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Atomic Power in Space II

January 2015

Greg Hula

Changing the World's Energy Future

Idaho National Laboratory

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ATOMIC POWER IN SPACE II

A History of Space Nuclear Power and Propulsion in the United States

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Prepared by
Idaho National Laboratory
Battelle Energy Alliance, LLC
Space Nuclear Systems and Technology Division

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Preface

Atomic Power in Space II is a sequel to *Atomic Power in Space* (published by the Department of Energy [DOE] in 1987). Beginning with a brief overview of the programs and systems developed through the late 1970s, *Atomic Power in Space II* traces the development and use of space nuclear power systems, including the missions and programs for which they were developed, to the present day. The history is written largely in nontechnical language so as to be useful to the general reader as well as the seasoned space nuclear professional.

Completion of this book would not have been possible without the help of many dedicated individuals. First and foremost is Steve Johnson, Director of the Idaho National Laboratory (INL) Space and Nuclear Systems and Technology (SNST) Division, whose vision and confidence were crucial in the undertaking of this assignment and whose balance of competing priorities helped ensure its fruition. Carl Friesen of the DOE-Idaho Operations Office and Wade Carroll of DOE-Headquarters provided many of the resources necessary to complete the project. A draft partial manuscript and resource library, developed by Janine Finnell, Richard Price, Ellen Clark, and their colleagues under another DOE contract prior to INL SNST involvement, was made available for use. That information, which included a series of interviews with many individuals who were involved in various aspects of space nuclear power system development over the years, was drawn upon during the research, writing, and development of this history. DOE also coordinated an independent technical review of the draft manuscript, which was provided by Dr. Gary Bennett (DOE/NASA retired), Earl Wahlquist (DOE, retired), John Warren (DOE/NASA), Robert Wiley (DoD/DOE/NASA contractor and DOE, retired), and Robert Carpenter (Orbital Sciences Corporation). Their comments, insight, and suggestions greatly improved the final manuscript. Any factual or technical accuracy errors that remain are the sole responsibility of the INL author and technical lead.

Graphics development and layout, technical editing, and other assistance were provided by Kris Burnham, Ann Riedesel, Lori McNamara, Travis Moedl, and Whitney Richardson of North Wind, Inc. Tamera Waldron, Tam Elingford, and Jackie Loop of the INL Technical Library provided invaluable assistance in locating journal articles, technical reports, Congressional hearing manuscripts, and other historical documents. James Werner of the INL SNST Program provided insight and perspective pertaining to space nuclear system technologies early in the development process. Several others assisted in the retrieval and provision of historical

photos and images for the book, including Doug Gabriel and Dick Madding at the Mound Museum in Miamisburg, Ohio; Nicholas Natanson of the National Archives and Records Administration; Heidi Palombo of DOE Energy Technology Visuals Collection and Document Imaging; Paul Ostdiek of Johns Hopkins University Applied Physics Laboratory; George Ulrich of the Oak Ridge National Laboratory; Jay Ray of DOE Savannah River; Scott Wold and Chris Morgan at INL; Richard Robinson and Alan Carr at Los Alamos National Laboratory; Ron Lipinski at Sandia National Laboratory; and Dwayne Brown at NASA.

My hope is that this history presents a meaningful and accurate sequel to that which was published almost 30 years ago. I also hope that the reader walks away with a sense of the wonder and amazement that I discovered as I learned about space nuclear power systems and their potential, both realized and unrealized, in the future of space exploration. Finally, for the dedicated individuals who spent countless hours and years laying the foundation of these remarkable systems and continuing the advancement of the technology, I hope the story stirs up memories (mostly fond!) of your labor and service to the U.S. space program, both civilian and defense.

Greg Hula
Idaho National Laboratory
Space Nuclear Systems and Technology Division

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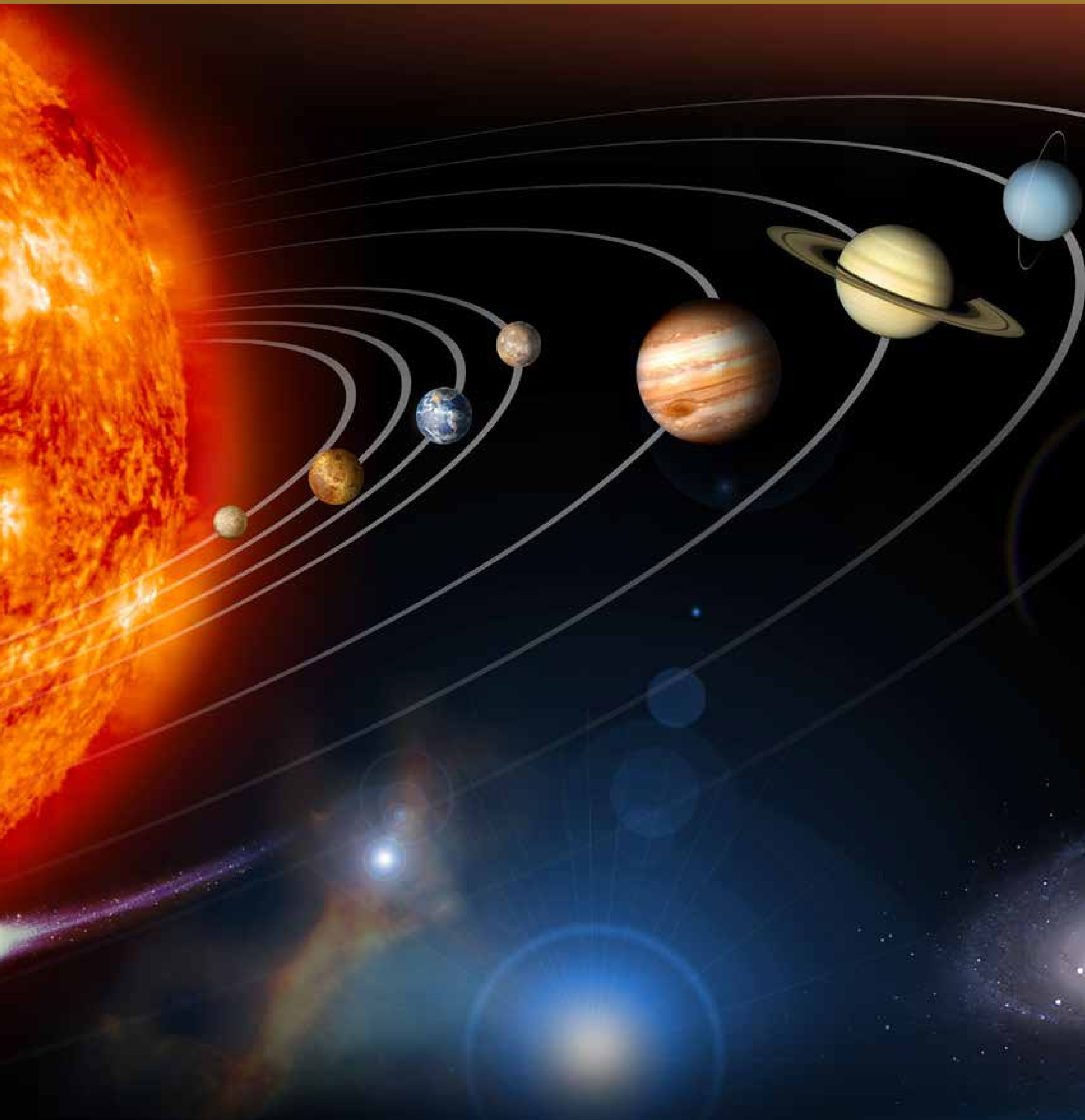
"Innate to the human experience is our yearning to explore; to know the unknown; to discover the undiscovered."

–Alice Caponiti



Foreword
To Know the Unknown

Innate to the human experience is our yearning to explore; to know the unknown; to discover the undiscovered. Humans continue to uncover new things about planet Earth and we routinely interact with satellites that allow us to communicate across the globe, view images of our homes as seen from space, or navigate to unfamiliar locations. Satisfying the urge to explore requires moving ever further from our planet, to the far reaches of our solar system and beyond. But such exploration requires reliable and long-lived power often beyond the capabilities afforded by solar and chemical systems.

