AVIONICS 8

Fly by voice

Q & A 12

FAA's Jim Eck on NextGen

INTELLIGENCE 30

Lockheed Martin's TR-X pitch

AEROSPACE

★ ★ ★ AMERICA ★ ★ ★

THE BUZZ OVER BATTERIES

Researchers are undaunted by doubts over electricity as a quick solution to aviation emissions

PAGE 16

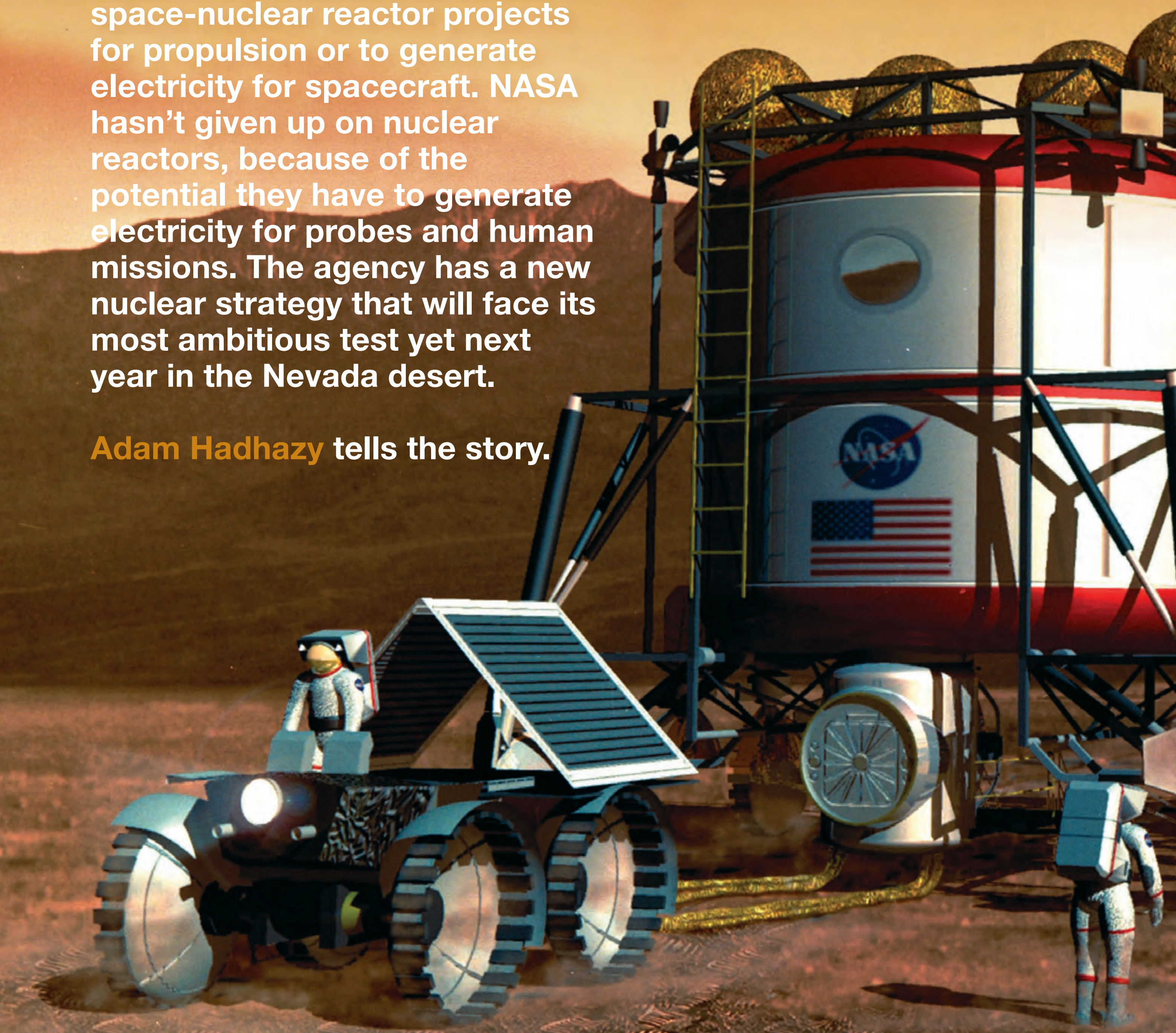
OCTOBER 2016 | A publication of the American Institute of Aeronautics and Astronautics | www.aerospaceamerica.org

