At NASA, hopes for a new planetary mission to Saturn had been in the works since the early 1980s. Scientists had long sought to visit the second-largest planet in the solar system, with its fascinating system of rings, numerous moons, and unique magnetic field.

11

Visiting Saturn
The Cassini Mission

As the 1980s drew to a close, the DOE Office of Special Applications had its hands full with space nuclear power system work. Although assembly and testing of four GPHS-RTGs (including one spare) for the Galileo and Ulysses missions were complete, other projects filled the time. Ongoing assessment and development of DIPS, begun under SDI, continued on a limited basis under SEI. The SP-100 space reactor program and TFE verification program were in the midst of ongoing development and testing. DOE also continued supporting DoD in development of a space nuclear thermal propulsion system that had begun under the auspices of SDI.

At NASA, hopes for a new planetary mission to Saturn had been in the works since the early 1980s. Scientists had long sought to visit the second-largest planet in the solar system, with its fascinating system of rings, numerous moons, and unique magnetic field. Flybys of Saturn by the RTG-powered Pioneer 11 spacecraft in 1979 and the Voyager 1 and Voyager 2 spacecraft in 1980 and 1981, respectively, provided information that further piqued that interest. Efforts to acquire a Saturn mission finally came to fruition in 1989 with the authorization of Congressional funding.

Conceived as an international partnership with the ESA and Italian Space Agency, the Cassini-Huygens mission (alternately the Cassini mission) began in 1990 and consisted of an orbiter (Cassini) and a probe (Huygens). The Cassini orbiter was designed to circle the planet and several of its moons over a four-year period. The mission of the Huygens probe was to pass through the atmosphere of Saturn's largest moon, Titan, and briefly survey its surface during a short-lived mission that was less than one hour. With 12 instruments on the orbiter and six on the probe, the deep space planetary scouts were set up to gather an abundance of information about the planet, its ring system, and its moons.

Because Saturn is almost 10 times farther from the sun than is the Earth, it receives only approximately one percent of the sunlight per square meter as does Earth. Thus, solar power for the new NASA mission was never really an option—the size and weight of the panels would have made their launch unfeasible.[1] Therefore, NASA turned to DOE to provide

A seven-year journey to the ringed planet Saturn began with the liftoff of a Titan IVB/Centaur carrying the Cassini orbiter and its attached Huygens probe. (Photo: NASA/JPL/KSC)

What's In a Name

While Galileo Galilei was the first to observe Saturn through a telescope in 1609, limitations of the optics he used precluded his ability to discern the planet's rings. Discovery of the planet's rings is attributed to Dutch scientist Christian Huygens who, with the use of improved optics, observed the ring system in 1659. Huygens also discovered Titan, the planet's largest moon. Several years later, Italian French astronomer Jean-Dominique Cassini discovered several additional Saturn moons as well as a narrow gap that separates the ring system into two parts. The gap has since been known as the Cassini Division.[1]

three GPHS-RTGs for the Cassini spacecraft to meet its almost 900-watt power requirement, and over 100 small one-watt RHUs to keep scientific instruments and other equipment warm aboard Cassini and Huygens during their nearly eight-year journey to Saturn and follow-on missions.

Powering and Heating Cassini

With the experience gained during assembly and testing of the GPHS-RTGs and RHUs for the Galileo and Ulysses missions, it would seem that repeating the effort for the Cassini mission would be relatively straightforward. As time would tell, however, that would not be the case. In preparing for the planned 1997 Cassini launch, the DOE space nuclear power system group faced several challenges in meeting the needs of NASA. Challenges came in the form of several firsts for its Federal contractors. For example, production of the plutonium fuel pellets and subsequent encapsulation (activities that had been performed at SRS for the Galileo and Ulysses missions) were transferred to LANL in 1990. Production of iridium cladding and frit vent components (called a clad-vent set) in which the fuel pellet was encapsulated was moved from Mound Laboratory to ORNL in 1987. Finally, DOE would usher in a new transportation system to ship the assembled GPHS-RTGs from Mound Laboratory to KSC in Florida.

At ORNL, the Materials Engineering Department began a multi-year effort to establish the capability to produce the iridium cladding cups and frit vent assemblies. With assistance from Mound, the effort necessitated the duplication of tooling designs, tooling, processing steps, and inspection processes that had been successfully used at Mound to fabricate flight-certified iridium hardware for the Galileo and Ulysses missions. Once operational, but before any iridium components were produced for mission use, the new manufacturing processes at ORNL were subjected to a rigorous review and demonstration process to ensure the final product would meet the exacting requirements for flight-qualified hardware. The process included a series of qualification tests and studies followed by a pilot production effort to provide assurance that the ORNL team could reliably produce the iridium components for use in the Cassini RTGs.[2]

Despite rigorous preparations, production of flight quality hardware wasn't without its bumps. Although initial production of the iridium alloy components started in 1989, concerns eventually arose related to the metallurgical integrity of the frit vent assemblies. The integrity of the frit vent is critical in that it allows the helium gas produced from the decay of plutnonium-238 to vent from the fueled clad so as to preclude the buildup of pressure that could rupture the cladding. The concerns resulted in a six-month shutdown of operations beginning in

GPHS Fueled Clad Frit Vent

"The vent technology is really pretty elegant...It's what's called a frit. You start out with...iridium powder. You compress it into a tablet... and...fire that at a high temperature to the point where some of those individual grains of the power begin to fuse together... so what you end up with is a kind of porous media that you can pass gas through but you can't pass particles through... and they sandwich [the frit] between...thin layers of... iridium metal... and then that assembly gets welded together and then the whole assembly gets welded into a capsule."

–Tim George, LANL

Iridium and Tungsten

"Tungsten and iridium are the two highest-melting-point metals on the table of elements. The challenge that we had was to develop a metal that… could contain all of the plutonium-238 and that would… survive both a launch pad explosion and a reentry into the earth's atmosphere… so we had to have a material that was… able to withstand great temperatures and was also ductile, so when it hit the earth rather than shatter it would … deform without breaking. It is a very highly specialized metal…"

–Gordon Michaels, ORNL

September 1992, during which time the ORNL manufacturing processes and product were scrutinized and reviewed. After successfully demonstrating the rigor of the manufacturing processes, production resumed the following year.[3] The clad vent set production campaign would eventually result in the production of 425 flight-quality sets, over 500 weld shields (used to protect the fuel pellet during welding of the iridium alloy cladding cups), and other supporting hardware.[4] The flight-ready hardware was subsequently sent to LANL, where new fuel pellet production and encapsulation operations were being established to support the Cassini mission.

Some expected difficulties came as a result of the fuel pellet production transfer. Like any good mass-production process, the goal is to produce widgets that are identical. The processes by which fuel pellet production operations had been performed at SRS had been perfected during the work to support Galileo and Ulysses. If performed exactly the same way time after time, DOE knew what the result would be. Such is the nature of a rigorous manufacturing process. In the

Shield cup assemblies (top) and vent cup assemblies with its frit vent (middle) are matched after all fabrication steps are completed (bottom). (Photos: ORNL) early 1990s, LANL was largely a research and development facility; production operations were not their forte. While researchers and developers strive for consistency and repeatability, there is also a tendency to experiment and try to make things better. As a result, with the transfer of fuel pellet production operations to LANL, DOE had to ensure that the production process rigor that had been perfected at SRS was instilled in the new fuel pellet production and encapsulation operations to be performed at LANL.[5]

Production of the heat sources and heater units landed within the Actinide Ceramics and Fabrication Group of the Nuclear Materials Technology Division at LANL. Following two years of operational preparations and one year of internal and independent readiness reviews, production of LWRHUs and GPHS fueled clads began in 1993. Over the course of three years, the LANL teams produced 157 LWRHUs and 216 GPHS fueled clads for the Cassini mission.[6]

With ORNL on board for production of iridium hardware, and LANL preparing for production and encapsulation of fuel pellets, DOE awarded a contract to GE Aerospace in 1991 for production of the thermoelectric generator units to be used for the Cassini mission. Although the Cassini GPHS-RTG program began under GE Aerospace, changes at the corporate level soon followed. In 1993, GE Aerospace was bought by Martin-Marietta. Only two short years later, Martin-Marietta merged with the Lockheed Corporation to become Lockheed-Martin, which carried responsibility for the GPHS-RTGs through the Cassini launch.[7]

GPHS plutonium oxide fuel pellets. (Photo: LANL)

For the GE team and its successors, the scope of work for the Cassini project was relatively straightforward—fabricate, assemble, and test two new electrically-heated thermoelectric generators (ETGs) to be fueled at Mound Laboratory and fabricate the components for a third ETG for long-term storage. Only three new electrically-heated units were needed because one ETG (E-2) and one fueled GPHS-RTG (F-5) that had been assembled as spares for the Galileo and Ulysses missions were still available for use.[j] In addition to production of the new ETGs, technical expertise and

j. Converter E-2 had been built and tested in 1983 to support the Galileo and Ulysses missions. Having not been used, it was stored and maintained until its use for the Cassini mission.

support were also to be provided in areas such as safety assessment preparation, shipment of the assembled RTGs to KSC, and integration of the assembled RTGs into the Cassini spacecraft.

One of the major tasks facing GE and its successors was the need to re-establish the capability to produce silicon-germanium thermoelectric materials and the production processes for the silicon germanium unicouples used in the GPHS-RTG. Due to the lack of a follow-on mission after Galileo and Ulysses, the thermoelectric production and manufacturing processes had been shut down in the mid-1980s.[7]

Re-establishing the capability was not a trivial exercise—raw materials and equipment had to be identified and procured, equipment had to be installed and proper operation verified, and the workers who would be performing the manufacturing processes, as well as those who would provide for independent inspection, had to be trained and qualified. Just like fuel pellet production at LANL and iridium component production at ORNL, the manufacturing processes used to produce new silicon-germanium unicouples were subjected to a rigorous review by DOE to ensure the final product would be ready for use in its space application. After two and one-half years of preparations, during which several manufacturing issues had been addressed, silicon-germanium unicouple production was deemed ready to proceed in May 1993.[7]

Over the course of the Cassini production campaign, 2,000 individual silicon-germanium unicouples, requiring tens of thousands of individual manufacturing steps, were produced for the ETG converter units, one qualification unit, and for spares. Once completed, the assembled qualification and ETG converter units were shipped to Mound for subsequent fueling and testing.

In Ohio, workers at the Mound Laboratory had begun receiving the LANL-produced fueled clads in 1996.[k] The fueled clads were subsequently assembled into GPHS modules, the basic heat source building block of the GPHS-RTG. Mound workers assembled and inspected 72 GPHS modules in all, 18 modules for each RTG.

Mound technicians moving a GPHS-RTG in the vibration test cell using a crane on wheels. (Photo: Mound Museum Association)

k. Following assembly and testing of the GPHS-RTGs for the Cassini mission, RTG operations performed at Mound were subsequently transferred to ANL-W, as discussed in Chapter 10, Infrastructure.

Over the course of the Cassini production campaign, 2,000 individual silicon-germanium unicouples, requiring tens of thousands of individual manufacturing steps, were produced…

Fueling of the E-2, E-6, and E-7 ETG converter units was completed in 1996, resulting in GPHS-RTGs F-2, F-6, and F-7. After fueling, the RTGs were subjected to a series of tests, including vibration and thermal vacuum tests, and magnetic field and mass properties measurements, to determine acceptable operational performance for the planned mission. With an average power output of approximately 296 We (beginning of mission), the combined power output of the three units exceeded the mission-required minimum of 826 We. GPHS-RTG unit F-5, which had served as the spare unit for the Galileo and Ulysses missions, was once again placed in the same capacity for the Cassini mission. Upon completion of testing in early 1997, the RTGs were placed in storage until the time for their shipment to KSC.[8]

Shipment of the GPHS-RTGs to KSC brought a new opportunity for the RTG team at Mound. A new RTG transportation system, which consisted of three new 9904 shipping packages and two new semi-trailers, had been transferred to Mound from its production location at Hanford in early 1997. With the new equipment came the responsibility for operations and maintenance. The new RTG transportation systems would see their maiden voyage later that year when the three Cassini RTGs were transferred from Mound to KSC in anticipation of an October 1997 launch.[9]

Facing Opposition

While LANL and Mound were fabricating fuel pellets and assembling thermoelectric converters, NASA and its international partners were building the Cassini spacecraft and Huygens probe and the 19 scientific instruments that would be located on the deep-space sojourners. Behind the scenes, the agencies were heading up another task that would eventually take center stage as preparations for the Cassini mission continued to unfold. That task involved the analysis and assessment of risks associated with the plutonium that was contained in the three GPHS-RTGs aboard the spacecraft.