Space nuclear power systems have the unique capabilities that make them especially well-suited for space exploration; indeed, many of the National Aeronautics and Space Administration's (NASA's) most ambitious missions would not be possible without them. Ironically, the contribution of nuclear power to the success of many iconic space missions has often gone unnoticed by the public, in part due to its track record of safety and quiet reliability. Nuclear power has been utilized for 26 successful American space missions, both in Earth orbit and beyond. Space nuclear power systems have been aboard satellites and facilitated navigation, communication, and weather forecasting. Many have enabled scientific and exploratory missions. The Viking landers sent the first images from the surface of Mars, and the Voyager probes have traveled to the edge of the solar system, with one entering interstellar space, inspiring a generation of scientists. The nuclear-powered rover Curiosity is exploring Mars using sophisticated scientific instruments to search for conditions favorable to life in Mars' past. This year the New Horizons spacecraft completed its nine-year, three-billion-mile trip to the Kuiper belt, and begins a close encounter with Pluto and other objects on its mission of discovery. Mankind's instinct for exploration has naturally led us to look beyond Earth; what we have learned so far has been astounding. Best of all, our journey is still in its infancy.

The U.S. Department of Energy (DOE) has a unique role in the history of American space nuclear power. DOE has been integrally involved in its development and use for both civilian and defense space missions. The Department owns and operates the facilities that are used to produce and handle nuclear fuel as well as the facilities in which fueled components and systems are assembled and tested. These systems have been vital for both NASA and Department of Defense (DoD) mission applications. Aligned

Artist's concept of our solar system and points beyond. (Photo: NASA/JPL)

Alice Caponiti,
U.S. Department of Energy
Director, Space and Defense Power Systems Program

with these two agencies, DOE has overcome numerous hurdles and has been a partner in many successful missions.

Integral to the history of space nuclear power is the theme of safety, which has always been a central consideration for its development and use—from design to fabrication and through launch. Nuclear power systems are safe to build, assemble, and use, and devices are engineered with multiple layers of containment should a mission falter. All nuclear power systems designed for use in space undergo meticulous flight qualification testing that simulates extreme scenarios, and no system is ever used unless it passes mission acceptance requirements.

To that end, *Atomic Power in Space II* presents a history of U.S. space nuclear power during the past 30 years—its development and use, the missions in which it was incorporated, and the research and accomplishments that served to move the technology forward. It is a story of the dedicated professionals from many organizations working together to build amazing and complex systems. It is also a story of struggle with both technical and non-technical issues, of remarkable successes, and of marvelous opportunities within our reach. This book tells the story through 2013; however, this is only an introduction to the possibilities of space exploration that might be enabled in the future by space nuclear power.

Integral to the history of space nuclear power is the theme of safety, which has always been a central consideration for its development and use…

And what does the future hold? The nuclear-powered Galileo and Cassini spacecraft have found evidence of underground oceans on the moons of Jupiter and Saturn. Such oceans have the potential for life but further exploration is required. The planets Uranus and Neptune have only been explored by brief flybys of the Voyager spacecraft, and future missions will likely yield amazing discoveries. Closer to home, further discoveries of our own Moon require an uninterrupted power source to enable work to continue through the long lunar nights. Perhaps most alluring of all is manned exploration beyond Earth, including landing humans on Mars. When and if these missions become a reality remains to be seen, but nuclear power will likely be the means to make them possible.

Alice Caponiti,
U.S. Department of Energy
Director, Space and Defense Power Systems Program, 2015

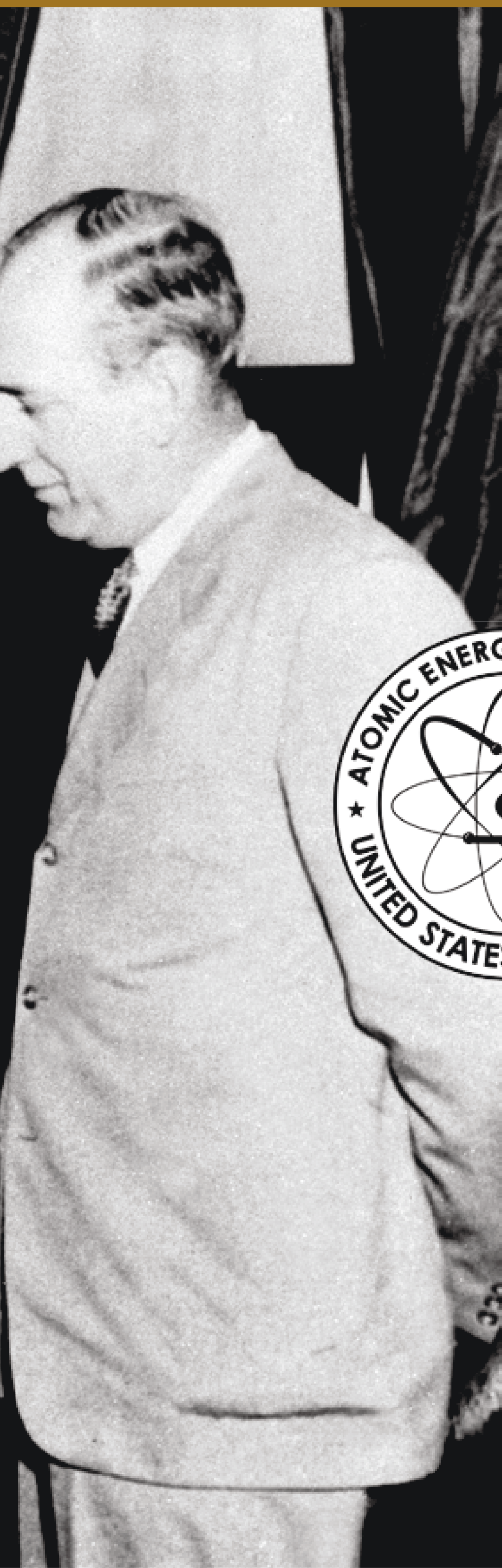
On June 29, 2011, NASA and the Smithsonian National Air and Space Museum in Washington, D.C. held an event to commemorate both the launch of the first space nuclear power system, and to recognize the several decades of discovery that radioisotope power systems have enabled. Pictured left to right: Peter Lyons, Assistant Secretary for Nuclear Energy, DOE; Roger Launius, Senior Curator, Smithsonian National Air and Space Museum; Don Ofte (Honoree); Pat Rawlings, Space Artist; John Dassoulas (Honoree); Steve Squyres, Cornnell University; James Hagan (Honoree); Ralph NcNutt, Applied Physics Laboratory; Paul Dick (Honoree); Chris Scolese, NASA Associate Administrator; and Robert Carpenter (Honoree). (Photo: NASA)

"There are only three possible sources of energy which can be used to generate electricity in space – chemical, nuclear, or solar. Each energy source, . . . has its own intrinsic characteristics, and their differences determine which source is uniquely the best for a specific mission."

Systems for Nuclear Auxiliary Power...A Report by the Commission – 1964

1

The Early Years
Space Nuclear Power Systems Take Flight



Only a few years separate the operation of mankind's first nuclear reactor at the University of Chicago in 1942[1] and the first U.S. research on the use of nuclear power in space. Shortly after the end of World War II, control of atomic energy was transferred from military to civilian hands when Congress enacted the Atomic Energy Act of 1946.[2] The Act created the Atomic Energy Commission (AEC), which began operation on January 1, 1947. Although responsibility for atomic energy development was now under the new civilian agency, its development continued to remain tied to military purposes.

By the late 1940s and early 1950s, studies by the AEC and the Department of Defense (DoD) began to show that the energy generated from the decay of radioisotopes and the process of nuclear fission held much promise for uses other than atomic weapons. Performed against the backdrop of the early days of the Cold War between the United States and the Soviet Union, in which each country sought military and technological prowess over the other, those studies envisioned radioisotope and reactor power for military reconnaissance satellites and a nuclear reactor propulsion system for intercontinental ballistic missiles.

