Steve Johnson, the DOE's national technical director for Space Nuclear Power and an ANS Fellow, shown here next to a mock radioisotope power system at Idaho National Laboratory.

Photo: INL

Nuclear technology enables space power systems

Nuclear experts across the nation contribute to NASA's vision: to discover and expand knowledge for the benefit of humanity.

By Cory Hatch

Idaho National Laboratory's Stephen Johnson, director of the Space Nuclear Power and Isotope Technologies Division, grew up during the 1960s at the height of the space race. As NASA landed the first man on the moon and launched the first spacecraft to orbit Mars, a young Johnson thumbed through *Above and Beyond: The Encyclopedia of Aviation and Space Sciences* and built a two-foot model of the Saturn V rocket in his backyard.

Still, Johnson never dreamed that he'd someday be part of a team that plays a critical role in powering NASA's latest generation of spacecraft and rovers.

In 2002, when the Department of Energy asked Johnson to move from a high-level radioactive waste characterization group to lead the development of the Space Power Systems program at INL, he thought his tenure would be short-lived. "I kept thinking they were going to replace me," he said. "I thought, 'This is probably a better job for an engineer, and here I am a Ph.D. chemist.'" And yet, for 18 years, Johnson has led the INL team that fuels, tests, and delivers radioisotope power systems for NASA programs.

Now, as a newly minted Fellow of the American Nuclear Society, Johnson is one of hundreds of experts from INL, Oak Ridge National Laboratory, and Los Alamos National Laboratory who are preparing nuclear power systems for upcoming NASA missions. These missions include the Mars 2020 rover and Dragonfly—a drone that will fly over the surface of Titan—and could potentially include future missions that will use nuclear-powered propulsion systems and nuclear fission generators.

NASA has safely used nuclear power in space since the 1960s, mostly in the form

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Photo: INL

Workers examine a video screen showing the interior of the Multi-Mission Radioisotope Thermoelectric Generator prior to fueling.

of radioisotope thermoelectric generators (RTG). RTGs convert heat from the radioactive decay of plutonium-238 into electricity using specialized thermocouples—devices that make electricity without moving parts that might fail during a long space mission.

RTGs are used whenever lack of sunlight, rugged conditions, or the length of the mission necessitate a robust, long-lived power supply. They have provided power and heat for both Voyager spacecraft, Cassini, Galileo, the Viking landers, Mars rover Curiosity, New Horizons, and more than two dozen additional satellites, spacecraft, and vehicles.

Researchers began developing RTGs in the late 1950s at Mound Laboratories in Miamisburg, Ohio. The lab produced the first plutonium-powered RTG in the mid-1960s. The lab continued making nuclear power systems for NASA until, in the aftermath of 9/11, the DOE made the decision in 2002 to move the radiological facility to INL for increased security. With the New Horizons mission to Pluto slated to launch in 2006, Johnson was tapped to lead efforts to move the materials from Mound Laboratories, build the new Space and Security Power Systems Facility at INL, hire and train a staff, and fuel the New Horizons RTG.

The short timeline to plan, build, and staff the facility meant some missed deadlines. “We were supposed to have the power system down in Florida in July of 2005,” Johnson said. “We didn’t even start fueling it until August. Still, as long as you have everything at the finish line by the time it launches, all is forgiven.”

Working in lockstep

More recently, the DOE has tasked the three national laboratories with producing Pu-238 to replace its diminishing stockpile, in addition to making and fueling RTGs. “This is a program that really requires all three of the national labs to be in lockstep,” said Robert Wham, Pu-238 supply program manager at ORNL. “In a lot of programs, you do individual research projects. In this case, we’ve got dozens and dozens of people at each site who have to be focused on an effort and a schedule.”

Each step is carefully documented to make sure NASA gets the high-quality products it needs for a successful mission. “We have a coordinated approach to quality assurance,” Johnson said. “If you start with the finished product and work backwards, all the raw materials have to have proof that you met NASA’s specification.”

Wham’s team at ORNL is responsible for receiving the neptunium-237 from INL, fabricating the Np-237 into a target, irradiating the target in the High Flux Isotope Reactor (INL’s Advanced Test Reactor is another reactor capable of performing the irradiation step), and then separating the resulting mixture of Pu-238, Np-237, and fission products.