AIAA

Shaping the Future of Aerospace

Since the 1960s, the U.S. has repeatedly started and folded space-nuclear reactor projects for propulsion or to generate electricity for spacecraft. NASA hasn't given up on nuclear reactors, because of the potential they have to generate electricity for probes and human missions. The agency has a new nuclear strategy that will face its most ambitious test yet next year in the Nevada desert.

Adam Hadhazy tells the story.



Missio

NASA

Sustained human presence on Mars could be enabled by the thousands of watts of electricity made available by nuclear fission reactors. NASA plans to test one in 2017.

n: Fission

Department of Energy

▲ **The 1965 flight of SNAP 10A**, the Systems Nuclear Auxiliary Power spacecraft, turned out to be the only time the U.S. orbited a fission reactor.

The future of human robotic space exploration might depend on a technology from the past: The nuclear fission reactor. Fueled by the element uranium, these reactors have produced energy commercially on terra firma since the 1950s, and currently supply a fifth of United States' electricity. Nevertheless, despite decades of on-and-off development across a litany of canceled NASA programs, fission has failed to break into the final frontier.

Its promise has long tantalized. For missions to deep space, fission could offer magnitudes more power than NASA's current workhorses: Solar cells and radioisotope thermoelectric generators. RTGs typically contain plutonium-238 pellets that passively emit enough heat to generate a few hundred watts of electricity — about as much as a kitchen blender requires. RTGs are handy when spacecraft are far from the sun, but mission planners must ration power for scientific payloads and limit data transmission rates, while relying on limited chemical fuel for spacecraft maneuvering.

Fission has been repeatedly doomed by prohibitive development costs and questions over the demand for power beyond tried-and-true solar and RTGs. Bucking this history, researchers now have high hopes for a new fission project, called Kilopower. Designers of the Kilopower reactor are testing components and finalizing plans for a kilowatt-level test in 2017, after demonstrating a small-scale version at the Nevada National Security Site, a Department of Energy facility near Las Vegas, in 2012. That lab experiment marked the first production of electricity from a space nuclear reactor by the U.S. since 1965's first, and only, flight of a reactor. The Soviet Union went on to use fission reactors in more than 30 reconnaissance satellites into the late 1980s, but the technology has otherwise remained grounded.

If Kilopower can break fission's losing streak, a robotic probe could someday land on Jupiter's moon Europa and have enough juice to drill into its icy crust to potential pocket pools of liquid near the surface. Another possibility: Human explorers could set up a fission-powered outpost on Mars to turn Martian air and dirt into rocket propellant for the return trip to Earth. NASA thinks it knows how to succeed this time, and the strategy has as much to do about management as technology.

"With Kilopower, we're starting small and keeping it simple and affordable," says NASA's Lee Mason, the principal technologist for power and energy storage at Glenn Research Center in Ohio. "Every time we've tried to deliver fission before we've started at a very aggressive, optimistic endpoint where we're trying to develop a pretty advanced, high-tech system."

This time, NASA has set modest power goals and is applying existing, regulatory-approved testing hardware and reactor architecture.

Should the 2017 test go well, Kilopower and its descendant reactors will still have hurdles to overcome before taking to space. Safety and nuclear proliferation concerns must be assuaged, funding lined up and, most importantly, NASA will need to greenlight costly, ambitious missions in dire need of kilowatt-levels of power.