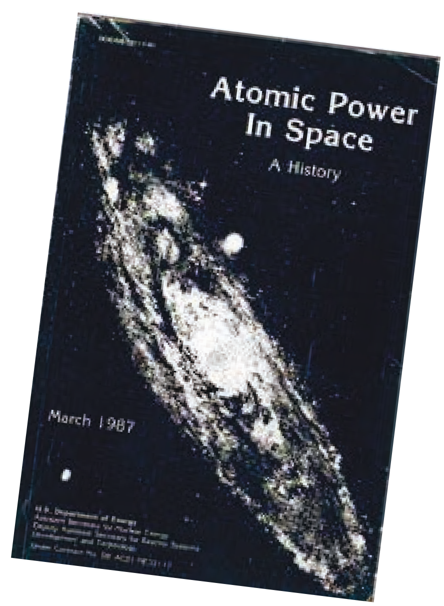
Around the same time, the United States began efforts to expand the peacetime development of atomic energy. In his Atoms for Peace speech before the United Nations General Assembly in New York City on December 8, 1953, President Dwight D. Eisenhower presented a vision for the international management of atomic energy as well as its development and use for peaceful purposes. The following year, in 1954, Congress passed a new Atomic Energy Act that opened the door for the development of nuclear power by private industry and improved exchange of nuclear technology with other nations.[3]

On August 1, 1946, President Harry S. Truman signed the bill creating the U.S. Atomic Energy Commission. (Photo: DOE Flickr)

The studies of atomic energy feasibility for satellite power were soon bolstered by a demonstration of that feasibility. In early 1954, two Monsanto scientists at the AEC Mound Laboratory in Ohio demonstrated a device that was able to convert the heat from the natural decay of the radioisotope polonium-210 to electricity. Using the principle of thermoelectricity, otherwise known as the Seebeck effect, the researchers used the heat from the polonium isotope to induce a temperature differential across a thermocouple. The result was the generation of 1.8 milliwatts of electricity (mWe) and demonstration of the world's first radioisotope thermoelectric generator (RTG).[4, 5]

These early efforts gave rise to two major AEC programs in 1955: 1) Systems for Nuclear Auxiliary Power (SNAP), which focused on the use of nuclear reactors and radioisotopes for satellite-based electrical power generation, and 2) Rover, which focused on development of a nuclear rocket. Shortly after these early research and development efforts began to bear fruit, the launch of the first man-made satellite placed in space (Sputnik I), by the Soviet Union in October 1957, gave added impetus for the development of these new power systems. Soon an entire industry emerged as scientists and engineers learned to harness and

Dr. Ken Jordan and Dr. John Birden with first RTG. (Photo: Mound Museum Association)



Cover of A*tomic Power In Space, A History*, published by DOE in 1987.

use the energy of the atom in ever newer and more creative ways, eventually leading to the far reaches of space.

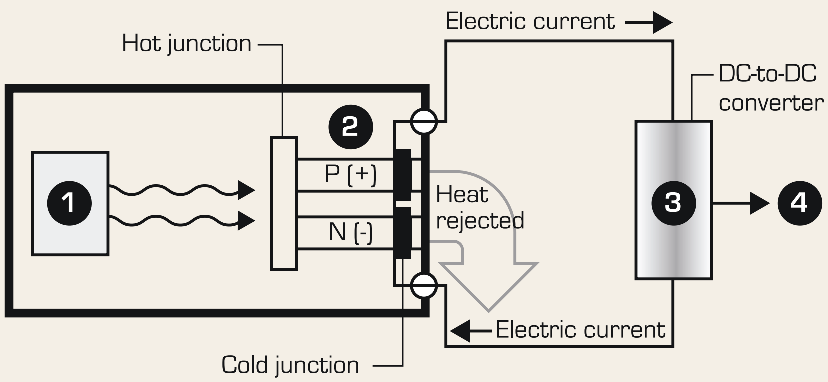
The space nuclear power system technologies and programs undertaken in the United States since the mid-1950s include radioisotope power systems (RPSs) (both static and dynamic) as well as reactor systems developed for space power and propulsion. An earlier history (pre-1987) of space nuclear power development and use, which focused largely on RTG technology, is presented in *Atomic Power in Space*.[3] The history and technologies captured in that and other works describe the pioneering efforts that solved many of the technical problems of using nuclear power in space and demonstrated that nuclear power is well-suited for certain types of space missions. These early efforts are briefly reviewed in this chapter because they set the stage for the programs and missions discussed in the remainder of this book. They also provide a basis for understanding the evolution of space nuclear power system technologies and some of the political and social environments that influenced their development.

Seebeck Effect: Producing Electricity from Heat

In 1821, German scientist Thomas Johann Seebeck observed that an electric voltage is produced when two different conductive materials are joined in a closed circuit and the two junctions are kept at different temperatures. The pairs of junction are called a thermoelectric couple, or thermocouple.

Basic thermoelectric generator operation

1. Nuclear fuel (e.g., plutonium-238) decays spontaneously producing heat
2. Thermocouples convert heat directly into electricity
3. Electricity is tapped from terminals connected to thermocouples
4. Power output



SNAP Takes Hold

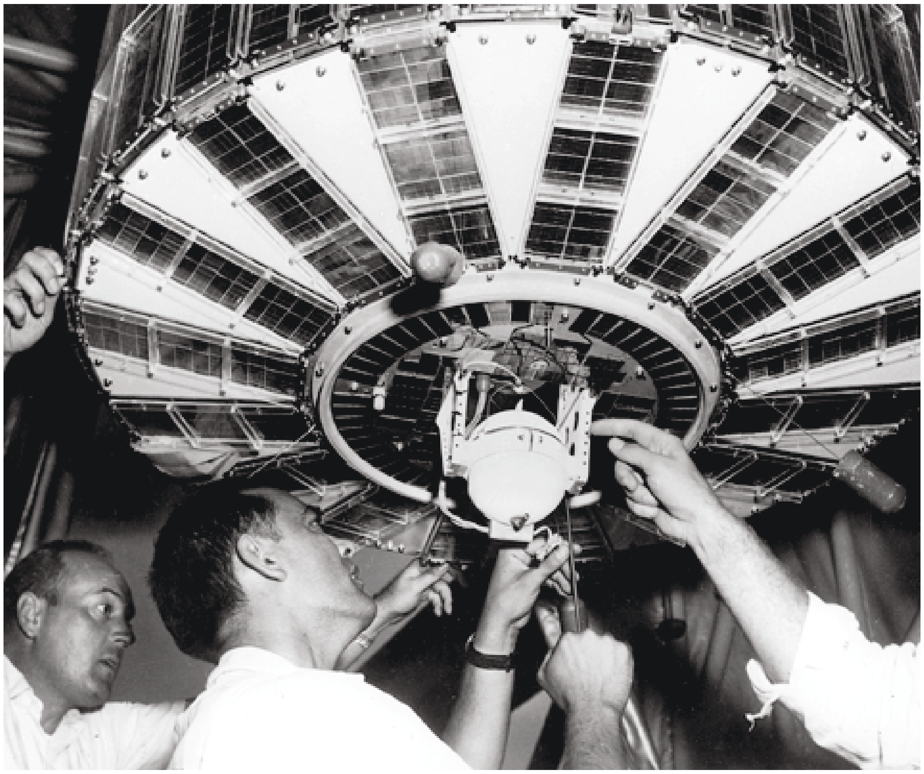
The SNAP program consisted of two separate but parallel efforts. Development of systems for the conversion of heat generated from the natural decay of radioisotopes was awarded to the Martin Nuclear Division of the Martin Company out of Baltimore, Maryland. Development of systems to employ the heat generated from the fission process within nuclear reactors was awarded to the Atomics International Division of North American Aviation, Inc. To differentiate the radioisotope systems from the reactor systems, AEC devised a simple numbering scheme—odd numbers (i.e., SNAP-1) were used to designate RPSs while even numbers (i.e., SNAP-2) were assigned to reactor systems. Letters of the alphabet were used to indicate design differences among the same system. Although systems were developed for space and terrestrial uses, this book focuses only on space nuclear power systems.