The three GPHS-RTGs planned for use on Cassini held a combined mass of 72 pounds, or 400,000 curies, of plutonium oxide fuel. In addition to the RTGs, the mission planned to use 117 LWRHUs, each producing approximately one watt of heat. The LWRHUs were dispersed on both the Cassini and Huygans spacecraft to keep the instruments and other spacecraft equipment warm in space. It was the largest quantity of nuclear material ever planned for launch with a NASA spacecraft. As for the Cassini payload, with a mass of slightly more than 12,500 pounds (5,670 kilograms), it was the largest interplanetary spacecraft-probe NASA had planned to launch. Unlike Galileo and Ulysses, which were ferried to space aboard the space shuttle, NASA planned to use a Titan IV-B rocket and Centaur upper-stage launch vehicle to lift Cassini from its launch pad at Cape Canaveral. The Titan IV-B/Centaur rocket was 180 feet tall and used two large solid-fuel rocket boosters and a two-stage liquid-fuel core to perform its designed task. At launch, the system held approximately two million pounds

(907,185 kilograms) of propellant.[10] Hypothetical accidents involving a launch vehicle failure and other scenarios such as spacecraft re-entry were the focus of the safety and risk analyses performed by DOE and NASA.

By the summer of 1995, NASA had completed an evaluation of the potential environmental impacts associated with the planned Saturn mission in its final EIS.[11] NASA considered several alternatives to the planned 1997 launch, including multi-year launch deferrals and mission cancellation. However, in October 1995, the agency announced its intent to proceed with the Cassini mission as planned. In its formal decision, Wesley Huntress, Associate Administrator for Space Science, noted "I am confident that reasonable means to avoid or minimize environmental harm from the Cassini mission have been adopted; or, if not already adopted, will be adopted, upon conclusion of the safety analyses." Following completion of a supplemental environmental evaluation prepared to reflect the results of the safety analyses, the agency stood by its earlier decision.[12]

The safety analyses referred to by Huntress in his decision were those being performed by DOE and, eventually, the INSRP for the Cassini mission. Similar to NASA, DOE was responsible to prepare a separate and more detailed Safety Analysis Report in which the risks associated with accidents that could adversely affect the plutonium fuel in the RTGs were formally assessed and documented. The Cassini INSRP prepared an independent review of the DOE Safety Analysis Report and prepared yet a third evaluation that provided the basis upon which launch approval would either be granted or denied by the White House. The analysis and review process utilized for Cassini continued a system of checks and balances, rigor, and independence that had been used for all launches involving a nuclear power source dating back to 1961.[13]

In keeping with the Presidential directive[14] governing the approval to launch a nuclear power system into space, approval authority resided with Dr. John H. Gibbons, Director of the White House Office of Science and Technology

Operators remove an empty 9904 shipping package from an RTG transportation system trailer during training (circa 2005). The same system was used to move the Cassini GPHS RTGs from Mound Laboratory to KSC in 1997. (Photo: INL RPS Program)

Policy. After a careful review of the assessments, Gibbons noted that "NASA and its interagency partners have done an extremely thorough job of evaluating and documenting the safety of the Cassini mission." Regarding mission risk versus scientific benefit, Gibbons concluded that "the important benefits of this scientific mission outweigh the potential risks."[15]

Not everyone was as confident in the safety analysis prepared for the mission. For example, the "STOP CASSINI!" movement, initiated in the mid-1990s, was one of several groups that opposed the launch of any nuclear material into space.[16] From their perspective, the release of any plutonium resulting from any accident was unacceptable. Of particular concern was the planned use of several gravitational assist maneuvers to increase the speed of the spacecraft to shorten its travel time to Saturn. Following two gravitational assists at Venus, the spacecraft would be traveling to Earth for a third gravitational assist. If a computation error or other mishap led to inadvertent re-entry at that speed, the ability of the GPHS to contain its plutonium fuel could be severely challenged. The risks and consequences of such accidents, presented by DOE and NASA, were questioned amidst the skepticism and distrust.[16]

With this and other concerns at the core of the anti-Cassini sentiment, local and national newsprint picked up the debate. Headlines included "Critics Warn of Nuclear Mayhem for NASA Launch"[17] and "Saturn Mission's Use of Plutonium Provokes Warnings of Danger."[18] In addition to print and other media, some groups had also capitalized on the worldwide web, the computer-based network through which information could be rapidly and broadly distributed. As its users would soon discover, the relatively young web allowed information to be directly disseminated without the filtering or constraints imposed by other media outlets such as newsprint, television, and radio.[19]

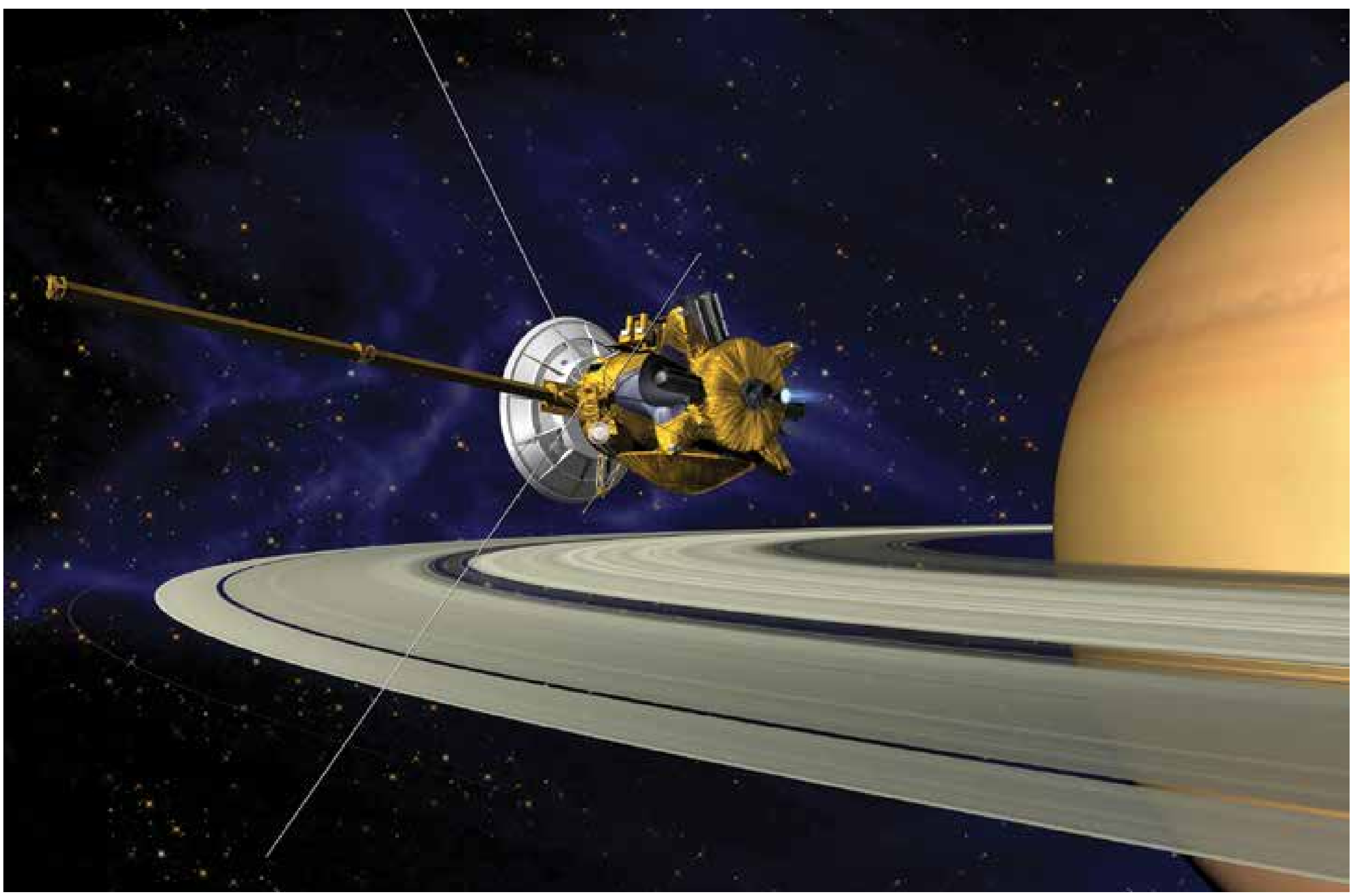
> The risks and consequences of such accidents, presented by DOE and NASA, were questioned as skepticism and distrust ran high.

As anti-Cassini and anti-nuclear sentiment continued in the months leading up to the launch, NASA and DOE steadfastly continued their own public education and outreach efforts. They sought to reassure the public of the safety of launching Cassini and its nuclear power system and assuage them of all fears. At the core of their assurance and confidence was the design of the plutonium heat sources and the safety testing to which they had been subjected; such testing proved their ability to withstand myriad energetic accidents, including explosions, high-velocity impacts, projectile impacts, fires, and re-entry heat. Every facet of the heat sources, from its ceramic fuel form to the iridium that encapsulated the fuel and the graphite components surrounding the clad fuel, were specifically designed and selected to ensure that minimal, if any, plutonium would be released in the event of an accident.

This was the message of Beverly Cook, Director of Space Nuclear programs in DOE. Having several years of experience in nuclear reactor design and safety, and responsibility for the safety of the Cassini mission for DOE, Cook had an excellent grasp of the technical details pertaining to the GPHS-RTG nuclear power system. By 1997, she had become the de facto spokesperson for DOE and NASA on the topic of nuclear safety as it pertained to the Cassini mission. She had a knack for conveying technical information using every-day concepts and, as a mother who planned to have her daughter observe the launch, she could connect with the public on a personal level. Through interviews, communication forums, and airtime on the likes of CNN, Good Morning America, and C-Span, Cook, along with others from the agencies, sought to educate and remove the fear of the unknown.[5]

Against the backdrop of protests, NASA and DOE continued their work for a safe and successful launch while the anti-Cassini protestors fought to keep that day from coming. On October 3, 1997, Gibbons granted approval for the Cassini launch. Mission proponents were elated. Although the anti-Cassini campaign had failed to stop the launch, their efforts were later credited by some for getting NASA to reconsider its use of space nuclear power systems and for gaining the attention of members of Congress, who subsequently sought additional analysis from NASA and DOE.[16]

In the years following the Cassini launch, DOE embarked on a safety improvement program whereby the GPHS aeroshell design was modified to improve its overall strength and survivability against more-severe impact and re-entry



Artist's concept of Cassini spacecraft, showing one of its three RTGs, as it passes by Saturn. (Image: NASA) events. The program resulted in development of a Step-1 design, which was subsequently used in the Pluto-New Horizons mission launched in 2006 (discussed in Chapter 12). A Step-2 design, which further increased the survivability of the aeroshell against impact and re-entry, was used in the multi-mission radioisotope thermoelectric generator (MMRTG), which was launched aboard the MSL in 2011 (discussed in Chapter 13). In both cases, the quantity of ablative material (i.e., FWPF) for the aeroshell was increased.[20]

Saturn at Last

On October 15, 1997, the Cassini-Huygens spacecraft was launched at 4:43 a.m. Eastern Daylight Time against a black backdrop of the early morning sky. The ground lit up like daytime as the Titan rocket lifted the spacecraft to begin its seven-year, 2.2 billion-mile journey to Saturn. The launch went off as planned, and there were no explosions or other problems.