First, experts blend a powdered form of Np-237 with aluminum powder, press the mixture into pellets about the size of a pencil eraser, and load those pellets into aluminum tubing that is welded closed to make a fabricated target. These targets are grouped in bundles, and the bundles are placed in one of the two reactors, where they are bombarded with neutrons for multiple reactor operating cycles. After the targets are irradiated, they’re allowed to cool in the local reactor pool and are then moved to ORNL’s Radiochemical Engineering Development Center, where they are chemically processed. The aluminum is removed, at which point the mixture consists of 85 to 90 percent re-

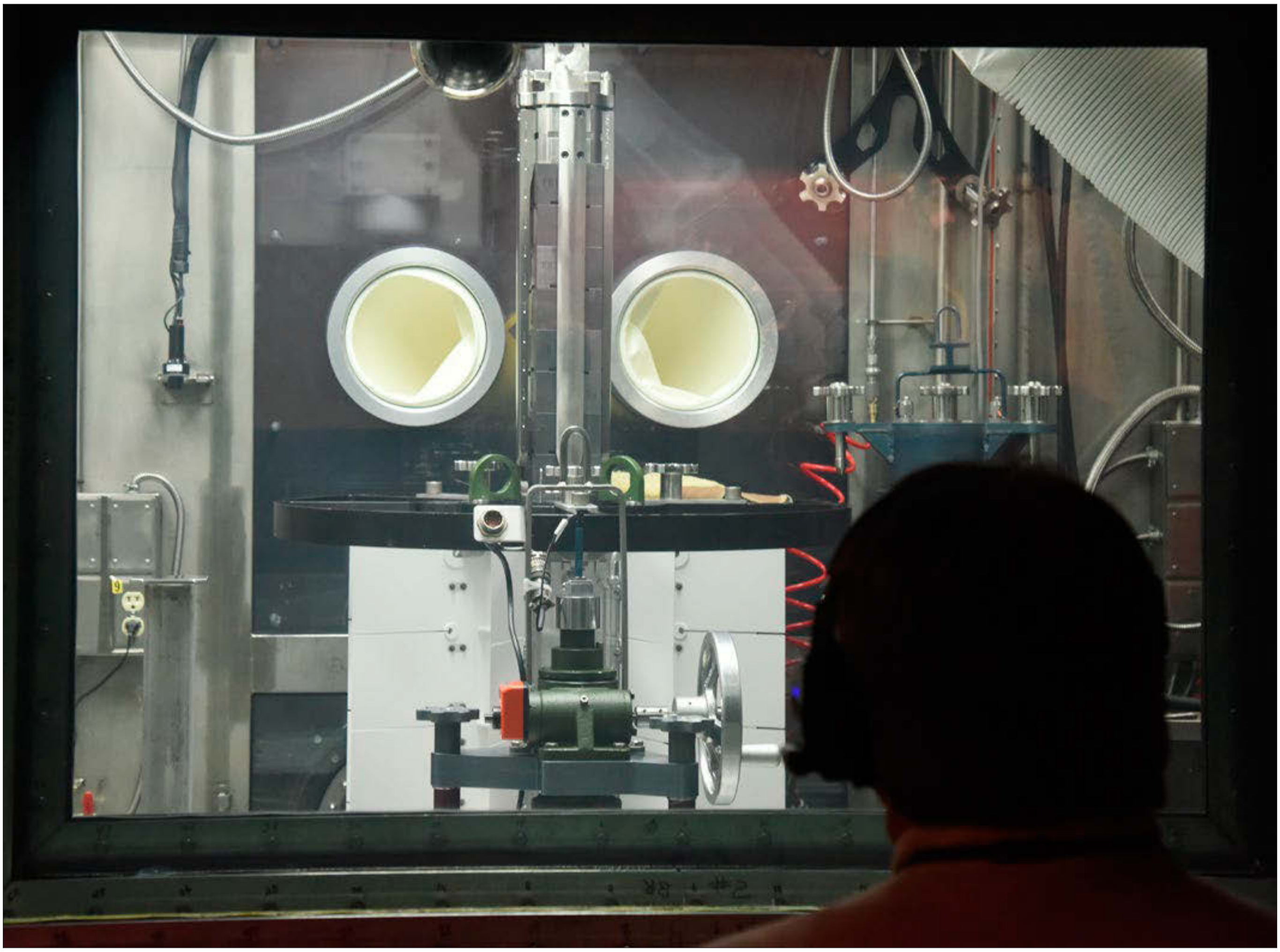

Photo: INL

Inside a glove box at Idaho National Laboratory, heat sources are stacked (top center) and loaded into the radioisotope thermoelectric generator (lower center) for NASA's Mars 2020 mission.

sidual Np-237 and 10 to 15 percent newly produced Pu-238, with small quantities of other isotopes. The two key materials, plutonium and neptunium, are separated, and the Pu-238 is converted to an oxide. The Np-237 is recycled back to the target fabrication step. The Pu-238 is then packaged in special shipping containers and sent to LANL. Starting in 2027, the new Pu-238 from ORNL will be integrated into the fueling process. For now, the existing inventory of Pu-238 is used to power NASA's nuclear power systems.

Another team at ORNL fabricates iridium clad vent sets—special containers that encapsulate the plutonium during the mission—as well as carbon-bonded carbon fiber insulators. The clad vent sets and insulators are eventually incorporated into the General Purpose Heat Source (GPHS) module, a graphite housing that serves as yet another layer of containment for the Pu-238 during the mission.