The first RPS developed by the Martin Company, SNAP-1, used the heat from the decay of cerium-144 to boil liquid mercury to drive a small turbine, with the goal of generating 500 watts of electric power (We) for a 60-day lifetime. Although testing demonstrated the feasibility of the first dynamic RPS that used a Rankine thermodynamic cycle, the unit was never fully developed for space use due to factors that included the need for a system with a longer operating life and the advent of thermoelectric materials with high efficiency.[3]

As development of SNAP-1 progressed, Martin subcontracted with Westinghouse Electric and the Minnesota Mining and Manufacturing Company (3M) to develop an RTG, a type of power system with no moving parts similar to the concept demonstrated by Dr. Ken Jordan and Dr. John Birden. Such systems are referred to as static RPSs. In December 1958, 3M delivered an RTG that used a pellet of polonium-210 encapsulated by the AEC Mound Laboratory to produce 2.5 We. The small atomic battery, dubbed SNAP-3, was displayed by President Eisenhower in the Oval Office on January 16, 1959.[3]

Public debut of the SNAP-3 RTG technology demonstration device displayed on President Eisenhower's desk, January 16, 1959. Pictured left to right: President Eisenhower, Major General Donald Keirn, AEC Chairman John McCone, Colonel Jack Armstrong, and Lt. Colonel Guveren Anderson. (Photo: DOE Flickr)

With development of RTG technology rapidly progressing, it wasn't long before the first RTG found its way to space. The genesis for that opportunity arose from the desire for a navigational satellite for use by naval ships and planes—a precursor to today's global positioning system (GPS). The Navy Transit program desired a power source that would enable a satellite to operate for five years. Unsure that a standard chemical battery would last that long, John Dassoulas of the Johns Hopkins University Applied Physics Laboratory learned about the SNAP program during a chance conversation with G. M. Anderson of AEC while on a return flight from a conference. Following a visit to the Martin facility in Baltimore, Dassoulas received permission from AEC to use an RTG with the Transit satellite. The 3M SNAP-3 RTG was modified to use plutonium-238 rather than polonium-210, thereby taking advantage of the much longer half-life of the plutonium isotope (88 years versus less than five months for polonium-210).[3]



Installation of the SNAP-3B device to the Navy's navigational satellite at Cape Canaveral by technicians of the Johns Hopkins Applied Physics Laboratory. This is the first atomic power supply used in space. (Photo: DOE Flickr)

The modified RTG, named SNAP-3B, produced 2.7 We and was launched aboard a Transit-4A satellite in June 1961, thereby marking the world's first use of nuclear power in space. The Transit-4A satellite operated until 1976, well beyond its intended lifetime. Another SNAP-3B RTG was launched aboard the Transit-4B satellite in November 1961 and operated until 1971. The successful use of the SNAP-3B RTGs, which supplemented the solar power systems aboard the satellites, clearly demonstrated the feasibility of the RTG for use as a space nuclear power system. The satellites and their RTGs remain in orbit above Earth.[3, 6]

While the SNAP-3B unit provided supplementary power for the Transit-4 satellites, the next goal was to demonstrate the feasibility of using an RTG as the sole source of power for a Navy satellite. Driven by the desire for a power source with improved survivability, the SNAP-9A RTG was created, which was used on the Navy navigational satellites Transit-5BN-1, 5BN-2, and 5BN-3. Like SNAP-3B, the SNAP-9A unit was fueled with plutonium-238 but was designed to generate 25 We, almost 10 times the power of the SNAP-3B unit. Transit satellite 5BN-1 was successfully launched on September 28, 1963, and Transit-5BN-2 was successfully launched on December 5, 1963. The third satellite, Transit-5BN-3, was launched on April 21, 1964. However, when the satellite failed to achieve orbit, the SNAP-9A RTG re-entered the atmosphere. Consistent with the burnup-dispersion safety design philosophy in use at the time, the SNAP-9A unit and its metal plutonium fuel burned up, resulting in its dispersion into the atmosphere. Although there were no unacceptable health risks, with larger quantities of plutonium fuel planned for future RTGs, AEC changed its safety philosophy for space nuclear power systems to one of intact re-entry.[3]

AEC Chairman Glenn T. Seaborg, left, compares a SNAP-9A "atomic battery" (bottom center) with a full-scale model of a SNAP-3B atomic battery held by Major Robert T. Carpenter, AEC-SNAP project engineer. (Photo: 434-N-AEC-63-7042. General Records of the Department of Energy, RG 434, National Archives Still Picture Branch, College Park, Maryland)

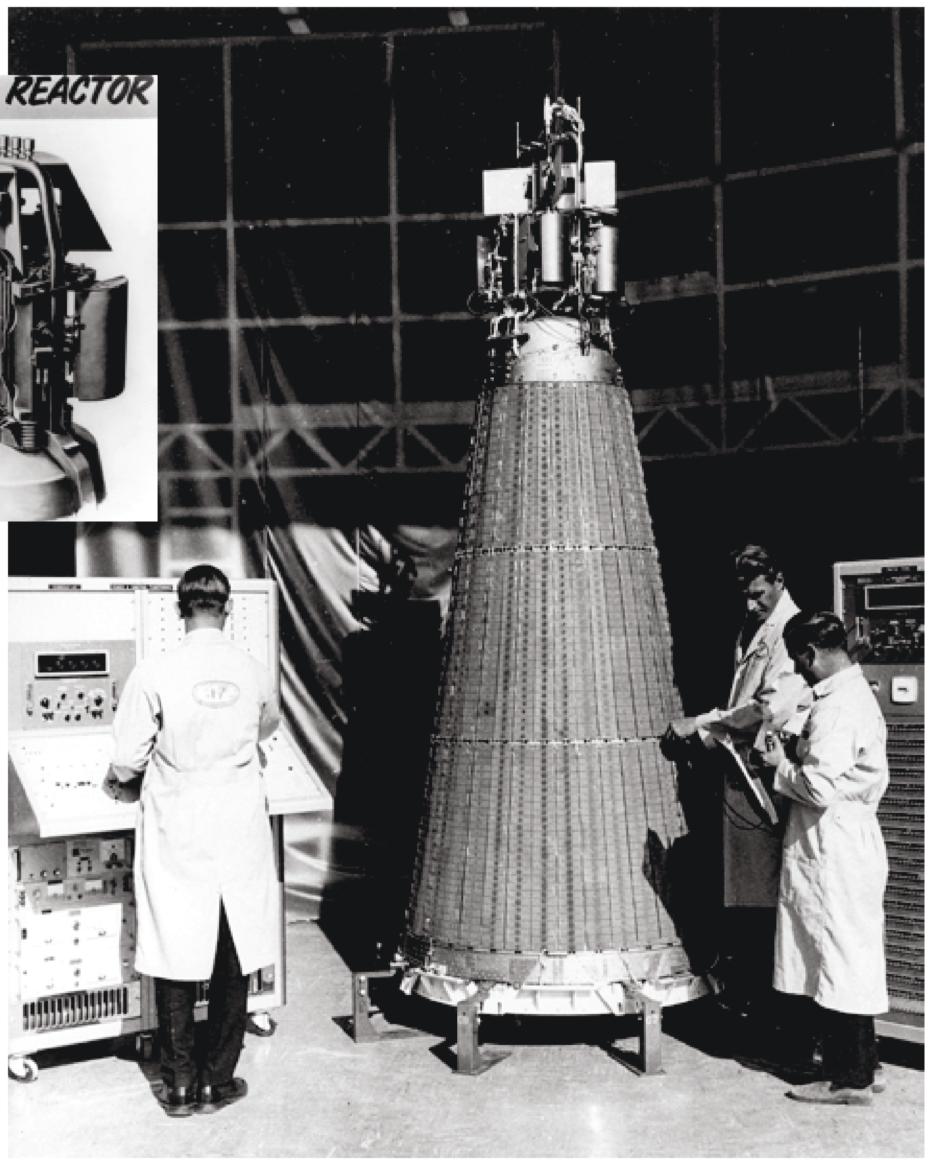
Following the 1964 Transit-5BN-3 accident, four years passed before another RTG was launched into space. During those years, AEC and its contractors continued RTG development, including incorporation of the intact re-entry safety philosophy into new RTG designs and development of new plutonium fuel forms to replace the metal fuel used in the SNAP-3A and SNAP-9A RTGs.