After traveling to Venus, where it received two gravitational assists, the Cassini-Huygens spacecraft was on a trajectory that returned it near Earth. On August 17, 1999, the spacecraft passed Earth at an altitude of 727 miles and received a gravity assist that boosted it onward to Jupiter at a speed of 42,000 miles per hour, where it would receive its final assist on its way to Saturn.[21]

At the end of its seven-year journey through space, the Cassini spacecraft entered orbit at Saturn on July 1, 2004. As of July 2014, the spacecraft had returned hundreds of gigabytes of scientific data from which over 3,000 scientific reports were written. Over 300,000 images of the Saturn system had been taken during over 200 orbits. Over 130 close flybys of Saturn's moons were completed, and seven new moons were discovered. Among its countless accomplishments were the first complete view of the hexagon-shaped north pole, the discovery of giant hurricanes at both of Saturn's poles, and intensive study of the planet's ring system. As for the ESA/Italian Space Agency Huygens probe, it was the first man-made object to land on a moon (Titan) in the outer solar system, having provided data and images during its descent and short 30-minute battery-powered life. With three years remaining in its final mission, time will tell what additional discoveries Cassini will make.[22]

As for the three GPHS-RTGs aboard the Cassini spacecraft – they performed splendidly. They have provided a consistent, steady source of power to the instruments and other systems and are expected to continue to do so as long as the Cassini mission continues.

Saturn and its rings. Images such as this are possible by the electrical power provided by RTGs. (Photo: NASA)

After years of sending mechanical ambassadors to neighboring planets and the far reaches of the solar system, Pluto remained a distant, icy, and largely unknown orb.

12

To Pluto and Beyond
New Horizons

After years of sending mechanical ambassadors to neighboring planets and the far reaches of the solar system, Pluto remained a distant, icy, and largely unknown orb. Although missions to the distant body had often been envisioned, none had ever become a reality. However, that would soon change.[1, 2]

Planning the Trip

In January 2001, NASA issued an Announcement of Opportunity in which proposals were solicited for a mission to Pluto and the neighboring Kuiper belt, a large band of icy objects that includes Pluto. The primary goals of the mission focused on the geology, morphology, and surface composition of Pluto and its largest moon, Charon. The mission also sought to study the Plutonian atmosphere due to the possibility of its freezing as Pluto continued to move further from the sun during its 248-year orbit.[1]

The following months were filled with proposal development and a downselect process, after which only two proposals would have their mission concepts refined. In November 2001, the evaluation process concluded when NASA selected the New Horizons proposal for its Pluto mission. Dr. S. Alan Stern of the Southwest Research Institute served as principle investigator for the mission in partnership with the Applied Physics Laboratory of Johns Hopkins University and others. The mission name, New Horizons, symbolized the new scientific horizons of exploring Pluto and the Kuiper belt, and the new programmatic horizon of having an outer-planet mission led by a principle investigator rather than a Federal agency.[1] As the project unfolded, New Horizons would take on an even broader meaning for the larger project team. With a $500 million contract and a launch date of January 2006, the groundwork was laid to finally reach Pluto and the Kuiper belt, one of the highest-priority solar-system-exploration missions identified by the broader planetary science community.[3]

Artist's concept of Pluto and its moon Charon. (Image: NASA.gov)

The space probe designed for the historic journey to Pluto was built by the Applied Physics Laboratory and designed to carry a suite of seven scientific instruments. The instruments themselves were designed and built by Stern and others. With names like "Alice" and "Ralph," reminiscent of the Kramdens of The Honeymooners comedy series from the 1950s, and LORRI and REX, each instrument brought a unique capability to the mission. Alice was designed to gather data on the composition of the atmosphere. Ralph would map surface compositions of the Pluto-Charon system. LORRI, a long-range imaging device, would take pictures of the surface as the spacecraft approached its target.[4] The instruments and the data-transmission systems that would someday send images back to Earth needed power from a source other than solar due to the immense distance from the sun. That power would be provided by a GPHS-RTG, the same technology that had been successfully used on several previous NASA missions.

Artist's concept of the New Horizons spacecraft and science instruments. The GPHS-RTG, shown in the left side of the image, is mechanically attached to the spacecraft. (Image: NASA)

An RTG Fast-Track

As in the past, the RTG would be assembled, tested, and delivered by DOE and its contractors. The generator would be built by Lockheed-Martin at its facilities near Valley Forge, Pennsylvania, and LANL would provide the encapsulated fuel. ORNL would provide materials expertise. SNL would later support the safety analysis prepared by Lockheed-Martin. RTG assembly and testing, historically performed at Mound, would take place at ANL-W, its first such effort since receiving the mission in 2002.

With New Horizons planned to launch in January 2006, DOE and its new ANL-W team, under the leadership of Stephen Johnson, had three years to fuel, test, and deliver an RTG. Under normal circumstances, such a schedule would have been considered manageable. But three years to relocate a program (following its transfer from Mound in 2002), including the construction of a new facility and standing-up a new operation, was a tall order. There was little, if any, room for errors. Such a move would require more than a can-do attitude. It necessitated a will-do attitude in which failure was not considered an option. And that's the attitude that DOE and Johnson brought to the table.

Johnson realized early on that the chances for project success could be greatly improved with the help of Mound workers who had hands-on RTG experience. After much discussion and negotiation, eight Mound workers agreed to hire on with Johnson and help with the move. By the time the RTG was assembled three years later, only one of the workers remained with the Idaho team; however, their dedication and contribution to the success to the relocation effort, and the RPS program as a whole, was considered invaluable. It was that kind of dedication that had permeated the DOE RPS program and their customer at NASA for decades and would continue to prevail in the years to come.

To support the move, DOE had set an aggressive schedule to have everything out of Mound by the end of September 2003. On the other end of the move, it was decided that the new ANL-W RTG facility needed to be operational by the middle of 2004 to allow sufficient time to assemble and test the GPHS-RTG for New Horizons. With teams in place, expectations defined, and a schedule before them, the real work began in January 2003. Between January and September 2003, 28 semi-trailers carrying over 300 tons of equipment was transferred from Mound to Idaho. At the same time, Merrick Engineering and other members of Johnson's team worked on the design for the RTG facility.

A Building Takes Shape

The ANL-W RTG facility ended up being a 10,000-square foot annex to an existing building. The facility was designed to withstand the hazards posed by extreme winds, earthquakes, and other natural events, thereby providing maximum protection for the valuable space batteries that would eventually be assembled and stored in the facility.[5] Excavation and construction of the building foundation were completed between August and November 2003. Facility construction began in January 2004, in the middle of the Idaho winter, which can pose unique construction challenges, particularly when pouring concrete in sub freezing temperatures. While construction crews use special means to keep equipment from freezing and ensure proper concrete curing, sometimes things can still go awry. Johnson recalled one such episode:

"Our first day pouring concrete… started on a Saturday and it was about 9 degrees outside…We had the forms up. We had tubing running through it outside the forms and we had vibrational thumpers so that we could pour the concrete without it freezing. But the pneumatic lines to the thumpers actually froze first. And we were pouring I think 10 or 12 cement trucks of concrete that day and we did that for quite a few days and it was a challenge. I always think of that experience when people say, we can't get that done. We only have this amount of time. I'm like, you know, you can get just about anything done if you're organized and you don't give up."[6]

The design and construction crews were as dedicated as the men and women who moved the RTG operation. Construction of the Space and Security Power Systems Facility (SSPSF), as it would later be called, was completed in July 2004 in a period of approximately 13 months and at a cost of slightly less than $5 million.

While facility construction was progressing, other project activities were focused on ensuring the people and paper were ready for eventual operations. Procedures were written to provide instructions for all aspects of operations, such as ventilation systems, glovebox atmospheres, and RTG assembly and testing. The procedures were validated, a process by which the entire procedure is performed step-by-step but without nuclear material, to ensure that RTG assembly and testing was done right the first time. Operators, quality assurance staff, and engineers, none of whom had ever assembled or handled an RTG, were trained, and the newly installed equipment was tested to ensure proper operation. Following a thorough review of the facility, equipment, personnel, and procedures by DOE, ANL-W got the green light from DOE to begin operations in October 2004.

Repurposing an RTG

The New Horizons mission called for a single GPHS-RTG, the same power system that had been used on the Cassini, Ulysses, and Galileo missions. The GPHS-RTG utilized 18 heat source modules, each containing four fueled clads. The fueled clad consists of the plutonium oxide fuel pellets, clad in iridium metal. Of the 72 fueled clads needed for the RTG, 20 new ones were provided by LANL. Safety and security issues at the LANL site during 2004 resulted in a prolonged shutdown of operations, precluding their ability to provide the full complement of heat sources. Fortunately, DOE didn't have to look far to find 52 other fueled clads.[6,7]

Equipment set up to pour concrete for the walls of the new SSPSF. (Photo: INL RPS Program)

Back in 2002, when DOE relocated its heat source material from Mound in the wake of anticipated security upgrades, one of the items transferred to ANL-W was a fueled GPHS-RTG. The RTG, referred to as F-5, was assembled in the mid-1980s and served as a spare unit for the Galileo, Ulysses, and Cassini missions. While never used, DOE continued to maintain the flight-qualified status of the power system, keeping it for a time when its use might be needed. That day had finally arrived.[8]

Use of the heat sources from the F-5 generator posed some unique, but not insurmountable, challenges to the builders of the New Horizons RTG. First, because the plutonium oxide fuel in F-5 was approximately 20 years old, it had lower thermal wattage per mass of fuel than the new fuel present in the LANL fueled clads. To ensure the New Horizons RTG would meet mission power requirements, engineers had to determine and then select the F-5 heat sources with the highest thermal wattage for use with the new heat sources that been supplied by LANL. Second, the GPHS modules used in the F-5 RTG were based on the original design, referred to as Step-0.

Ribbon-cutting at the newly-completed Space and Security Power Systems Facility. Pictured from left to right are John Sackett, Associate Laboratory Director for ANL-W; William Magwood, DOE Assistant Secretary for the Office of Nuclear Energy, Science, and Technology; Kyle McSlarrow, DOE Deputy Secretary; and Congressman Mike Simpson, Idaho. (Photo: INL RPS Program)

Because the modules had since been redesigned to improve their ability to withstand re-entry heating in the event of a high-altitude accident, the older Step-0 modules would not be used in the New Horizons RTG. Consequently, the F-5 unit was disassembled in an inert chamber in SSPSF in May 2005 to recover the fueled GPHS modules. Once recovered, the modules were disassembled to remove the graphite impact shells containing the clad plutonium oxide fuel pellets. The graphite impact shells containing the fueled clads were then assembled into new Step-1 GPHS modules for use in a new GPHS-RTG generator (later named F-8).[8]

The unfueled RTG power converter assembly, which was fabricated and tested by Lockheed-Martin Space Power Group, was received by the Idaho team in June 2005. The new fueled clads had been shipped from LANL earlier in the year. Assembly of the GPHS modules occurred in an inert argon atmosphere in the Module Assembly Glovebox. Following assembly, the modules were transferred to the Inert Atmosphere Assembly Chamber, where they were stacked and assembled into the F-8 converter assembly.

NASA Mission GPHS-RTGs

The GPHS-RTGs that have been assembled and flown on NASA missions are:[9]

Galileo:	**F-1, F-4**
Ulysses	**F-3**
Cassini	**F-2, F-6, F-7**
Spare	**F-5** (subsequently disassembled for New Horizons)
New Horizons	**F-8**

By early September 2005, assembly of F-8 had been completed, marking the eighth flight-qualified GPHS-RTG built by DOE and the first RTG assembled in Idaho. The RTG was assembled using five GPHS modules containing new fuel and 13 modules containing fuel from F-5. The 18 combined modules contained 24 pounds (11 kilograms) of plutonium oxide fuel and had a thermal power of almost 4,000 watts. The RTG was expected to deliver approximately 200 We by the time the New Horizons

> By early September 2005, assembly of F-8 had been completed, marking the eighth flight qualified GPHS-RTG built by DOE and the first RTG assembled in Idaho.

spacecraft reached Pluto, exceeding the minimum mission power requirement of 191 We. Other mission requirements such as RTG mass were also met or exceeded.

