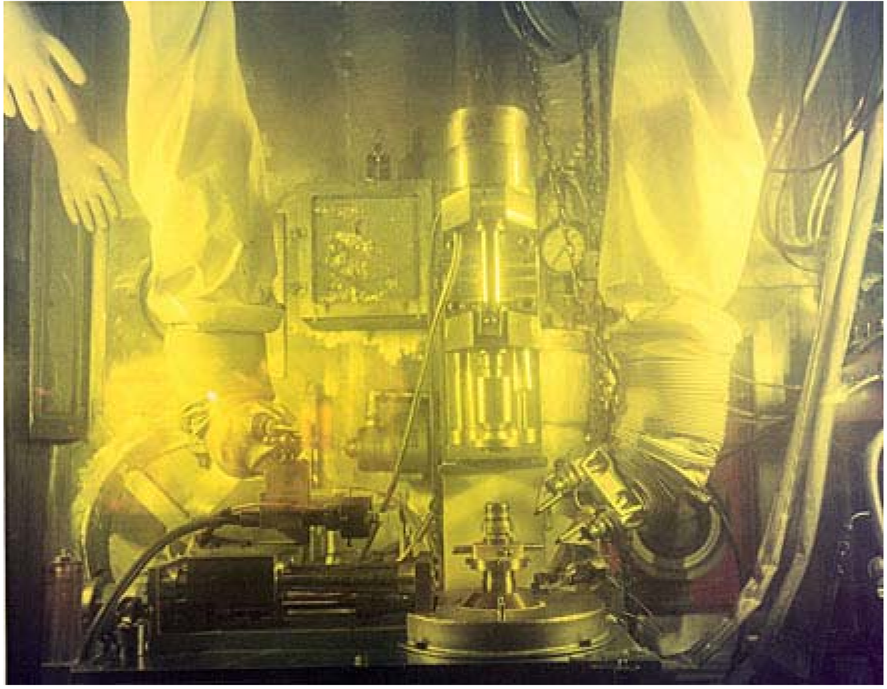
The only natural supplies of plutonium-238 vanished eons before the Earth formed some 4.6 billion years ago. Exploding stars forge the silvery metal, but its half-life, or time required for 50 percent to disappear through decay, is just under 88 years.

Fortunately, we figured out how to produce it ourselves — and to harness it to create a remarkably persistent source of energy. Like other radioactive materials, plutonium-238 decays because its atomic structure is unstable. When an atom's nucleus spontaneously decays, it fires off a helium core at high speed while leaving behind a uranium atom. These helium bullets, called alpha radiation, collide *en masse* with nearby atoms within a lump of plutonium — a material twice as dense as lead. The energy can cook a puck of plutonium-238 to nearly 1,260 degrees Celsius. To turn that into usable power, you wrap the puck with thermoelectrics that convert heat to electricity. Voila: You've got a battery that can power a spacecraft for decades.

"It's like a magic isotope. It's just right," said Jim Adams, NASA's deputy chief technologist and former deputy director of the space agency's planetary science division.



A radiation-shielded glove box at Savannah River Site. In chambers like these during the cold war, the government assembled plutonium-238 fuel for use in spacecraft such as Galileo and Ulysses. (*Savannah River Site*)

U.S. production came primarily from two nuclear laboratories that created plutonium-238 as a byproduct of making bomb-grade plutonium-239. The Hanford Site in Washington state left the plutonium-238 mixed into a cocktail of nuclear wastes. The Savannah River Site in South Carolina, however, extracted and refined more than 360 pounds during the Cold War to power espionage tools, spy satellites, and dozens of NASA's pluckiest spacecraft.

By 1988, with the Iron Curtain full of holes, the U.S. and Russia began to dismantle wartime nuclear facilities. Hanford and Savannah River no longer produced any plutonium-238. But Russia continued to harvest the material by processing nuclear reactor fuel at a nuclear industrial complex called Mayak. The Russians sold their first batch, weighing 36 pounds, to the U.S. in 1993 for more than $45,000 per ounce. Russia had become the planet's sole supplier, but it soon fell behind on orders. In 2009, it reneged on a deal to sell 22 pounds to the U.S.