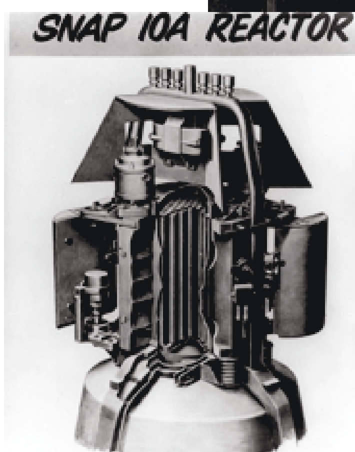
SNAP Reactors Heat Up

As success mounted with the early RTG efforts, development of space nuclear reactor concepts under the SNAP program also began to bear fruit. Under contract to AEC, Atomics International began development of a compact uranium-zirconium hydride reactor for use as a heat source in space nuclear power systems in the mid-1950s. By 1959, AEC and the Air Force had initiated a joint program, dubbed SNAP-2, to develop a power system that utilized a reactor coupled with a liquid-metal (mercury) Rankine power conversion unit (the conversion technology used in the SNAP-1 program). Development of the mercury Rankine cycle conversion system was led by the Thompson-Ramo-Wooldridge Company. However, due to the lack of a mission, the SNAP-2 program was redirected into a broader space nuclear power program in 1963.[7]

Under the SNAP-10 program, a 300-We reactor power system was designed that utilized a silicon-germanium thermoelectric generator developed by the Radio Corporation of America (RCA). Completed in 1959, the program was subsequently redirected in 1960 to develop a higher-power reactor system that incorporated the SNAP-2 reactor. That redirection resulted in the SNAP-10A program, under which the SNAP-2 reactor developed by Atomics International was coupled with the RCA thermoelectric generator to produce a 950-pound (430-kilogram), 500-We space reactor power system for use in a proof of principle flight.[7]

The SNAP-10A reactor power system was launched into space from Vandenberg Air Force Base, located in southwestern California, on April 3, 1965, in a flight test named SNAPSHOT. Once in its 700-mile orbit, reactor startup was initiated by remote signal. For 43 days the system operated as designed and produced 500,000 watt-hours of electricity. However, a voltage regulator on the spacecraft failed, causing the reactor





SNAP-10A space nuclear power unit. The reactor is located at the top end of the cone (radiator), and shown in inset, top left. (Photo: DOE Flickr)

SNAP-10A remains a significant milestone for the U.S. space program.

to shut down, putting the satellite out of commission. SNAP-10A remains a significant milestone for the U.S. space program. Not only did it demonstrate the feasibility of operating a liquid-metal-cooled reactor power system safely and reliably in space, with remote startup and control, it was also the world's first reactor power system to be successfully launched and operated in space.[7]

Although SNAP-10A remains the most notable achievement in the SNAP reactor program, other notable SNAP reactor programs include SNAP-8 and SNAP-50. The SNAP-8 program was initiated in 1959, at the request of the National Aeronautics and Space Agency (NASA), to develop a reactor for use in a nuclear electric propulsion system. The resultant reactor power system employed a mercury Rankine cycle to generate 30 to 60 kilowatts of electric power (kWe). Under the SNAP-50 program, development efforts focused on demonstration of a lithium-cooled reactor coupled with a potassium Rankine cycle capable of generating 300 to 1,000 kWe for use in electric propulsion, as well as power supplies for space vehicles and large manned satellites.[7]

Further research into reactor-based space power systems continued through the 1960s, but was largely discontinued in 1973 due to changing national priorities. As discussed in later chapters, interest in space nuclear reactor systems would be renewed under programs such as the Space Power Advanced Reactor (SPAR) project and the SP-100 program.[8] On the RTG front, however, no such slow down occurred, as the young RTG technology was soon put to use by an even younger national space agency.

RTGs Bring Power to NASA Missions

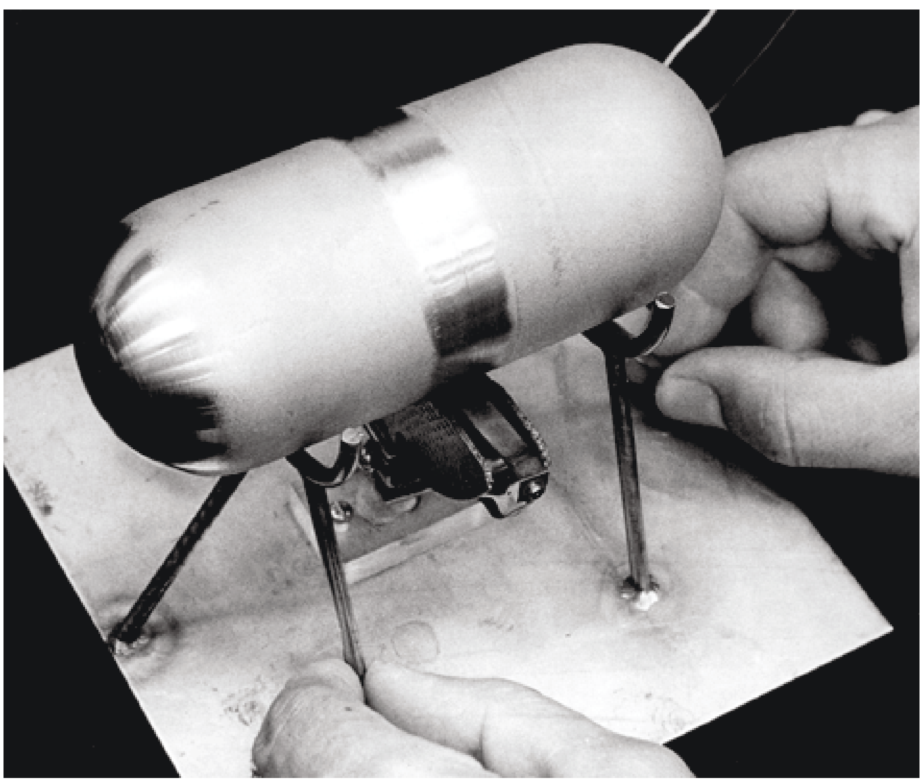
NASA's interest in space nuclear power systems grew against the backdrop of the Navy Transit program and the ongoing space power system development efforts of the SNAP program. NASA's first use of the new space nuclear technology was in Earth orbit aboard a Nimbus weather satellite. A desire to supplement a 200-watt solar power system with approximately 50 We of RTG power led to development of the SNAP-19B RTG.

With a power output of approximately 23.5 We, the SNAP-19B RTG used a new heat source that reflected the intact re-entry safety design philosophy adopted by AEC following the Transit-5BN-3 accident in 1964. As such, the SNAP-19B heat source was designed to contain its plutonium fuel (microspheres) under normal operating conditions and during abnormal conditions such as a launch abort or re-entry. The first use of the new RTG occurred in 1968 when NASA launched a Nimbus B weather satellite carrying two SNAP-19B RTGs from Vandenberg Air Force Base.

Approximately two minutes after lift-off, the rocket, carrying the satellite and its SNAP-19B RTGs, veered off course, prompting a mission-abort command. The abort-induced explosion destroyed the launch vehicle, after which the two RTGs fell into the Santa Barbara Channel just north of San Miguel Island off the coast of California. Five months later, the SNAP-19B units were recovered – intact – from the ocean floor at a depth of approximately 300 feet (90 meters). The SNAP-19B heat sources had performed as designed and were returned to Mound Laboratory, where the fuel was recovered and reused in a later flight.

In April 1969, NASA successfully launched a Nimbus-3 weather satellite, again carrying two SNAP-19B RTGs. The Nimbus-3 weather satellite marked the first successful use of an RTG by NASA, thus beginning a partnership with nuclear technology that soon found itself on the moon.[9]

As part of the Apollo scientific missions in the 1970s, several science stations (i.e., Apollo Lunar Surface Experiments Packages) were placed on the moon. Beginning with the second lunar landing, a new RTG (SNAP-27) was used to power the experiments packages. Built by General Electric (GE) under an AEC contract, the SNAP-27 design employed the lead-telluride thermoelectric conversion technology used by the Martin Company in previous SNAP RTGs but in a system that was designed to have the heat source inserted on the moon. Similar to other Martin RTGs, the thermoelectrics were produced by 3M. Designed for a power output of approximately 63.5 We, a total of five SNAP-27 RTGs were eventually used in that capacity. All of the systems worked exceedingly well and provided power to more than 50 scientific experiments, as well as to the communications equipment that relayed data back to Earth, until the Apollo Lunar Surface Experiments Packages were shutdown in 1977.[4]