Following assembly, F-8 was subjected to a variety of tests to ensure it would properly operate in space. Mass properties testing determined the RTG center of gravity, which was used by NASA in their planning for control of the spacecraft once in space. Thermal vacuum testing determined the RTG power performance in a high-vacuum condition, similar to the environment in space. Vibration testing was performed using a shaker table to subject the RTG to forces similar to those associated with launch. Radiation measurements and radiography of the assembled RTG were also performed. Testing of the RTG was successfully completed by the end of October. All assembly and testing operations were reviewed by DOE, and F-8 was finally accepted for flight use in December 2005.[5]

To Pluto via Florida

Following assembly and testing of F-8, the RTG was transported to the RTG facility at KSC. The RTG was subsequently subjected to a hot-fit check during which it was fully integrated with the New Horizons spacecraft, just as it would be in space, to ensure that all systems checked out acceptably. Following successful completion of the hot-fit check, the RTG was returned to storage at KSC where it awaited the day of its final integration with the spacecraft.

As with previous missions that used a nuclear power source, New Horizons was subjected to rigorous nuclear safety assessments that included an EIS required by the National Environmental Policy Act, and a safety analysis report and safety evaluation report prepared for the Presidential Nuclear Launch Approval Process.[10] The assessments served to ensure that accidents and consequences had been adequately evaluated and analyzed.[11] However, the launch approval process for the Pluto-New Horizons mission was unusually compressed and had to be completed in less than two-and-one-half years. From the safety perspective, the New Horizons INSRP raised questions about the integrity of the GPHS fuel pellets after being encapsulated for 20 years. In response, Lyle Rutger (the DOE Nuclear Launch Safety program manager) pointed to the rigorous safety testing under which the GPHS components had been subjected and a detailed inspection process that the fueled clads had been subjected to following their removal from the original RTG qualification unit. After thorough analyses, evaluation, and discussions, the Office of Science and Technology Policy eventually granted approval for Pluto-New Horizons to launch with the F-8 generator.

Conversely, NASA was addressing concerns with the rocket propellant tank on the New Horizons launch vehicle. A qualification tank similar to the one on the launch vehicle had failed during testing in September 2005, just months before the planned launch date. With the mission potentially at stake, NASA performed a comprehensive review, investigation, and evaluation that, along with the technical input and experience of many involved in the program, led to the decision to proceed with the launch during the planned January 2006 launch window.[12]

The F-8 GPHS-RTG during assembly in the Inert Atmosphere Assembly Chamber. (Photo: INL)

Just days before the planned launch date of January 17, the RTG was moved to the Vertical Integration Facility at Cape Canaveral Air Force Station, Florida, where it was integrated with the New Horizons spacecraft for the final time. On January 19, 2006, at 2 p.m. Eastern Standard Time, a Lockheed-Martin Atlas V 551 launch vehicle lifted off from Space Launch Complex 41 at Cape Canaveral Air Force Station. The New Horizons spacecraft had finally begun its 10-year journey to Pluto.

For everyone involved, there was an indescribable feeling of awe and a deep sense of accomplishment as the rocket arched ever-higher over the Atlantic Ocean. NASA had overcome several hurdles, including questions about the structural integrity of a fuel tank.[l] The DOE team had built a new RTG assembly and test facility, transferred RTG operations from Mound to the new SSPSF, and assembled and tested their first RTG in Idaho. And another RTG-powered spacecraft was on its way to deep space.

l. The decision process undertaken by NASA that led to acceptance of the fuel tank for the New Horizons mission provides an excellent example of balancing an equipment qualification process founded upon thorough technical investigation, evaluation, and review, with the application of sound engineering judgment.

Asteroid 5886 Rutger

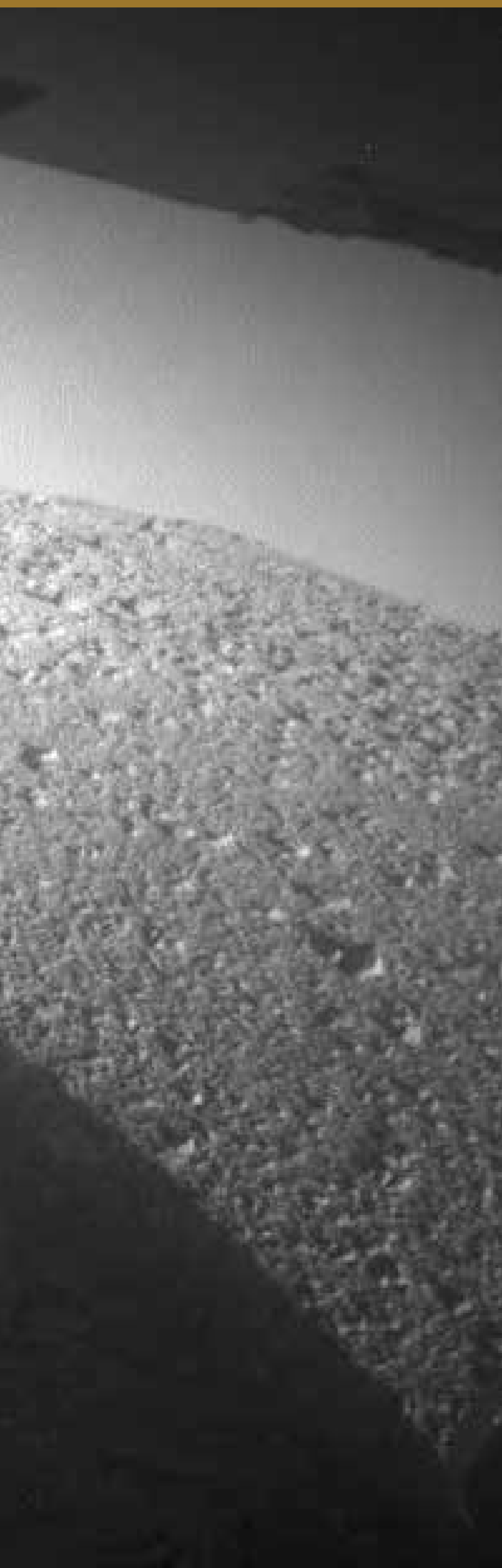
Asteroid 5886 Rutger (formerly 1975 LR) was named after Lyle Rutger in recognition of his role as the DOE Nuclear Launch Approval program manager for the Pluto-New Horizons mission. The name was given by Dr. Alan Stern of the Southwest Research Institute, and principle investigator for the New Horizons mission.

The New Horizons spacecraft launches from Complex 41 at Cape Canaveral Air Force Station on January 19, 2006. (Photo: NASA.gov)

…the new MSL rover represented a significant leap in exploration capability on another world.

13

Roving Mars
Return to the Red Planet



With the announcement of its intent to continue an ongoing Mars Exploration Program and the launch of the Mars rovers Spirit and Opportunity, 2003 gave birth to a new chapter in the decades-old exploration effort of the red planet. Exploration of Mars dates back to the 1960s, when the first Mariner fly-bys returned images of a moon-like surface, likely disappointing to those who had hoped for an Earth-like environment teeming with life. Exploration continued in the 1970s. The successful touchdown of the Viking 1 and Viking 2 orbiter-landers in 1976, planned to coincide with the Bicentennial celebration of the nation, continued the quest to learn more about this distant cousin of Earth. The multi-year life of those first man-made robotic explorers to set foot on the Martian surface was sustained through the use of the SNAP-19 RTG. Nearly 30 years later, the SNAP-19 technology would beget a new RPS to sustain the next generation of robotic explorers on Mars.[1,2]

A New Mission to Mars

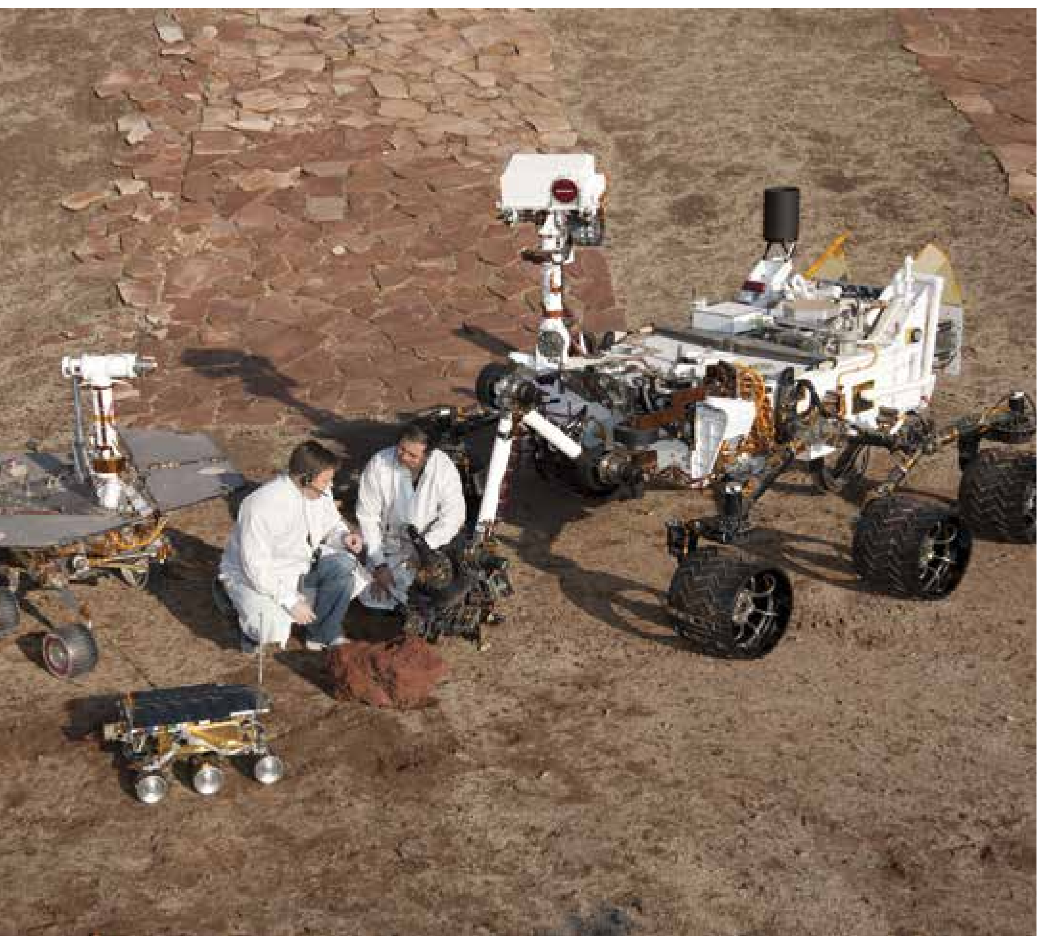
In March 2004, NASA announced its intent to solicit proposals for instrumentation and science investigations to be part of Mars Science Laboratory (MSL), a mission planned for launch in 2009. Later that year, the eight proposals that had been selected to be part of the rover-based mobile laboratory were announced. The suite of scientific capabilities included high-tech cameras to collect pictures of the planet while on the surface (as well as during spacecraft descent and landing) x-ray spectrometer and fluorescence instruments for chemical analysis of rock and soil samples, and instruments to analyze the makeup of the Mars atmosphere. With instruments and investigators from organizations like the Russian Federal Space Agency, the Spanish Ministry of Education and Science, and the Canadian Space Agency, MSL was a melting pot of scientific capability reflecting ongoing partnerships among international space organizations.[3,4]

In addition to the broad suite of investigative capabilities that would make up MSL, the planned rover would be the largest NASA ever landed on a planet. Significantly larger than the small rover Sojourner, which landed on Mars on July 4, 1997, and four times larger than the Mars exploration