Whether or not Russia has any material left or can still create some is uncertain. "What we do know is that they're not willing to sell it anymore," said Alan Newhouse, a retired nuclear space consultant who spearheaded the first purchase of Russian plutonium-238. "One story I've heard … is that they don't have anything left to sell."

By 2005, according a Department of Energy report (.pdf), the U.S. government owned 87 pounds, of which roughly two-thirds was designated for national security projects, likely to power deep-sea espionage hardware. The DOE would not disclose to WIRED what is left today, but scientists close to the issue say just 36 pounds remain earmarked for NASA.

That's enough for the space agency to launch a few small deep-space missions before 2020. A twin of the Curiosity rover is planned to lift off for Mars in 2020 and will require nearly a third of the stockpile. After that, NASA's interstellar exploration program is left staring into a void — especially for high-profile, plutonium-hungry missions, like the proposed Jupiter Europa Orbiter. To seek signs of life around Jupiter's icy moon Europa, such a spacecraft could require more than 47 pounds of plutonium.

"The supply situation is already impacting mission planning," said Alice Caponiti, a nuclear engineer who leads the DOE's efforts to restart plutonium-238 production. "If you're planning a mission that's going to take eight years to plan, the first thing you're going to want to know is if you have power."

Many of the eight deep-space robotic missions that NASA had envisioned over the next 15 years have already been delayed or canceled. Even more missions — some not yet even formally proposed — are silent casualties of NASA's plutonium poverty. Since 1994, scientists have pleaded with lawmakers for the money to restart production. The DOE believes a relatively modest $10 to 20 million in funding each year through 2020 could yield an operation capable of making between 3.3 and 11 pounds of plutonium-238 annually — plenty to keep a steady stream of spacecraft in business.

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In 2012, a line item in NASA's $17-billion budget fed $10 million in funding toward an experiment to create a tiny amount of plutonium-238. The goals: gauge how much could be made, estimate full-scale production costs, and simply prove the U.S. could pull it off again. It was half of the money requested by NASA and the DOE, the space agency's partner in the endeavor (the Atomic Energy Act forbids NASA to manufacture plutonium-238). The experiment may last seven more years and cost between $85 and $125 million.

At Oak Ridge National Laboratory in Tennessee, nuclear scientists have used the High Flux Isotope Reactor to produce a few micrograms of plutonium-238. A fully reconstituted plutonium program described in the DOE's latest plan, released this week, would also utilize a second reactor west of Idaho Falls, called the Advanced Test Reactor.

That facility is located on the 890-square-mile nuclear ranch of Idaho National Laboratory. The scrub of the high desert rolls past early morning visitors as the sun crests the Teton Range. Armed guards stop and inspect vehicles at a roadside outpost, waving those with the proper credentials toward a reactor complex fringed with barbed wire and electrified fences.

The Advanced Test reactor's unique four—leaf—clover core design. (*Idaho National Laboratory*)

Beyond the last security checkpoint is a warehouse-sized, concrete-floored room. Yellow lines painted on the floor cordon off what resembles an aboveground swimming pool capped with a metal lid. A bird's-eye view reveals four huge, retractable metal slabs; jump through one and you'd plunge into 36 feet of water that absorbs radiation. Halfway to the bottom is the reactor's 4-foot-tall core, its four-leaf clover shape dictated by slender, wedge-shaped bars of uranium. "That's where you'd stick your neptunium," nuclear chemist Steve Johnson said, pointing to a diagram of the radioactive clover.

Neptunium, a direct neighbor to plutonium on the periodic table and a stable byproduct of Cold War-era nuclear reactors, is the material from which plutonium-238 is most easily made. In Johnson's arrangement, engineers pack tubes with neptunium-237 and slip them into the reactor core. Every so often an atom of neptunium-237 absorbs a neutron emitted by the core's decaying uranium, later shedding an electron to become plutonium-238. A year or two later — after harmful isotopes vanish — technicians could dissolve the tubes in acid, remove the plutonium, and recycle the neptunium into new targets.