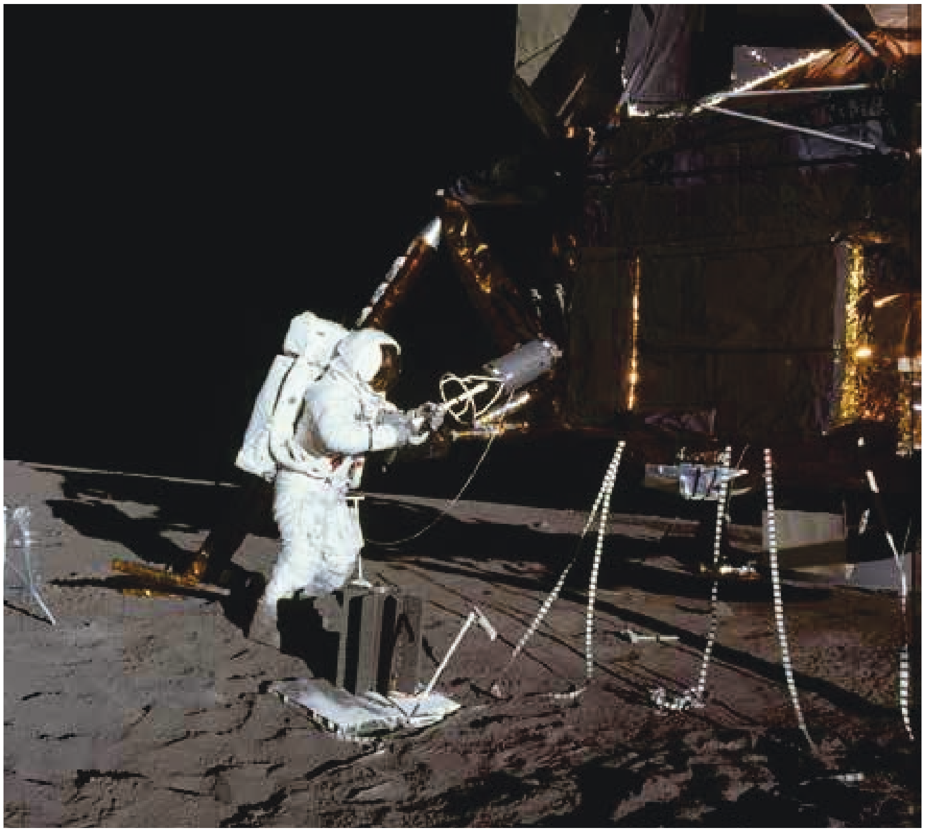


SNAP-19B intact re-entry heat sources fabricated at Mound Laboratory to power the nuclear generators for the Nimbus-B advanced weather satellite. (Photo: DOE Flickr)

Although never deployed on the moon, another SNAP-27 RTG was launched aboard the ill-fated Apollo 13 mission in 1970. Following an explosion on the main craft, the lunar module (with the SNAP-27 RTG onboard) was jettisoned from the command module upon return to Earth. During re-entry, the lunar module disintegrated and the RTG fell into the Pacific Ocean in the vicinity of the Tonga Trench. Subsequent monitoring found no detectable radioactivity, indicating that the RTG had survived re-entry intact.

Although used during the Apollo missions, the SNAP-27 RTGs were not the first use of nuclear energy on the moon. On the first Apollo mission, the Early Apollo Scientific Experiment Package deployed by Neil Armstrong and Edwin “Buzz” Aldrin included two radioisotope heater units (RHUs), each providing 15 watts of thermal power to keep the experiment warm during the long (14 Earth-days) and cold lunar nights. The experiment package used solar cells for electrical power, which meant that the experiments shut down during the lunar night.[10]

During this same period, NASA also found nuclear power sources to be useful in space exploration beyond the moon. Pioneer 10 was launched in March 1972, and Pioneer 11 in April 1973, to travel beyond the asteroid belt, fly past Jupiter, and leave the solar system. Each spacecraft carried four 40-We SNAP-19 RTGs and 12 RHUs, each designed for a heat output of one watt, to protect instruments and thrusters from low temperatures.[10] Solar panels were unworkable for these missions because the energy available from the sun at such a great distance was insufficient to power the spacecraft's systems and experiments. The RTGs performed perfectly, supplying power long after the original 30-month missions had been achieved.[3] Radio contact with Pioneer 11, which passed by Saturn as well as Jupiter, stopped in November 1995. The radio signal from Pioneer 10 was finally lost in January 2003, over 30 years after it was launched. The space probes, powered solely by the RTGs, provided invaluable information about Jupiter, Saturn, and the outer solar system. As one NASA historian wrote, "The program, perhaps this is an understatement, was a huge success. Such success would not have resulted without the four RTGs on each spacecraft providing power."[4]



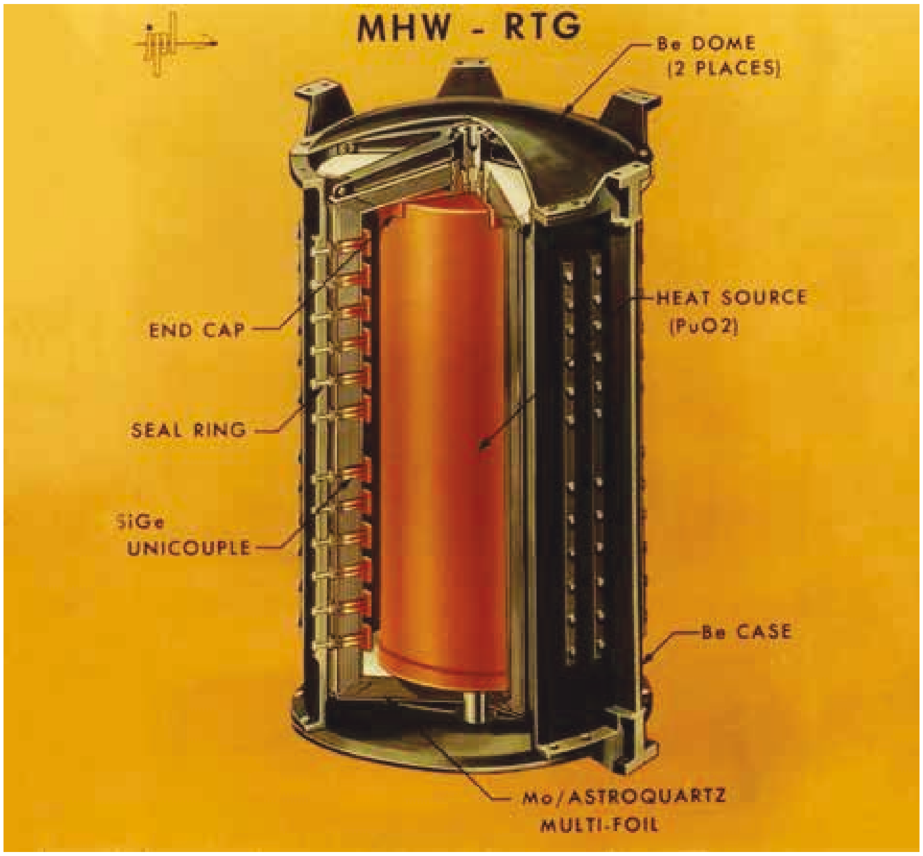
Apollo 12 mission with astronaut Alan Bean removing the SNAP-27 heat source from its carrying cask to insert it into the RTG housing. (Photo: NASA.gov)

After the Pioneer missions, NASA continued its use of RTGs when it sent two landers to Mars in 1975. Viking 1 and Viking 2, each powered by two SNAP-19 RTGs, were launched in August and September 1975, respectively. Originally designed to operate in the vacuum of space, the SNAP-19 RTGs had to be modified to operate in the atmosphere of Mars. NASA chose RTGs over solar panels because of the threat of dust collecting on the panels, reducing power generation. The RTGs enabled the characterization of the Martian environment, the transmission of thousands of pictures from the Martian surface, and the first testing of the Martian surface, and they operated for years beyond their original 90-day requirement.[3] Communication with the Viking 2 Lander was lost in April 1980, and the Viking 1 Lander in November 1982.[11]

As RTGs provided power for NASA missions throughout the 1970s, the technology again found application aboard a Navy navigation satellite in 1972. In the first of a series of three experiments designed to test a radiation-hardened satellite and demonstrate other improvements, the Transit-RTG was used aboard the TRIAD experimental satellite launched on September 2, 1972, from Vandenberg Air Force Base. The Transit RTG used a SNAP-19 heat source to provide approximately 37 We as the primary power source for the satellite. The system operated as designed for about one month, at which time a telemetry-converter failure precluded further monitoring of the RTG power level. Continued operation of the satellite for several years thereafter, however, indicated the RTG continued to provide power.[10]

John Hopkins University-Applied Physics Laboratory personnel install the nuclear heat source into the Transit RTG. (Photo: JHU-APL)

A model of the AEC-developed fuel capsule for each of the four SNAP-19 nuclear generators to power the NASA Pioneer spacecraft to Jupiter in early 1972 is displayed by Bernard J. Rock. (Photo: DOE Flickr)