NASA's Mars exploration rover Opportunity caught its own silhouette in this late-afternoon image taken by the rover's rear hazard avoidance camera. (Photo: NASA/JPL-Caltech) rovers Spirit and Opportunity, which landed on January 4, 2004 and January 25, 2004, respectively, the new MSL rover represented a significant leap in exploration capability on another world. Although solar power was considered for the MSL mission, nuclear-based power would allow the fullest set of mission objectives to be met, including the maximum latitudinal range over which the MSL could be landed. An RPS would also allow operation of systems, instrumentation, and science investigations day and night, thereby avoiding downtimes when the sun wasn't shining, and offering the use of reject heat for thermal control. The preference for an RPS culminated in the MMRTG that had been under development by DOE since June 2003.[5]

Multi-purposing an RPS

A MMRTG concept under consideration by DOE and NASA was confirmed in 2001 when the two agencies convened a joint agency team to ensure the convergence of RPS supply and demand for missions in the 2004 to 2011 timeframe. The team, led by John Casani of NASA, was tasked to provide a provisioning strategy to guide RPS-related decisions and support integrated planning between the agencies.[6]



Front and center is the flight spare for the first Mars rover, Sojourner, which landed on Mars in 1997 as part of the Mars Pathfinder Project. On the left is a Mars exploration rover project test rover that is a working sibling to Spirit and Opportunity, which landed on Mars in 2004. On the right is an MSL test rover the size of that project's Mars rover, Curiosity, which landed on Mars in August 2012. (Photo: NASA/JPL-Caltech)

The joint agency effort continued the practice of cooperation in matters involving space-based RPS development and supply that was embodied in the 1991 Memorandum of Understanding in which the authorities and responsibilities for each agency had been formally defined.[7]

In the process of developing a strategy, a small set of questions were deemed fundamental to establishing a framework for future planning—would potential missions operate in the vacuum of space or in a planetary atmosphere or both? How much electrical power would the potential missions require? While the GPHS-RTG supplied a large amount of power (greater than 300 We) in the vacuum of space during the most recent space exploration missions, lower power levels were anticipated for future missions. The maturity level of various RPS technologies, important to deliverability and the safety- and launch-approval processes, also required careful consideration.

How much plutonium-238 would be available? Domestic production of the heat source isotope had stopped with the shutdown of SRS production reactors in the early 1990s, and the finite domestic inventory of the heat source material was being augmented with a finite supply from Russia. Was production capability available for various RPS components? With termination of silicon-germanium thermoelectric production following the Cassini mission, the RPS program faced a finite inventory of some materials unless production was restarted.

In a pre-decisional report, the team recommended development of an RPS capable of operating in both the vacuum of deep space and in a planetary atmosphere, such as on the surface of Mars. The team also recommended a two-path development strategy with a Stirling convertor (already under development at the time) and a new MMRTG as its foundation. Development of a new RTG was put forward to serve as a hedge against the technical immaturity of the Stirling technology at the time. Embodied in the strategy and recommendations, and the underlying evaluation, was a comprehensive snapshot of the state of RPS development for use by decision-makers from both agencies.

An MMRTG Takes Shape

Development of the new RTG began in 2003 when DOE awarded a contract to the Rocketdyne division of Boeing. Rocketdyne had partnered with TES, whose thermoelectric experience stretched back to the SNAP-19 RTG. With a proven track record of RTG operation in the atmosphere of Mars and the vacuum of space, Teledyne's experience was instrumental in creation of the new multi-purpose RTG.[8,9,10,11]

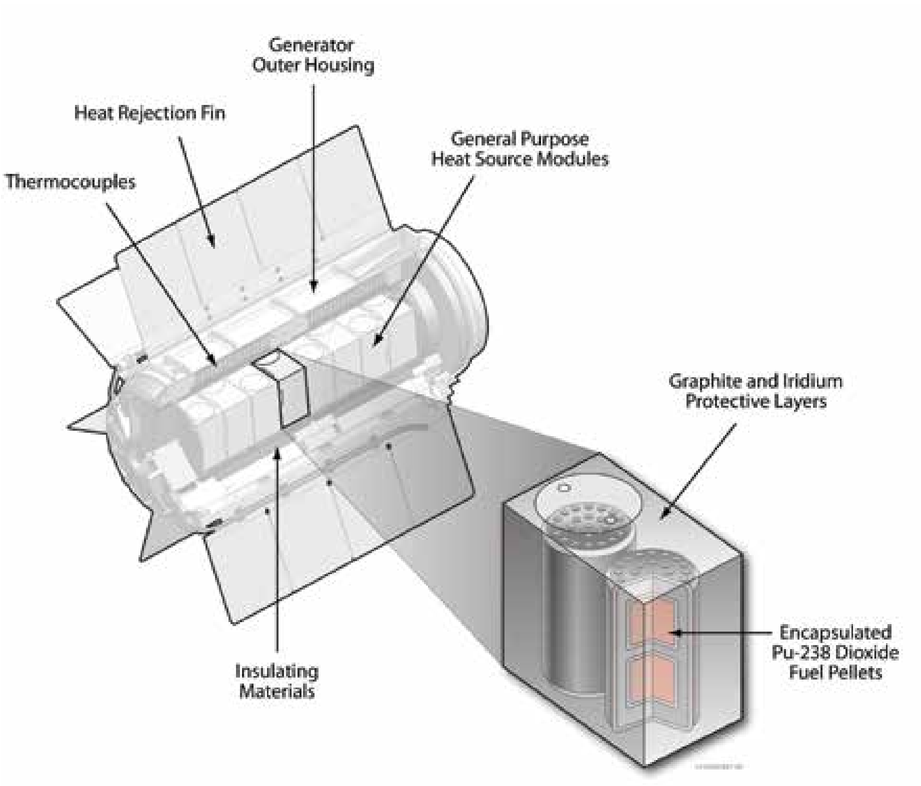
As development of the new RTG progressed, it was only a matter of time before it was connected to a NASA mission. That connection occurred in 2004 when DOE and NASA linked the generator to the upcoming Mars rover mission

Faster, Better, Cheaper

Under the leadership of Daniel Goldin, NASA Administrator from 1992-2001, NASA began an initiative centered on doing things faster, better, and cheaper. The initiative was part of an aggressive effort to address perceptions that the agency was bureaucratically bloated and in pursuit of missions that were too expensive, took too long to develop, and flew too infrequently. Workforce reductions, increased productivity, and reduced costs ensued. Relative to space missions, spacecraft became smaller, with lower power needs; gone were the days of MHW missions like Voyager and Galileo. The initiative provided an impetus for DOE and NASA to pursue development of a Stirling radioisotope generator and the MMRTG.

via a supplement to the 1991 Memorandum of Understanding between the agencies.[12]

The ensuing years were filled with design, engineering, fabrication, and testing activities as the Rocketdyne-Teledyne team transformed concept into product. Mission requirements and limitations, such as power levels, weights, and heat loads, were translated into an initial MMRTG design. From their facilities in Canoga Park, California, Rocketdyne served as system integrator for MMRTG development activities. Fabrication of the power conversion system and the lead telluride-TAGS thermoelectrics took place at Teledyne facilities in Hunt Valley, Maryland. The initial design gave birth to an engineering unit that was used to check every part of the new power system for proper fit, function, and operation. Like a master watchmaker, the Rocketdyne-Teledyne team brought the various pieces and components together to ensure the assembled product would operate as intended. The engineering unit was subjected to a full battery of performance and environmental tests. As design and development progressed, a qualification unit was then built to test the new RTG under thermal conditions similar to those that would be experienced once the unit was fueled with a nuclear heat source. Due to schedule constraints and limited availability of fueled clads, the qualification unit was never fueled but was fully tested as an electrically-heated unit, and was also used by the JPL for integration and testing exercises with the rover. Finally, the first of two flight units, F1, was built and prepared for shipment to INL, where it would be fueled and run through another battery of tests.



The MMRTG shown with its eight GPHS modules, thermocouples, housing, and heat rejection fins. (Image: INL RPS Program)

In designing an RTG that can operate in a planetary atmosphere, designers must consider the possibility of adverse reactions between compounds in the atmosphere and the thermoelectric materials. Thermoelectrics undergo a steady, but small and predictable, degradation in their conversion efficiency over their operating life. Such degradation is taken into account by power system designers to ensure adequate power levels will be available for the life of the mission. However, the reaction

Like a master watchmaker, the Rocketdyne-Teledyne team brought the various pieces and components together to ensure the assembled product would operate as intended.

of thermoelectric materials with atmospheric compounds, such as oxygen or the carbon dioxide present in the atmosphere of Mars, can accelerate that degradation. To avoid this problem in the MMRTG, the thermoelectric modules were located in a completely sealed enclosure that was filled with argon gas prior to closure. The inert argon gas wouldn't react with the thermoelectric components and because the thermoelectric modules were completely sealed, they were isolated from any interaction with the atmosphere of Mars.[13]

In addition to materials and chemistry challenges, engineers faced thermal challenges when designing an RPS. Given the relatively low efficiency (<seven percent) of the thermoelectrics used in current space-based RTGs, the design required provision to ensure excess heat was properly managed. Of the nominal 2,000 watts of thermal energy produced by the MMRTG heat source at the beginning of mission, only about 120 watts was converted to useable electricity. The residual unused heat had to be properly managed to ensure long-term efficient operation of the RTG and the surrounding spacecraft. Through the use of a heat rejection system, designers employed various methods to dissipate the excess heat during all phases of the mission, including cruise, entry/descent/landing, and surface operations on Mars. In addition, a heat exchanger on the rover was located to partially cover the MMRTG, capture some of its excess heat, and route the heat through a fluid loop to provide for thermal management of rover hardware during operation on Mars.

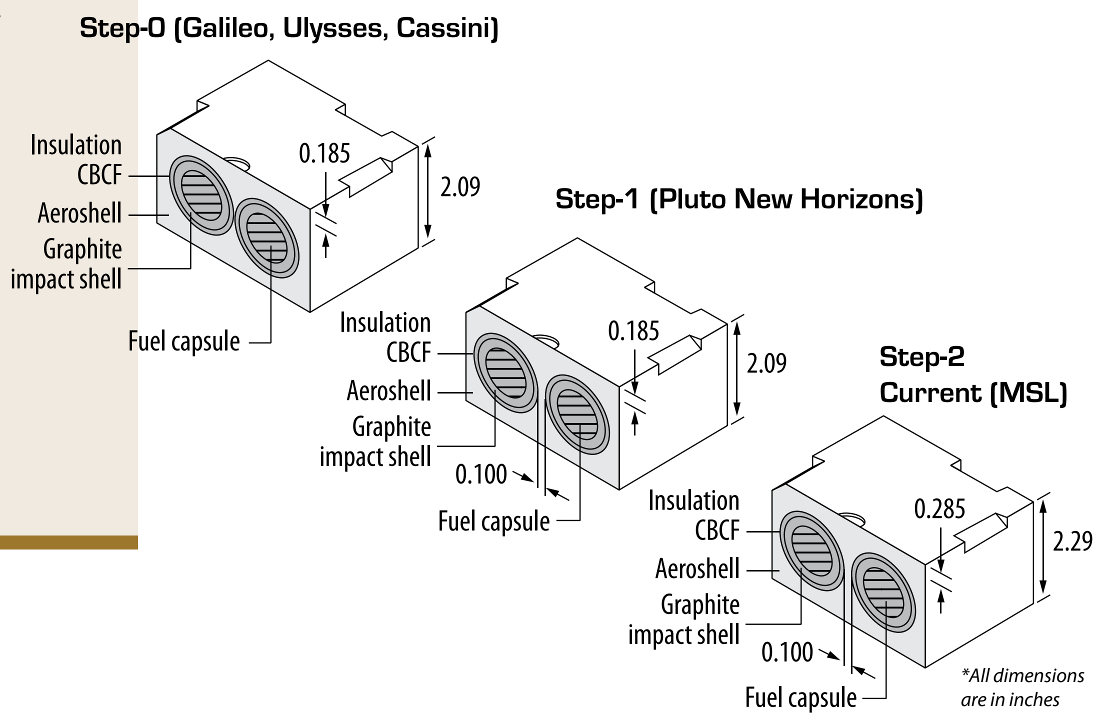
A cruise-stage heat rejection system also provided for heat management when the MMRTG was located inside the launch vehicle following integration with the rover but prior to completion of final integration prior to launch. Inside the confines of the launch vehicle, the heat generated by the MMRTG, if not properly managed, could cause overheating of avionics equipment and the tanks that held the hydrazine propellant for the spacecraft. Overheating of filled hydrazine tanks creates an explosion hazard. To address the concern, JPL engineers devised a simple set of jumper tube assemblies that mated the cooling tubes on the MMRTG housing to a chiller system located outside the launch vehicle, thereby providing a means to remove heat from the MMRTG following its integration with the rover. When integration of the cruise-stage system was complete, the temporary jumpers were disconnected. While seemingly simple, the installation, operation, and removal of the jumper tubes required the coordination of personnel from at least nine separate organizations. That close-knit coordination was but a microcosm of the coordination required among the multiple organizations involved with the multitude of tasks associated with the MSL mission.[14, 15]

As development of the MMRTG proceeded under the Rocketdyne-Teledyne team, the components needed to fuel the GPHS modules were being prepared by the DOE laboratories. For example, the iridium cups and frit vents that comprised a clad-vent set were fabricated by ORNL. The completed clad vent set hardware was shipped to LANL, where the plutonium-238 fuel pellets had been prepared and readied for encapsulation. Assembled fueled clads were shipped from LANL to INL where they were assembled into GPHS modules, the building blocks of the MMRTG heat source.