Fission on the backburner

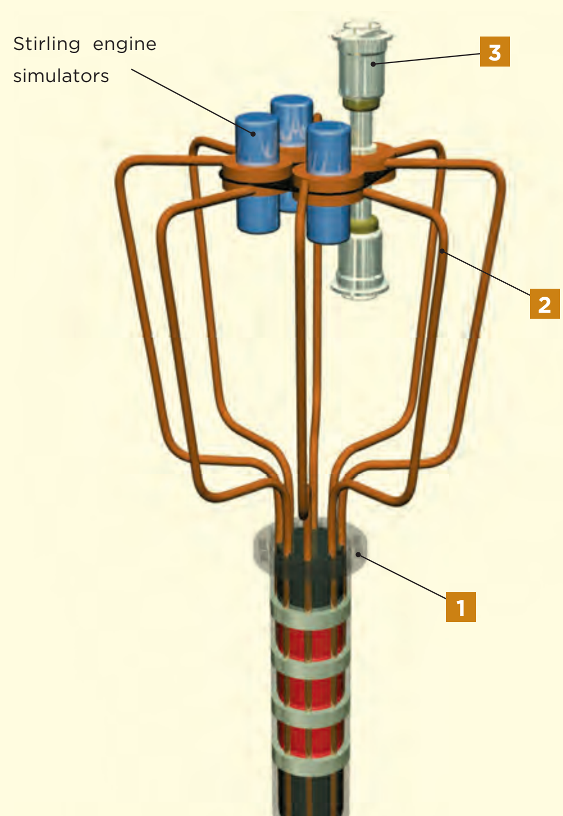
Fission for space began with a flourish. After NASA's inception in 1958, the agency worked with other federal entities on nuclear reactors for

NASA

▲ **Workers at NASA's Kennedy Space Center** install the radioisotope thermoelectric generator onto the New Horizons probe for its journey past Pluto. A fission reactor on a probe would be much more powerful than such RTGs.

Reactor setup

In the Kilopower test that NASA and the Energy Department plan to run in mid-2017, a uranium-fueled fission reactor **1** will produce heat carried by eight sodium heat pipes **2** to Stirling engines **3** which convert heat into electricity.



launch vehicles and space propulsion under the Nuclear Engine for Rocket Vehicle Applications, or NERVA, project. On the electricity front, the Systems Nuclear Auxiliary Power, or SNAP, effort culminated in the flight of the SNAP 10A spacecraft in 1965, the only fission reactor the U.S. has ever orbited. The satellite cranked out 590 watts, but stopped working 43 days after launch due to a non-reactor, voltage regulator issue. NASA abandoned SNAP in favor of well-understood chemical rockets for NASA's astronaut flights. RTGs, also developed in the SNAP program, offered sufficient electricity at lower cost than fission.

"Missions have typically required less than 500 watts electric, and at that power level, RTGs weigh less, and you're always trying to keep your mass down at launch," to cut down on costs, says John Casani, who retired in 2012 from NASA's Jet Propulsion Laboratory in Pasadena, California.

During his career, Casani served as project manager for the Voyager 1 and 2, Galileo and Cassini spacecraft, all of which relied on RTGs to take them to planets of the outer solar system (and in Voyager 1's case, all the way into interstellar space). RTGs have performed well on dozens of missions because they have no moving parts but an ability to provide heat and steady power even in the extreme cold and dark of space, or on the dim, dusty surface of Mars.

A renewed case for fission

The overall nuclear landscape has changed considerably since RTG's dominance was established. Availability of the isotope plutonium-238, once a byproduct of nuclear weapons production, plummeted after the element's domestic manufacture by the Department of Energy ended in 1988 with the Cold War's decline. In the 1990s, the U.S. government had to purchase plutonium for NASA's Cassini mission from Russia, at around $3 million a kilogram, according to Casani, though that pipeline has now also closed.