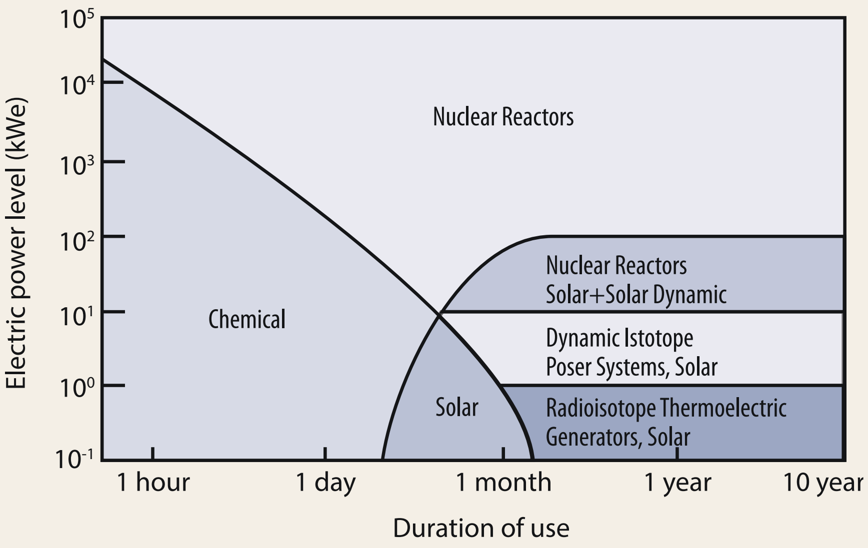
A Changing Landscape

While the Apollo, Pioneer, and Viking missions of the 1970s were hugely successful, the decade brought a major change to U.S. nuclear research. As a result of the Energy Reorganization Act of 1974,[12] the AEC was abolished and its functions split between a new Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission. Two years later, ERDA, along with the Federal Energy Administration, the Federal Power Commission, and other agencies, were integrated into a new Department of Energy (DOE) upon enactment of the DOE

Cutaway of the multi-hundred watt RTG. (Image: INL RPS Program)

Power Systems for Space

Qualitative regimes (power vs. duration) where different space power systems are generally applicable. Nuclear power sources are particularly applicable to long-duration and, especially in the case of nuclear reactors, high-powered missions. Nuclear power systems also have the benefit of lower vulnerability to harsh environments (e.g., natural radiation around Jupiter, meteoroids, or Mars dust storms).



Organization Act of 1977. The new department began operations on October 1, 1977.

Space nuclear power applications were not ignored when these changes were taking place in the Executive branch. Efforts were spent developing advanced thermoelectric materials such as selenides, with the hope of increasing the overall power conversion efficiency of thermoelectric generators. Building on work that began in the early 1960s, NASA and DOE began new development efforts associated with technologies that utilized Brayton and Rankine thermodynamic cycles, as interest in the higher efficiency of dynamic power conversion was renewed. In addition to ongoing research and development, DoD turned once again to RTG technology.[a]

> The grand finale of RTG flights in the 1970s was one of the most daring space missions ever undertaken — a pair of spacecraft known as Voyager 1 and Voyager 2.

On March 14, 1976, the Air Force successfully launched Lincoln Experimental Satellites 8 and 9, each of which was powered by two multi-hundred watt (MHW) RTGs. Designed by GE, the MHW-RTG provided 157 We at the beginning of the mission. The use of silicon-germanium thermocouples, rather than the lead-telluride thermoelectrics used in the SNAP-19 RTGs, allowed operation at a higher temperature, which improved overall efficiency. With the higher temperature, the MHW-RTG provided a significant improvement in specific power (4.2 We/kilogram) over the SNAP-19 (3 We/kilogram). The satellites were launched aboard the same launch vehicle but were subsequently moved into separate orbits. Once in orbit, the satellites linked with each other and with surface terminals to provide communication across more than three quarters of the surface of Earth.[3]

The grand finale of RTG flights in the 1970s included one of the most daring space missions ever undertaken — a pair of spacecraft known as Voyager 1 and Voyager 2. Launched in August and September of 1977, respectively, the Voyager 1 and Voyager 2 spacecraft were each powered by three MHW-RTGs that provided a total of 475 We. Each spacecraft also carried nine 1-Wt heater units similar to those used on Pioneer. The MHW-RTGs enabled the Voyager spacecraft to operate for extended mission lifetimes, making it possible to explore Jupiter, Saturn, Uranus, and Neptune. It was the longest mission ever planned at that time. The dramatic photographs sent back from Voyager impressed the public, and the new data from the missions changed scientists' understanding of the solar system.[3] As of 2014, the Voyager spacecraft were still working after more than 34 years of service, continuing to send scientific data back to Earth —Voyager 1 from interstellar space and Voyager 2 from the edge of our solar system.

As the 1970s drew to a close, the NASA space program maintained a high profile in spite of the termination of the Apollo lunar missions. The Viking missions to

a. Efforts undertaken by DOE (and its predecessors) and NASA to develop advanced thermoelectric materials and dynamic isotope power systems are described in Chapter 3, Advanced Isotope Power Systems.

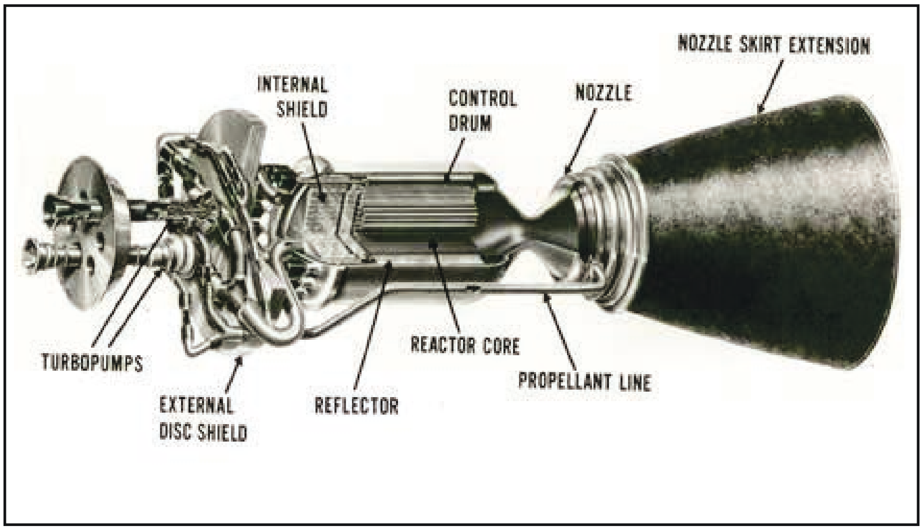
Mars and the Voyager missions to the outer planets kept space exploration in the public eye and helped maintain research and development funding. The advancement of RTG and heat source technology led to safer and more powerful RTGs. However, space radioisotope and reactor power systems were not the only focus for DOE and its predecessors in those early years. In an effort largely parallel to the SNAP program, a considerable effort was also devoted to the development of technology for space-based nuclear thermal propulsion as well as nuclear electric propulsion.

A Rocket Named Rover[b]

Like its nuclear power counterpart, development of a nuclear thermal propulsion system had its origins in 1955, when the possibility of using a nuclear reactor as a propulsion system for ballistic missiles found renewed interest within the Air Force and AEC. That interest had been spurred by a 1953 paper by R. W. Bussard in which the case was made for reactor-based rockets being superior to chemical propulsion for heavy payloads. With hopes for such a system, research programs were initiated at Los Alamos Scientific Laboratory (LASL), later renamed Los Alamos National Laboratory (LANL), and Lawrence Radiation Laboratory (LRL), now known as Lawrence Livermore National Laboratory, to develop a nuclear thermal rocket for use in a propulsion system for ballistic missiles.[13]

Although the AEC laboratories initially worked in parallel, funding limitations led to the consolidation of all reactor work to LASL in early 1957. Ironically, the new LASL effort was named Rover, the name by which the former LRL nuclear rocket division had called itself (LRL was subsequently given responsibility for work on a nuclear ramjet program called Pluto[14]).