At SNL in New Mexico, a DOE safety assessment team began an assembly process of a different sort—the thorough and exhaustive process of preparing the analyses and reports that would ultimately provide the basis for launch approval of the MSL and its nuclear power source. The process included evaluation of the new Step-2 GPHS aeroshell design that was to be showcased in the MMRTG. The MSL mission would also mark the first time that SNL was solely responsible for producing a Safety Analysis Report for a space nuclear mission. The SNL launch safety team was first assembled in late 2005 and had to produce a full and comprehensive assessment by late 2008 to support a Fall 2009 launch.[5, 16, 17, 18, 19]

Evolution of the GPHS Module

The module identified as Current was Step-0, the first-generation design used in the Galileo, Ulysses, and Cassini missions. Following the launch of Cassini, DOE undertook a two-phase effort to enhance the GPHS aeroshell relative to postulated launch and re-entry accidents. In the Step-1 module used in Pluto-New Horizons, the graphite impact shell openings are separated by 0.1 inch and the openings are fully encased in the aeroshell material. In the Step-2 design, the module is lengthened 0.2 inches in the vertical direction. Each change also resulted in a small increase in module weight (Step-0 was 3.1 pounds [1.4 kilograms]; Step-1 was 3.3 pounds [1.5 kilograms]; Step-2 is 3.5 pounds [1.6 kilograms]). Because of the increased length, the Step-2 design could not be used in the GPHS-RTG without significant changes to the convertor and heat source structural support system therein. (Image: INL RPS Program)



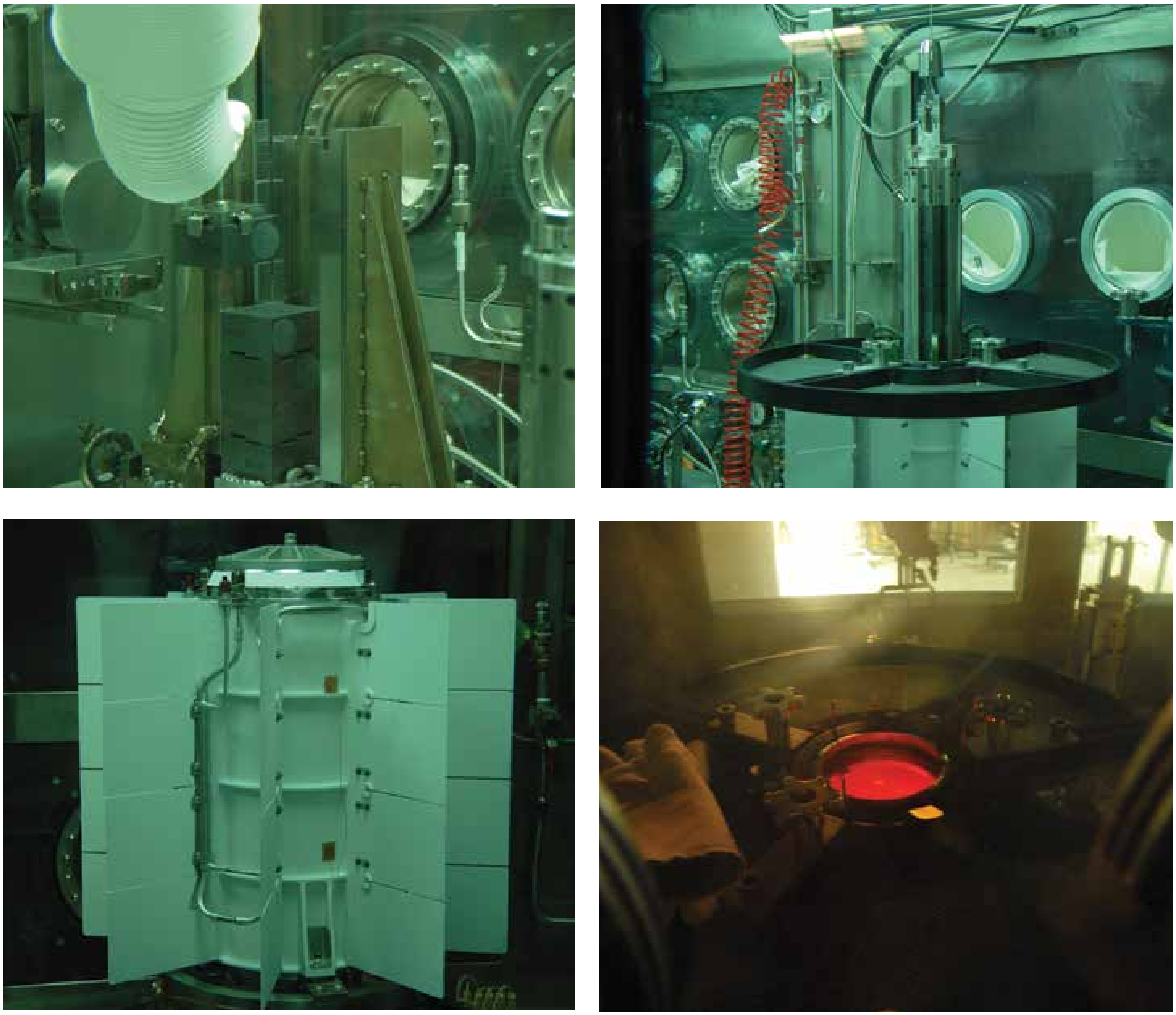
Assembly, Testing, and Bumps

The first MMRTG flight unit, F1, was received at INL in August 2008. By the end of October of that year, INL engineers, quality inspectors, and technicians fueled the new generator. Fueling of the generator was performed in the Inert Atmosphere Assembly Chamber at the SSPSF, where the Step-2 GPHS modules were assembled into a stack of eight and then placed inside the generator housing. Once fueled, the housing was closed and the MMRTG was prepared for its next round of testing.

In the months that followed, the fueled MMRTG was subjected to the normal suite of tests to ensure the unit was ready for operation in space and on the surface of Mars. A shaker table simulated conditions, such as vibration, that would be experienced during launch and passage through the atmospheres of Earth and Mars. Inside a thermal vacuum chamber, the electrical output of the unit was monitored to verify acceptable performance in vacuum conditions that mimicked those of outer space. The magnetic and radiation fields associated with the MMRTG, important to the NASA engineers designing the spacecraft electrical and data systems, were also mapped. Mass properties, including weight and center of gravity, were determined for use with similar properties for the spacecraft.

By May 2009, all testing had been successfully completed. The six-year development and testing effort marked the first time in almost 20 years that an RTG had been taken from concept to flight unit, the last time being the GPHS-RTG. As the new power system for NASA missions requiring power beyond the capabilities afforded by solar or chemical, the assembled MMRTG weighed approximately 99 pounds (45 kilograms) and measured 1.9 feet (0.6 meters) long and 1.9 feet (0.6 meters) wide at the cooling fin tips. At its heart, the eight GPHS modules contained approximately 11 pounds (5 kilograms) of plutonium oxide fuel. The plutonium oxide from which the fuel pellets were processed had been purchased from Russia, making the MMRTG the first DOE RPS to be fueled entirely of non-domestic material. The power conversion system utilized 768 lead-telluride/TAGS thermocouples to convert the 2,000 watts of thermal power into approximately 110 watts of useable electricity.[11]

As DOE and its contractors continued down the path to deliver the MMRTG for the planned 2009 launch, NASA found itself hitting some technical bumps along its path to Mars. By early 2008, problems with the material to be used for the heat shield had been identified during testing.[20] In the months that followed, other technical challenges continued to arise, and the viability of the planned 2009 launch date became increasingly questionable.[21] In December 2008, NASA finally postponed the MSL launch to the next available window, which would occur in late 2011. “We will not lessen our standards for testing the mission’s complex flight systems, so we are choosing the more responsible option of changing the launch date,” noted Doug McCuistion, director of the Mars Exploration Program at NASA Headquarters.[22] In making the postponement decision, NASA had taken the technical high ground and kept its eyes on the Mars prize.



MMRTG assembly inside the SSPSF Inert Atmosphere Assembly Chamber. Clockwise beginning at top left: 1) Fueled GPHS modules being stacked. 2) The stack of eight GPHS modules ready for installation in the MMRTG housing. 3) The heated GPHS modules glow red inside the insulated MMRTG housing. 4) MMRTG assembly complete. (Photo: INL RPS Program)

A Journey Begins

With a revised schedule and funding in place, the spacecraft and rover Curiosity (and the science instrument and launch vehicle) were made mission-ready during the following two years. At INL, the MMRTG was placed in a storage configuration to preserve the unit and minimize degradation of its thermoelectric elements, and engineers continued monitoring the electrical output and other conditions of the unit until it was ready for transfer to KSC. Throughout the testing, one unexpected performance condition arose. In late 2009, the measured power output of the MMRTG was found to be less than power predictions that had been made prior to fueling of the unit. Upon investigation, the discrepancy was determined to be caused by an error in a computer model that was developed to predict MMRTG power performance. Although the error was remedied, the slightly lower power output of the MMRTG did necessitate some adjustments to the rover power budget.[23]

MMRTG being integrated to the Curiosity rover for testing in the Payload Hazardous Servicing Facility at KSC. (Photo: NASA)

After two years of storage and monitoring, a small team of INL workers, along with a cadre of security personnel, accompanied the MMRTG on its 2,500-mile (4,000 km) voyage to KSC in June 2011, five months ahead of the MSL launch date. After safely arriving at KSC, the precious cargo was moved into the RTG Facility, which would be its home until launch.

During the second half of 2011, DOE and its contractors continued to maintain a watchful eye over the MMRTG as NASA completed their preparations for MSL launch. In one of the final activities to ensure the MMRTG was ready, it was connected to and fully integrated with the rover Curiosity. In one final hot-fit check, the rover and generator were run through a series of tests to ensure the electrical output and heat rejection system operated properly. It would be the last such test until November, when the MMRTG was relocated to the KSC Vertical Integration Facility, where it would be connected to the rover for the last time in preparation for launch.