The inescapable pace of radioactive decay and limited reactor space mean it may take five to seven years to create 3.3 pounds of battery-ready plutonium. Even if full production reaches that rate, NASA needs to squeeze every last watt out of what will inevitably always be a rather small stockpile. The standard-issue power source, called a multi-mission thermoelectric generator — the kind that now powers the Curiosity rover — won't cut it for space exploration's future. "They're trustworthy, but they use a heck of a lot of plutonium," Johnson said.

In other words, NASA doesn't just need new plutonium. It needs a new battery.

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Is It Safe to Launch Nuclear Batteries?

Anti-nuclear activists often state that just one microscopic particle of plutonium-238 inhaled into the lungs can lead to fatal cancer. There's something to the claim, as pure plutonium-238 — ounce-for-ounce — is 270 times more radioactive than the plutonium-239 inside nuclear warheads. But the real risks to anyone of launching a nuclear battery are frequently mis-represented or misunderstood. Statisticians compare apples to apples by looking at a threat's severity, likelihood and affected population. An asteroid able to wipe out 1.5 billion people, for example, hits Earth about once about every 500,000 years — so the risk is high-severity, yet low-probability. Nuclear battery disasters, meanwhile, exist as low-severity and low-probability events, even near the launch pad.

Cassini, for example, left Earth with the most plutonium of any spacecraft at 72 pounds . Late in that probe's launch there was about a 1 in 476 chance of plutonium release. If that had happened, fatalities over 50 years from that release would have numbered an estimated 1/25th of a person per the safety design of its nuclear batteries. The overall risk of cancer to a person near the launch pad during an accident was estimated at 7 in 100,000. Beyond that zone, risk was even lower.

Statisticians also considered a second hypothetical and potentially dangerous event with Cassini. To get to Saturn, the spacecraft swung back toward and flew within 600 miles of Earth, zooming by at tens of thousands of miles per hour. The chance of releasing plutonium then was less than 1 in a million. If a release of plutonium occurred, statisticians estimated it might cause 120 cancer fatalities — for the whole planet — over 50 years. By contrast, natural background radiation likely claims a million lives a year, and lightning strikes about 10,000 lives.

A launch accident with NASA's Curiosity rover had a roughly 1 in 250 chance of releasing plutonium. But the low chance of cancer fatalities brought individual risk down to about 1 in 5.8 million. “I feel that they're completely safe,” said Ryan Bechtel, DOE's nuclear battery safety manager. “My entire family was there at Curiosity's launch site.”

In a cluttered basement at NASA Glenn Research Center in Cleveland, metal cages and transparent plastic boxes house a menagerie of humming devices. Many look like stainless-steel barbells about a meter long and riddled with wires; others resemble white crates the size of two-drawer filing cabinets.

The unpretentious machines are prototypes of NASA's next-generation nuclear power system, called the Advanced Stirling Radioisotope Generator. It's shaping up to be a radically different, more efficient nuclear battery than any before it.

On the outside, the machines are motionless. Inside is a flurry of heat-powered motion driven by the Stirling cycle, developed in 1816 by the Scottish clergyman Robert Stirling. Gasoline engines burn fuel to rapidly expand air that pushes pistons, but Stirling converters need only a heat gradient. The greater the difference between a Stirling engine's hot and cold parts, the faster its pistons hum. When heat warms one end of a sealed chamber containing helium, the gas expands, pushing a magnet-laden piston through a tube of coiled wire to generate electricity. The displaced, cooling gas then moves back to the hot side, sucking the piston backward to restart the cycle.

“Nothing is touching anything. That's the whole beauty of the converter,” said Lee Mason, one of several NASA engineers crowded into the basement. Their pistons float like air hockey pucks on the cycling helium gas.

For every 100 watts of heat generated, the Stirling generator converts more than 30 watts into electricity. That's nearly five times better than the nuclear battery powering Curiosity. In effect, the generator can use one-fourth of the plutonium while boosting electrical output by at least 25 percent. Less plutonium also means these motors weigh two-thirds less than Curiosity's 99-pound battery — a big difference for spacecraft on 100 million-mile-or-more journeys. Curiosity was the biggest, heaviest spacecraft NASA could send to Mars at the time, with a vast majority of its mass dedicated to a safe landing — not science. Reducing weight expands the possibilities for advanced instruments on future missions.