Supplies have therefore continued dwindling. Just 35 kilograms of plutonium are now on hand, and only about half meet the power specifications for slated missions, like the Mars 2020 rover. In a bind, NASA in 2012 started paying the Energy Department to restart plutonium production. The first 50 milligrams from the effort at the Oak Ridge National Laboratory in Tennessee were announced in November 2015, with the goal to ramp up to 1.5 to 2 kilograms per year by 2018. The cost to NASA is about $100 million annually, though, because the extraction, irradiation, and fabrication of the material that becomes plutonium-238 fuel pellets occur at three sites. Ultimately, NASA, which is the sole end user of the dangerous material, could end up paying perhaps $50 million per kilogram of plutonium for major missions launching in the 2030s, or $240 million for a standard, 4.8-kilogram plutonium, multi-mission RTG like the one in the Curiosity rover.

Given NASA's big bet on RTGs, the technology will likely remain a pillar for conventional, low-power space exploration for another couple decades. But Casani and others think that fission's time has finally come.

"Plutonium has outlived its usefulness for space," Casani said to an audience at the AIAA Propulsion and Energy Forum in Salt Lake City in July. "That's why I am so much in favor of fission-powered missions ... we need to get on to uranium."

Nuclear engineer Susan Voss put it like this: "We have a real driver in a way we never have had before, which is that the cost of plutonium has gone up too much."

Voss is president of the Global Nuclear Network Analysis, a consulting firm in Corvallis, Oregon. In the 1980s and the '90s, she worked on the American SP-100 fission project, mostly at Los Alamos, and served as project leader for the TOPAZ fission reactor projects with the Russians. She thinks that NASA will have to make the jump to fission, assuming a viable pathway is demonstrated at last. For every decade or so, another NASA fission project has sprung up, sputtered, and gotten the ax. The last such effort, a proposed 200-kilowatt propulsion concept called Prometheus, which Casani managed, succumbed in 2005.

▲ **Fusion test:** A researcher adjusts a heat pipe as it's inserted into the reactor core reflector (the dark hemisphere) in preparation for a 2012 ground experiment called DUFF, for the Demonstration Using Flattop Fissions. DUFF marked the first U.S. production of electricity by a fission reactor for space since the 1965 SNAP 10A mission.

Onward, Kilopower

This time around, Kilopower is not swinging for the fences. The project passed its initial test in 2012 in an experiment called DUFF, for Demonstration Using Flattop Fissions. (Flattop is one of the critical assembly machines at the Nevada National Security Site long used for testing nuclear material.) For the first time ever, a heat pipe (filled with water) transferred thermal energy from a uranium source to a Stirling engine for conversion to electricity. Inside a Stirling engine, a heat source of some kind warms gas inside a loop. The gas expands and pushes a piston as it flows by, then cools in a perpetuating, power-generating cycle. When the Stirling cycle was conceived in the 19th century, coal was the preferred heat source. DUFF split uranium atoms to yield a mere 24 watts, but it functioned smoothly and was cheap, with a tab of less than a million dollars.

The mid-2017 test will expand on DUFF, and has its own amusingly contrived acronym, KRUSTY, for Kilopower Reactor Using Stirling TechnologY. At the heart of KRUSTY will be a 30-kilogram, coffee cylinder-sized chunk of highly enriched uranium, about 93 percent uranium-235 and 7 percent molybdenum, made by the Y-12 plant in Oak Ridge, Tennessee. Instead of the horizontal Flattop, the core will be placed in a vertically oriented critical assembly stand, called Comet, to better accommodate additional components, such as eight heat pipes. These will be placed at the core's periphery and filled with sodium, which will vaporize and transport heat to two Stirling engines. Criticality will be induced in the uranium core by raising a beryllium reflector over the core to bounce back some neutrons into it, spurring a heat-producing, fission chain reaction.

For both DUFF and KRUSTY, NASA has so far budgeted around $10 million over three years — peanuts when compared to the $464 million NASA sunk into Prometheus over three years.