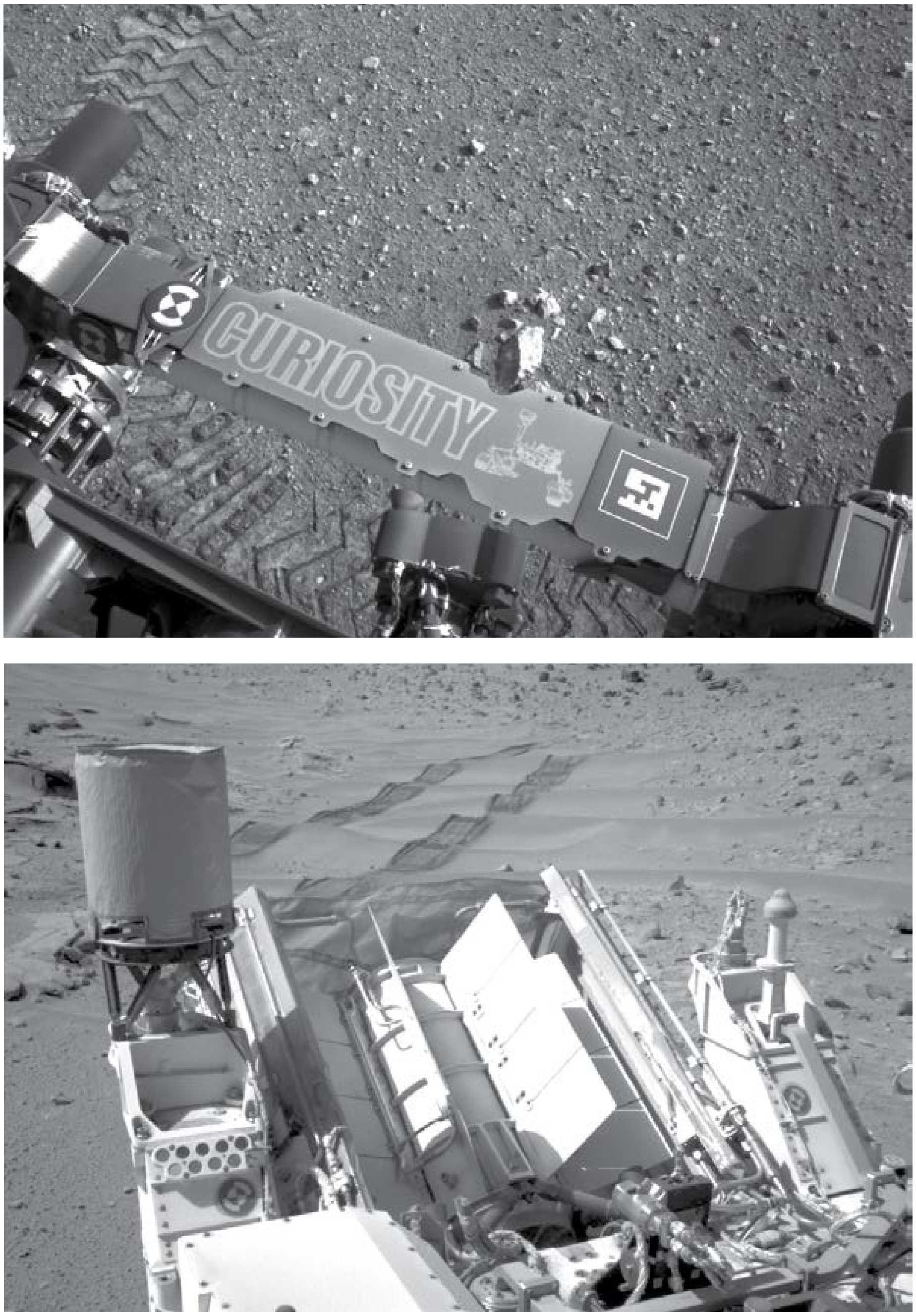
On November 26, 2011, seven-and-a-half years after the MSL was announced, an Atlas V 551 rocket lifted off from Space Launch Complex 41 at Cape Canaveral Air Force Station. While many watched from a designated viewing location at KSC, many others simply lined the byways and highways around KSC and Cape Canaveral to catch a glimpse of the launch. At liftoff, a white cloud of steam erupted beneath the launch vehicle and the vehicle slowly rose above the pad. As seconds became minutes, NASA provided continuous status of the launch via the internet, allowing listeners to catch each phase of progress. MSL had begun its eight-and-one-half month journey to Mars.

On November 26, 2011, seven-and-a-half years after the MSL was announced, an Atlas V 551 rocket lifted off from Space Launch Complex 41 at Cape Canaveral Air Force Station.

NASA's MSL spacecraft, sealed inside its payload fairing atop a United Launch Alliance Atlas V rocket, clears the tower at Space Launch Complex 41 at Cape Canaveral Air Force Station in Florida. The spacecraft's payload included the car-sized rover, Curiosity. (Photo: United Launch Alliance)

On August 5, 2012, many of the same individuals who had gathered to watch the launch gathered again to witness the landing of MSL. In its "Seven Minutes of Terror" animated video, NASA/JPL provided a blazing description of the end of the voyage as the spacecraft ripped through the Mars atmosphere. With a seven-minute delay between the landing of Curiosity on Mars and receipt of the radio signal from the Mars Orbiter, people everywhere anxiously awaited for the first indication of success. The words announced by NASA/JPL commentator Al Chen, "Touchdown confirmed. We're safe on Mars," led to an eruption of cheers and hugs, not only in the offices of NASA and JPL but across the country. With the safe landing of Curiosity and the generation of images that shortly followed, American pride beamed as MSL began its new journey on Mars.

During the months that followed, MSL gathered countless images and collected numerous samples of the atmosphere, soils, and rocks. Man's understanding of Mars continued to expand as data and information were transmitted from the mobile laboratory to its users back on Earth. And that understanding is expected to continue to expand for years to come as an MMRTG quietly powers the distant laboratory.



NASA's Curiosity rover used the navigation camera (NavCam) on its mast to catch this look-back eastward at wheel tracks from driving. The MMRTG appears in center of the bottom photo. (Photo: NASA/JPL-Caltech/Malin Space Science Systems)

The march…gave rise to an industry focused on harnessing the energy of the atom for use in exploring and conquering the final frontier.

14

Into the Future
Powering New Missions

For over six decades, U.S. space nuclear power systems have continued a steady technological march forward. That march has encompassed radioisotope power systems and space nuclear reactors, static and dynamic power conversion systems, and passive and active heat rejection concepts. The march has been conducted in support of civilian and military missions, across numerous presidential administrations, and amidst the ebb and flow of congressional support. It gave rise to an industry focused on harnessing the energy of the atom for use in exploring and conquering the final frontier.

The march gave us the RTG which, with its incredible simplicity and reliability, has powered missions in the orbit of Earth and on the moon, to the sun and most of the planets in the solar system, and even beyond our solar system. And yet the RTG is but one system in a suite of space nuclear power technologies, which include dynamic RPS and space nuclear reactors, that might one day power new and ever larger missions in the decades to come.

As our survey of space nuclear power through the decades comes to a close, it is worthwhile to reflect upon the accomplishments and successes, and even the failures, of the past 30 years, the main period covered by this book. It is also instructive to note trends and lessons that might serve to guide future space nuclear system development and use. For these efforts, founded upon the labor and work of countless individuals, provide the firm technical foundation, experience base, and resources necessary to power new missions for decades to come.

Three (More) Decades of Power

For the quiet technology of the RTG, the highlight of the last three decades was the successful development and use of two new systems: the GPHS-RTG and MMRTG. The GPHS-RTG became a true workhorse for NASA, having powered four separate missions (Galileo, Ulysses, Cassini, and New Horizons) with a combined seven individual RTGs. With the retirement of the GPHS-RTG following the New Horizons launch in 2006, DOE delivered the first-ever MMRTG, which has successfully powered the rover Curiosity since its landing on Mars in August 2012. As of 2014, all RTGs have provided reliable and consistent power that has enabled the collection

In this concept image, a resource prospector carrying a Regolith and Environment Science and Oxygen and Lunar Volatiles Extraction payload roves on the lunar surface. (Image: NASA)

Radioisotope Power Systems: Providing Power Where the Sun Don't Shine

"…one of the captions or slogans I kind of wanted to use for the program was 'we give them power where the sun don't shine…'"[1]

Richard R. Furlong
DOE (retired)

The unique characteristics of these power systems make them especially suited for environments where large solar arrays are not practical, and at long distances from the sun. To date, DOE has provided radioisotope power systems for use on 24 missions, and a space nuclear reactor power system used on one mission, that provided some or all of the spacecraft on-board electrical power (excluding the three failed missions/launches). In addition, RHUs have been provided for nine missions for thermal heating of critical spacecraft and/or rover components. These nuclear power systems have enabled many space and planetary exploration missions in places scientists would otherwise have not been able to study.

of countless images and data that have greatly expanded and enriched mankind's understanding and knowledge of the solar system.

At the heart of both RTG designs is the GPHS, which has been successfully used for over 30 years. In addition to its modularity, the GPHS met another goal of its designers, which was to eliminate the need for costly mission-specific flight requalification. On the power conversion side of RTG technology, the silicon-germanium thermoelectric material and unicouple, first used in the MHW RTG of the 1970s, continued to see use in the GPHS-RTG. Similarly, the lead-telluride/TAGS thermoelectric materials used in the SNAP-19/Pioneer RTGs of the early 1970s were used, with minor changes, in the MMRTG. With their very high reliability and performance record, both thermoelectric materials have been in use for several decades. Such success, however, is not deterring ongoing research into new materials that hold the hope for improved power conversion performance.

One such thermoelectric material is a family of cobalt arsenide compounds called skutterudites. Early testing conducted by JPL and TES indicate the possibility for conversion efficiency approximately 25 percent higher than the lead-telluride-TAGS material used in the MMRTG. In addition, the skutterudites appear to have a lower degradation rate than the MMRTG thermoelectric materials, which would further improve lifetime efficiency. Future plans include development of the manufacturing capability for the skutterudite thermoelectric materials, thermoelectric couples, and modules for possible use in an enhanced MMRTG, or eMMRTG.[2]

In addition to RTGs, the compact LWRHU saw use in several NASA missions as DOE and its contractors delivered over 250 heater units for use aboard the Galileo and Cassini spacecraft as well as on the Mars rovers Pathfinder, Spirit, and Opportunity. The small size of the heater units, coupled with their simplicity, continue to make them a very effective means to maintain desired thermal environments for spacecraft instruments and other electronic devices.

Through the course of preparing and delivering the RTGs and LWRHUs, DOE transferred RTG assembly and test operations from Mound to INL. The birthplace of the RTG (Mound) was subsequently shut down in 2004 after 50 years of notable service in RTG technology.

In addition to the infrastructure change, DOE and NASA initiated a Plutonium-238 Supply Project in 2013 to restart production of the heat source isotope following a 25-year hiatus. In a break from previous funding arrangements, NASA will fund DOE to establish and maintain the capability to produce approximately 3.3 pounds (1.5 kilograms) of plutonium-238 oxide per year. DOE will continue to draw upon its existing nuclear infrastructure, including two nuclear reactors (High Flux Isotope Reactor at ONRL and Advanced Test Reactor at INL) and a modified chemical processing facility at ORNL. Such efforts will bring to a close the long-standing need for a long-term domestic plutonium-238 supply, which had been temporarily met through the purchase of Russian fuel material.

The reactor pool at the High Flux Isotope Reactor. (Photo: ORNL Flickr)

As 2014 came to a close, DOE and NASA were looking ahead to a Mars 2020 mission as the next opportunity to assemble and test an MMRTG. As in the past, responsibility for delivery of the MMRTG will reside with the Space and Defense Power Systems group within DOE-NE. With its infrastructure in place and a future supply of plutonium-238 assured, DOE appears to be well-positioned to deliver RTGs for future NASA missions.