But the Stirling generator's relatively complicated technology, while crucial to the design, worries some space scientists. “There are people who are very concerned that this unit has moving parts,” said John Hamley, manager of NASA Glenn's nuclear battery program. The concern is that the motion might interfere with spacecraft instruments that must be sensitive enough to map gravity fields, electromagnetism, and other subtle phenomena in space.

As a workaround, each generator uses two Stirling converters sitting opposite each other. An onboard computer constantly synchronizes their movements to cancel out troublesome vibrations.

To detect and correct design flaws, engineers have abused their generator prototypes in vacuum chambers, assaulted them on shaking tables, and barraged them with powerful blasts of radiation and magnetism.

But NASA typically requires new technologies to be tested for one and a half expected lifetimes before flying them in space. For the Stirling generator, that would take 25 years. Earnest testing began in 2001, cutting the delay to 13 years – but that's longer than NASA can wait: In 2008, only one of 10 nuclear-powered missions called for the device. By 2010, seven of eight deep-space missions planned through 2027 required them.

To speed things up, Hamley and his team run a dozen different units at a time. The oldest device has operated almost continuously for nearly 10 years while the newest design has churned since 2009. The combined data on the Stirling generators totals more than 50 years, enough for simulations to reliably fast-forward a model's wear-and-tear. So far, so good. "Nothing right now is a show-stopper," Hamley said. His team is currently building two flight-worthy units, plus a third for testing on the ground (Hamley expects Johnson's team in Idaho to fuel it sometime next year).

For all of the technology's promise, however, it "won't solve this problem," Johnson said. Even if the Stirling generator is used, plutonium-238 supplies will only stretch through 2022.

An early ASRG prototype. Its 10,016 hours of use has contributed to decades of combined data on the performance of NASA's revolutionary nuclear battery. (*Dave Mosher/WIRED*)

Any hiccups in funding for plutonium-238 production could put planetary science into a tailspin and delay, strip down, or smother nuclear-powered missions. The outlook among scientists is simultaneously optimistic and rattled.

The reason: It took countless scientists and their lobbyists more than 15 years just to get lawmakers' attention. A dire 2009 report about "The Problem," authored by more than five dozen researchers, ultimately helped slip the first earnest funding request into the national budget in 2009. Congressional committees squabbled over if and how to spend $20 million of taxpayers' money — it took them three years to make up their minds.

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"There isn't a day that goes by that I don't think about plutonium-238," said Jim Adams, the former deputy boss of NASA's planetary science division.

At the National Air and Space Museum in Washington, D.C., Adams stares through the glass at the nuclear wonder that powered his generation's space exploration. Amid the fake moon dust sits a model of SNAP-27, a plutonium-238-fueled battery that every lunar landing after Apollo 11 to power its science experiments. "My father worked on the Lunar Excursion Model, which that thing was stored on, and it's still up there making power," Adams said.

Just a few steps away is a model of the first Viking Lander, which touched down on Mars in 1976 and began digging for water and life. It found neither. "We didn't dig deep enough," Adams said. "Just 4 centimeters below the depth that Viking dug was a layer of pristine ice."

One floor up, a model of a Voyager spacecraft hangs from the ceiling. The three nuclear power supplies aboard the real spacecraft are what allow Voyager 1 and its twin, Voyager 2, to contact the Earth after 36 years. Any other type of power system would have expired decades ago.

The same technology fuels the Cassini spacecraft, which continues to survey Saturn, sending a priceless stream of data and almost-too-fantastic-to believe images of that planet and its many moons. New Horizons' upcoming flyby of Pluto — nine and a half years in the making — wouldn't be possible without a reliable source of nuclear fuel.

The Viking lander needed to dig deeper. Now we do, too.

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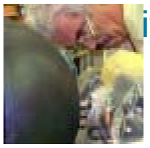
- 
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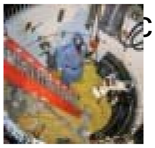
- 
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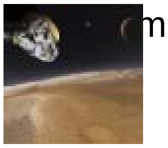
- 
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