"One of the reasons [space fission projects] have died is because they have lasted too long and cost too much money," says Patrick McClure, the project lead for Kilopower at Los Alamos National Laboratory in New Mexico.

Fuel costs-wise, the highly enriched uranium would be nearly free, being just a sliver of the couple hundred metric tons in the existing government stockpile from dismantled nuclear warheads. Fashioning the uranium metal into a solid cast core costs only a few million dollars, McClure says. This kind of core is ideal for relatively low-energy reactors like Kilopower's because of trivial fuel burnup or volume swelling issues overthe core's intended lifespan. So, while it looks like a Kilopower-style power system will be inexpensive, McClure is quick to note that at this early stage, a price point for future reactors cannot be set.

Continued development and funding for Kilopower will hinge, at least in part, on a successful outcome in the Nevada desert next year. KRUSTY is set up to closely mimic the architecture of a potential flight system.

"If we get KRUSTY done, we're confident we can build a flight version," says David Poston, the lead reactor designer for Kilopower at Los Alamos National Laboratory.

The road ahead

The flight version would likely be geared for Mars, but scalable for a range of environments.

"We would like the Kilopower unit we develop for Mars to be versatile enough to use on the moon, if we decide to go that way, or deep space," says NASA's Mason.

Solar power can only do so much on the Red Planet. Many regions of astrobiological or resource interest, where subsurface ice can be found, are at higher, dimmer latitudes. The ballpark goal for a Mars surface reactor would be 10 kilowatts, about twice what the average American home uses. To obtain that output in a Kilopower-style device, more thermal energy must be pulled from the reactor, so heat pipes would plunge into its core and be bonded to the uranium itself, requiring further development work.

As for safety, the Kilopower reactors' uranium is inherently far less radioactive than the plutonium routinely shot into space.

"On the launch pad, it has very minimal radioactivity," says McClure. A fission reaction would not start, and radioactivity soar, until the mechanical removal of a boron carbide control rod from the core. "The reactor is not going to get turned on until it gets where we want it to, either deep space or Mars," says McClure.

Should the rod's removal somehow happen during a botched launch operation, the reflector necessary to maintain fission would surely be damaged as well; even a millimeter crack would let out enough neutrons to stop the chain reaction.

"If there is a launch pad accident, the reactor is not going to go critical," says Poston.

A greater concern is the fact that the highly enriched uranium in the reactor is nuclear weapons-grade material. In light of the rarity of such specialized missions launching perhaps once a decade for the foreseeable future, Voss — who worked in non-proliferation — grants that the advantages to space science with fission justifies uranium-235 as a fuel choice.

Perhaps fission's biggest obstacle, though, will be getting NASA and its Congressional budget-setters to commit to the grander sorts of missions kilowatt power enables. In Salt Lake City, Leonard Dudzinski, a veteran of Prometheus and now NASA's radioisotope power systems program manager, offered a bold prediction: "Space fission power is going to cause a revolution," he said. "It supports, by its nature, larger, more capable missions." The trouble is missions of that scope would be "unaffordable in our current budget environment." For now, NASA is seriously considering only "small, cheap" missions falling under 500 watts. Until budgets increase and space fission proves itself, "we're going to have to pay the bill for plutonium-238," he added.

For his part, Casani would rather see the money for plutonium production "plowed into the Kilopower system."

Expect to hear plenty more debate in the years ahead should Kilopower indeed establish a toehold for fission in the great beyond. ★

Thermoelectric workhorses

Twenty seven NASA spacecraft have gotten their power from 46 radioisotope thermoelectric generators. Among these spacecraft, the Cassini Saturn probe set the power-level record with three RTGs combining to deliver a shade under 900 watts. Other iconic missions fueled by RTGs include New Horizons, which cruised past Pluto in July 2015; the Viking Mars landers in the 1970s; and the Curiosity rover, still treading on the Red Planet.