Dynamic Radioisotope Power System Advancements

While RTGs remained the mainstay of space nuclear power systems for NASA missions, DOE and NASA continued efforts to develop dynamic RPSs. Most notably over the last three decades was the effort to develop Stirling power conversion technology. Initiated under the SRG-110 project and continued under the ASRG project, significant advancements were made in two different Stirling convertor concepts during a cumulative 12-year effort. Development of the ASRG included the use of the Advanced Stirling

Convertor (ASC). Several different series of ASCs were developed as the technology matured towards qualification and flight hardware. Although advancements were made in all areas of Stirling convertor technology, budget conditions and the need for additional technology development led to termination of the ASRG project.[3]

Space Nuclear Reactors—Power and Propulsion

For space nuclear reactor technology, the last three decades were marked by two major periods of concept development and technology advancement work. The first period originated under the auspices of SDI and included the SP-100, TOPAZ, and Timberwind/SNTP programs. The second period originated a decade later under NSI and gave rise to the Prometheus/JIMO project. A third effort, albeit much smaller, was conducted under the auspices of SEI but was limited to evaluation and assessment of space reactor power and propulsion technologies.

The SP-100 program was by far the largest and most successful domestic space reactor development program undertaken since the Rover/NERVA program was terminated in 1973. From the onset, the program focused on developing a 100-kWe space reactor power system that would be scalable over a broad range of power levels (10 to 1,000 kWe) and could be adapted to the needs of multiple users. Scalability was to be achieved through the design and use of modular components such as the power conversion system. The scalability concept was of particular benefit due to the absence of a specific mission. While DOE, DoD, and NASA had a golden opportunity to develop the space reactor power system, division over technology (thermionic versus thermoelectric), ongoing funding shortfalls, and the lure of foreign power conversion technology worked against the program.

In spite of the obstacles, the effort to develop the SP-100 space reactor power system made significant progress.

In spite of the obstacles, the effort to develop the SP-100 space reactor power system made significant progress. The program completed a detailed reactor power system design, including the criticality experiments and hydraulic flow testing necessary to demonstrate the design. Uranium nitride fuel pin fabrication processes were re-established and techniques for fabricating the reactor vessel and its internal structural components from high-temperature refractory metal alloys were demonstrated. Fabrication and testing of a prototypic control rod drive assembly in high-temperature vacuum conditions were completed. Advancements were also made in silicon-germanium thermoelectric power conversion modules and the electromagnetic pumps to be used in the power conversion system. At the time of its termination, the program was considered to be within one year of demonstrating the ability to fabricate all of the key components required for a flight-ready power system. With the extensive hardware, documentation, and records-retention effort undertaken by DOE following termination of the SP-100 program, a solid technology base was established from which future space reactor power system technology efforts might build.

In the area of nuclear thermal propulsion, the sole technology development effort consisted of the classified Timberwind program was initiated under the auspices of SDIO and the DOE

Office of Defense Programs but transitioned to the purview of the Air Force and DOE-NE as the SNTP program. The Timberwind effort focused on a high-power particle bed reactor propulsion concept with development of the PBR fuel particle and fuel element as primary objectives. Although the same objectives were carried into the SNTP program, the desire for nuclear thermal propulsion eventually succumbed to other mission needs and the SNTP was terminated.

As the SDI-based efforts came to a close toward the end of the Cold War, SEI came on the horizon in 1989 and provided a brief three-year impetus under which DOE and NASA developed and evaluated several space reactor propulsion system concepts to support a manned mission to Mars, and various space reactor power system concepts for manned Lunar outposts. Due to the limited funding associated with SEI, work was directed at detailed evaluation of technology and assessments of potential reactor system concepts for both power and propulsion.

Ten years later, in 2002, NSI provided one last effort to develop nuclear electric propulsion. Under the Prometheus/JIMO project, NASA sought to develop a nuclear electric propulsion system powered by a space reactor concept developed by DOE-NR. The project was terminated after three years due, in part, to the significant costs anticipated for development of the space reactor power system.

While the large space reactor programs of SP-100 and Prometheus have long since passed, current space reactor development efforts are focused on smaller system concepts such as a Kilopower Fission Power system that is scalable from 1 kWe to 10 kWe.[4] In addition to the ongoing space reactor technology development efforts, NASA and DOE initiated a Nuclear Power Assessment study in 2014 that includes an evaluation of two potential NASA missions identified in the 2011 Decadal study, *Vision and Voyages for Planetary Science in the Decade 2013–2022*,[5] and the technology needed to accomplish those missions. The study was completed in early 2015 and provides information useful for the future development of space nuclear power systems.

Lessons, Trends, and Take-aways

Emerging from the accomplishments, successes, and failures of space nuclear power system development and use over the last three decades are a variety of lessons and trends. While presented in no order of importance or priority, they may serve to guide future development and planning efforts.

Need for Long-Term Commitment

The need for long-term commitment may be the biggest challenge facing DOE, NASA, and DoD in developing future space reactor power systems. As shown by historical space reactor programs such as Rover/NERVA (17 years of development upon its termination) and SP-100 (10 years of development upon its termination), it's clear that space reactor development requires a significant investment in time as well as money. Closely related is the need for a development effort focused on the advancement of technology that typically requires long lead times, such as nuclear fuel and materials qualification. There is simply no way to fast track the development and deployment of such systems. Therefore, there must be long-term commitment to any such development program, not just among the partner agencies but also by Congress through which the funding necessary for such development will come.

Technology Decisions in the Face of Limited Resources

The major space reactor development efforts conducted over the last 30 years have shown that a broad variety of technologies can be combined to develop a multitude of system concepts meeting the needs of a particular mission. The vast majority of system concepts are typically eliminated from further consideration following an appropriate screening process, leaving a small subset for final consideration by decision makers. Although competing technologies may offer a hoped-for level of performance, technology decisions must ultimately be driven by clear mission requirements and sound systems engineering and acquisition processes. In the long-run, system development efforts may actually be hampered when development work is spread among too many technologies. John Warren of DOE/NASA provided a relevant perspective when reflecting upon the various space reactor programs conducted through the 1980s and 1990s: "We had so many concepts competing with one another. And the problem is we had limited resources—by that I mean funds and people—and we still have limited resources, and I think the strategy has to be pick one and get it going."[6]

In the long-run, system development efforts may actually be hampered when development work is spread among too many technologies.

Downward Trend in Frequency of Missions Utilizing RTGs

The frequency of missions requiring RTGs has decreased significantly over the past 30 years. During the first 20 years of RTG use (1961–1981), 22 separate launches carrying 38 RTGs were completed. However, since the launch of Galileo in 1989, only five spacecraft and eight RTGs have been launched, the most recent being New Horizons with its GPHS-RTG (2006) and MSL with its MMRTG (2011). With the cancellation of the ASRG project in 2013, the next launch for which a space nuclear power system (MMRTG) will be utilized is planned for 2020. Almost 10 years will have lapsed since the last MMRTG was assembled and tested. In the past, DOE has felt the consequences of mission cancellation in two notable ways.

First, mission delays and lulls, such as occurred following the Galileo and Ulysses RTG production activities, led to decisions to terminate thermoelectric material production and defer processing equipment maintenance. In both instances, significant effort and cost were required to re-establish operations at new locations and with new contractors. Although maintaining a base level of operations between missions is desirable for worker proficiency and productivity, and equipment operability, limited funding and other factors may preclude such activities. When a definitive NASA mission was eventually announced (i.e., Cassini), DOE was faced with the need to re-establish production processes, including equipment and facility setup and worker training, typically against an aggressive mission schedule.

Secondly, less frequent missions can also present challenges in retaining knowledgeable and trained workers, including those associated with thermoelectric, heat source, and RTG assembly and testing operations, as well as support personnel (engineers and quality). Managers are often faced with the need to find interim work and worker qualification and training is often allowed to lapse.

Need for Robust Infrastructure

The advent of the DOE Office of Environmental Management program in the late 1980s and the de-emphasis on nuclear research and development through much of the 1990s resulted in a significant reduction in the number of facilities available to support space nuclear reactor system development. For example, nuclear reactors once available for materials and component testing in support of the SP-100 program, such as EBR-II and FFTF, were shut-down and dismantled. Other facilities that were available to support ground testing and flight qualification of space reactors, such as PRTR at Hanford, have also been dismantled. Future space reactor development efforts should therefore include a thorough inventory of existing DOE facilities against expected testing and development needs to ensure any gaps are included in long-term system development plans and budgets.

While the RTG operations infrastructure saw perturbations through the same period, it remained intact as DOE relocated operations and activities to new sites. As demonstrated by the operating experience with the SRS PuFF facility, the need to maintain plutonium-238 processing facilities and equipment will continue to require special attention.

Need for a Clear Mission—Maybe Not

For decades, the space nuclear power system community has operated under the premise that development efforts are best supported and justified when tied to a specific mission. The premise was strongly underscored in the 1983 National Research Council report that maintained the importance of matching research and development to a firm requirement, or at least the emergence thereof.[7] Clearly, the development of RTG technology benefited from well-defined missions where power levels were established early on and typically unchanged, giving power system developers a fixed target in terms of application, schedule, and funding. Most importantly, RTG missions rarely disappeared—when NASA said an RTG was needed by a given date, DOE delivered.

For decades, the space nuclear power system community has operated under the premise that development efforts are best supported and justified when tied to a specific mission.

By contrast, space reactor development programs over the last 30 years have experienced a different outcome. Missions came and missions went, generally in the context of a broader "initiative." When the need went away, support eventually dried up, and when support dried up, the technology development effort soon ended. In essence, development efforts were hampered by the lack of clear, enduring mission needs and associated requirements. The same pattern displayed itself in the SP-100, Timberwind/SNTP, TOPAZ, and Prometheus programs. Another factor that has adversely affected space reactor development programs is their high cost—it has proven difficult to maintain support when development costs begin to greatly outpace cost estimates, particularly when such trends recur. As such, it is clear that being tied to a specific mission brought no more success to the space reactor development programs of the last 30 years than most of those conducted previously.

In the absence of a clear and long-term mission, space reactor system development could benefit greatly from ongoing technology advancement between large mission-driven system development efforts. In addition to advancing various sub-system components, such as fuel or power conversion technology, such efforts could reduce the overall mission cost and schedule when a specific need arises in the future.

Alternatively, future space reactor development programs might adopt a pattern of development similar to that of RTGs—start small and grow gradually. The advancement of RTG technology occurred largely over a period of 20 years, during which power levels gradually grew from 2.7 We to 300 We through an ongoing evolution of several RTG designs. Starting with a much smaller system may offer advantages such as relatively low cost, shorter development times, and simpler technology. However, such advantages would have to be carefully weighed against technology breakpoint factors such as the operational aspects of heat generation versus propulsion, and power conversion breakpoints.

Nuclear Safety and Response Preparedness

Nuclear safety will remain a significant emphasis for all future space nuclear power system uses. That emphasis will continue to be driven by rigorous launch approval processes and supported by the ongoing enhancement of knowledge pertaining to potential launch accident environments and an ever improving ability to model the consequences of potential accidents. Coupled with the strong emphasis on safety will be the ongoing need for well-planned emergency response that can be quickly and decisively executed if the need arises. Such response must include provisions for timely and frequent communication with a concerned public.

Into the Future

From the underlying science and engineering by which electrical power is generated from the atom to the reliability and longevity for unattended operation of power systems for years and decades, the history of space nuclear power and the systems developed to date is truly fascinating. Equally fascinating is the development and advancement of nuclear-based propulsion systems. But integral to the story of the technology are the countless men and women whose knowledge, skill, ingenuity, and determination brought concepts to reality and paved a way for the use of such systems in the future.

After 60 years of invention, development, and use, space nuclear power systems continue to provide a unique niche that solar and chemical systems cannot fill. The power in the atom has, figuratively, taken mankind to every planet in the solar system (except Mercury) and beyond. It has powered rovers on Mars and orbiters around Saturn and enabled surveys of the sun. Such systems have allowed mankind to extend our reach to destinations within the solar system and beyond that would otherwise remain unknown. And yet the door to space exploration remains barely ajar.

As long as dreams and desires to explore the "final frontier" remain, the power in the atom will continue to lend itself as a means through which they might be fulfilled. And with six decades of experience at its back, DOE remains well-poised to carry space nuclear technology boldly and successfully into the future.

NASA's Spitzer Space Telescope observed a fledgling solar system, like the one depicted in this artist's concept, and discovered deep within it enough water vapor to fill the oceans on Earth five times. (Photo: NASA/JPL-Caltech)