Fabricating the iridium clad vent sets is a time- and labor-intensive process that involves pressing, sintering, melting, heat treating, grinding, extrusion, and acid cleaning steps, said George Ulrich, ORNL's radioisotope power systems program manager. "We start with iridium powder," Ulrich said. "To go from the raw powder to the finished blank and foil [the alloy precursors that are eventually fabricated into a clad vent set] is a nine-month process. Going from blanks to a finished clad vent set is another six-month process."

A filter called a frit is also fabricated and welded to the clad, allowing the helium decay gas from the Pu-238 to escape, but not the Pu-238 itself. The iridium clad is designed to deform without breaking in the event of a launch or reentry accident.

At LANL, the Pu-238 from ORNL is blended with existing inventory and again chemically processed to separate out uranium and to meet NASA's specifications, according to Jacquelyn Lopez-Barlow, radioisotope power systems manager at LANL. The Pu-238 oxide is then compressed into ceramic pellets and placed into the iridium clad, and the clad is welded shut.

The fueled clad goes through a decontamination step so that it can be removed from the glove box for quality checks, including a leakage test, ultrasonic testing, radiography, calorimetry, and neutron-emission testing. The fueled clads are then shipped to INL, where they are stored in a flight-ready state for future RTG fueling.

As needed, LANL experts can also perform impact testing on the fueled clads and, in some instances, an assembled GPHS module that is shipped back from INL. "We do all the nuclear impact testing on the components," Lopez-Barlow said. "We get a fuel clad or a module assembly, and we will shoot it at a steel plate to validate manufacturing performance."

At this point, experts from INL have received all the components necessary to fuel the RTGs, the devices that convert heat from Pu-238 into electricity. Since 2003, NASA's RTGs have been manufactured by a private company out of Los Angeles, Calif., called Aerojet Rocketdyne.

At INL, the unfueled RTG is removed from its shipping container, tested, and moved into a glove box where the radioactive fuel can be safety inserted. The fuel from LANL is removed from several layers of shielding in a protective glove box.

Experts place fueled clads into the GPHS module, a carbon composite housing. Four fueled clads go into each heat source. The RTG designed for the Mars


Photo: INL

The Multi-Mission Radioisotope Thermoelectric Generator that will power the Mars 2020 rover is placed in a thermal vacuum chamber to simulate the near-space environment and test its power performance.

2020 mission requires eight GPHSs, which are stacked on a rack that is then lowered into the central cavity of the RTG.

Once the RTG is fueled, experts remove it from the glove box to prepare for tests that will simulate the environments the rover will experience during its mission. First, electrical and radiation measurements confirm the RTG's power output and radiation field. Then it's transferred to a special room where a large machine vibrates the RTG in three dimensions to mimic the shaking that it will experience during liftoff.

Next, a series of tests determines the RTG's mass and center of gravity so that NASA experts know how it will ride in the rocket and on the rover. The final test determines how well the RTG performs in the vacuum of space. Inside the thermal vacuum chamber, the RTG experiences a tiny fraction of the earth's atmosphere.

Now the RTG is ready for shipping. It's loaded into a cask attached to a special cooling system for transport to Florida's Kennedy Space Center. There, an INL team helps NASA personnel unpack the RTG, attach it to the rover, and conduct another round of tests before launch. For the teams from the three national laboratories, the anticipation and excitement doesn't end there. "Something you're making is going into space," Lopez-Barlow said. "It's like a family. There's a level of pride and understanding there. Being a program manager, it's just—words can't describe it—it's so exciting and so interesting. I think it's totally cool that I get to say that I work with NASA."

Ulrich is equally enthusiastic. During the 33 years he has spent working on space power systems, the thrill has never gone away, he said. "For everybody who is involved, it's fantastic to see, one, a launch, and two, six months or so later, the landing for a mission to a place like Mars. And then the mission is successful and continues for years, like Curiosity rover has done, and we get to see information, pictures, and reporting of results.

"There are a lot of proud and happy people. In the whole scheme of things, the power system is a critical component, but it's just one small part. It takes a lot of players across the nation and the world. We really enjoy it. We're pleased as punch to be involved."

The future of nuclear in space

In preparation for future missions, NASA and the DOE have tasked the three laboratories with rejuvenating a program to make radioisotope heater units—smaller nuclear devices that are used to heat spacecraft or rover components in cold temperatures.

The labs are also developing two new types of power systems: fission surface power and nuclear thermal propulsion. Fission surface power systems are small nuclear reactors that would produce tens of kilowatts of thermal power to provide heat and electricity for an outpost on the moon or Mars. Nuclear thermal propulsion uses a nuclear reaction to heat liquid hydrogen. When the hydrogen is heated, it expands and is forced through a nozzle to produce thrust. "They're working to have something with enough oomph to make a manned mission to Mars possible," Johnson said.

As for Johnson, he keeps a set of those same space science books he read as a boy on the bookshelf above his desk. "I didn't plan on a career in space power systems," he said. "All you can do is what you're tasked to do at that moment, do a good job, and see what happens." NN