As the new Rover program got underway, the Nuclear Rocket Development Station was developed to support testing of nuclear rockets. The station was located in the southwest corner of the Nevada Test Site in an area known as Jackass Flats. It served as the center for U.S. nuclear rocket propulsion testing from 1958 to 1973. It became home to an infrastructure that eventually included three reactor test cells/stands; two maintenance, assembly, and disassembly buildings[15] (one for reactors and the other for nuclear



Rover rocket concept. (Image: grin.hq.nasa.gov)

b. For a detailed account of the Rover and NERVA programs, see "To the End of the Solar System – The Story of the Nuclear Rocket" by James A. Dewar.

engines); a technical operations complex; and various support buildings. Reactors were moved between the assembly/disassembly and test facilities via a railroad, humorously referred to as the "Jackass and Western Railroad." Years later, while speaking of his days managing the Rover program for AEC and NASA, Harold Finger was quick to note that "Jackass Flats is where we did our reactor and engine testing, but it is not descriptive of nor named for the people working on the program here."[16]

While the reactor research work was initially performed under the auspices of AEC and the Air Force, defense missions soon gave way to a civilian space focus. By the late 1950s, DoD had dropped further work on nuclear-powered ballistic missiles. Responsibility for nuclear rocket work was subsequently transferred to the newly formed NASA in 1958. While the new space agency assumed overall responsibility for the Rover program, the responsibility for its nuclear aspects remained with AEC. Responsibilities between the two agencies were formally established, as was a joint Space Nuclear Propulsion Office (SNPO), upon the signing of a Memorandum of Understanding in August 1960.[16]

Over time, the Rover program grew to include five major elements: 1) a reactor and fuel-development effort, called Kiwi, conducted by LASL and Rocketdyne; 2) a nuclear engine development project supported by Aerojet and Westinghouse; 3) development of advanced reactor designs, called Phoebus and Pewee, by LASL; 4) a reactor-in-flight test project run by Lockheed; and 5) a nuclear furnace fuel-testing project operated by LASL. Although each subproject had different objectives, they were all designed to lead to a high-powered nuclear thermal propulsion system with demonstrated reliability. Such a task would prove to be easier said than done, however, when considered in the light of the description offered years later by Glenn T. Seaborg, then Chairman of AEC:

"...What we must do is build a flyable reactor, little larger than an office desk, that will produce the 1,500 megawatt power level of Hoover Dam and achieve this power in a matter of minutes from a cold start. During every minute of its operation, high-speed pumps must force nearly three tons of hydrogen, which has been stored in liquid form at 420°F below zero, past the reactor's white-hot fuel elements, which reach a temperature of 4,000°F. And this entire system must be capable of operating for hours and of being turned off and restarted with great reliability."[17]

Ground Testing the Kiwi Reactors

The first step toward a nuclear thermal propulsion system involved a series of reactor tests called Kiwi, named after the flightless bird because they were only intended for ground testing and not for flight. The Kiwi tests were designed to demonstrate concept feasibility and basic nuclear rocket reactor technology such as high-temperature fuels and long-life fuel elements. The Kiwi reactors were designed to demonstrate reactor and fuel feasibility first at a power level of 100 megawatts of thermal power (MWt) (Kiwi-A reactor series) and then at a power level of 1,000 MWt (Kiwi-B reactor series). To that end, the Kiwi test series sought to establish basic testing procedures, demonstrate that a high-power-density reactor could heat a propellant quickly and to high temperatures, and determine material interactions at the high operating temperatures.

From July 1959 to October 1960, three Kiwi-A test reactors (Kiwi-A, Kiwi-A' [A-prime], and Kiwi-A3) were tested. Although testing revealed problems in reactor and fuel design, the problems were addressed and the feasibility of a 100-MWt reactor design had been demonstrated. By the end of 1960, LASL had also completed the first Kiwi-B reactor design using much

Kiwi-A reactor on a transfer cart. Note the Kiwi bird depicted on the side. (Photo: LANL Flickr)

of the technology foundation established during the Kiwi-A tests. In addition, NASA had initiated the reactor-in-flight test program, looking forward to the day when the first nuclear rocket might be launched.

Amidst this progress, an event in Earth's orbit soon brought additional impetus to the young reactor development program. On April 12, 1961, the Soviet Union sent Yuri Gagarin into orbit above the Earth, the first man ever to do so. The early successes and ongoing expansion of the Soviet space program were not taken lightly, and an American response quickly followed. On May 25, 1961, newly elected President John F. Kennedy spoke before a joint session of Congress. The speech, which famously included a commitment to go to the moon within the decade, also included a commitment to the Rover program:

"...Secondly, an additional 23 million dollars, together with 7 million dollars already available, will accelerate development of the Rover nuclear rocket. This gives promise of some day providing a means of even more exciting and ambitious exploration of space, perhaps beyond the moon, perhaps to the very end of the solar system itself."[18]

Kennedy's commitment soon turned to action. In June 1961, NASA and AEC awarded a contract to Westinghouse and Aerojet for the Nuclear Engine for Rocket Vehicle Application (NERVA) program. The goal of NERVA was to demonstrate a nuclear-powered rocket for flight testing based on the Kiwi-B reactor design. While NERVA referred to the entire rocket engine, including the reactor and the various propulsion components, the overall development program continued to be referred to as Rover.

With the NERVA program up and running, attention soon returned to the Kiwi reactor testing. Between December 1961 and September 1964, five Kiwi-B reactor tests (Kiwi-B1A, Kiwi-B1B, Kiwi-B4A, Kiwi-B4D, and Kiwi-B4E) were conducted in the ongoing effort to demonstrate the feasibility of a nuclear rocket. As with the Kiwi-A series, testing revealed problems with reactor and fuel design. One notable example was the Kiwi-B4A test conducted in November 1962. Although the liquid hydrogen startup was successful, *"...paralleling the rapid*

With the NERVA program up and running, attention soon returned to the Kiwi reactor testing.

increase in power was a rapid increase in the frequency of flashes of light from the nozzle; on reaching 500 megawatts, the flashes were so spectacular and so frequent that the test was terminated and shut down procedures began. Initial disassembly confirmed that the flashes of light were reactor parts being ejected from the nozzle; further disassembly and analysis revealed that over 90 percent of the reactor parts had been broken, mostly at the core's hot end."[17]

President John F. Kennedy speaking before Congress, May 25, 1961. (Photo: NASA.gov)

Unfortunately, the test had another unintended consequence. After visiting the test site, President Kennedy decided to slow down flight testing activities until the cause of the reactor failure was addressed, and a follow-on test successfully completed. The program was subsequently put on hold by SNPO in January 1963 when Harold Finger, then manager of SNPO, insisted that cold (non-nuclear) flow tests be completed before nuclear testing resumed. He was adamant that the problem be thoroughly understood and corrected before hot testing resumed.

Subsequent cold testing showed that the extremely high flow rate of hydrogen propellant through the reactor had caused severe vibration within the core, which in turn caused cracking of the fuel elements. After appropriate changes to the core design were completed, SNPO authorized resumption of hot testing, which resumed with Kiwi-B4D. The final Kiwi test, Kiwi-B4E, was successfully performed in September 1964. Having operated the rocket engine at nearly full power for 2.5 minutes, comparable to the performance of a chemical rocket, AEC and its contractor team had demonstrated the feasibility of the 1,000-MWt nuclear thermal reactor. Materials and operational issues were no longer an issue, and the final Kiwi-B design provided a baseline that was used in subsequent efforts to develop an integrated NERVA nuclear rocket.[17]

More importantly, cost estimates for the nuclear rocket flight program continued to escalate. As a result, the planned flight demonstration was canceled in late 1963.

The final Kiwi experiment, Kiwi-TNT, was a deliberate destructive test of a Kiwi reactor that had been modified to allow a rapid, large, positive reactivity – a sudden burst of power that exceeded the reactor design limits. Conducted in 1965, the test was designed to learn what would happen under an extreme reactor event and provide information on the energy produced in the reactor core and the energy released during the subsequent excursion, including the dispersion of fission products. Although such testing would be extremely unlikely under modern regulatory and safety environments, the test provided real data to support safety and accident analyses of interest to the Rover flight program. For example, the reactor core reached a temperature of approximately 2,160 Kelvin and generated a total number of fissions that approached 3.1×10^{20}. Only about 50 percent of the core material could be accounted for within a 25,000-foot (7,600-meter) radius; the remainder was presumably burned in the air or dispersed downwind. The heaviest piece of debris, a section of pressure vessel weighing approximately 150 pounds (70 kilograms), was located 750 feet (229 meters) from the reactor; smaller pieces of the core were found at even further distances.[17]

Developing a NERVA Flight Engine

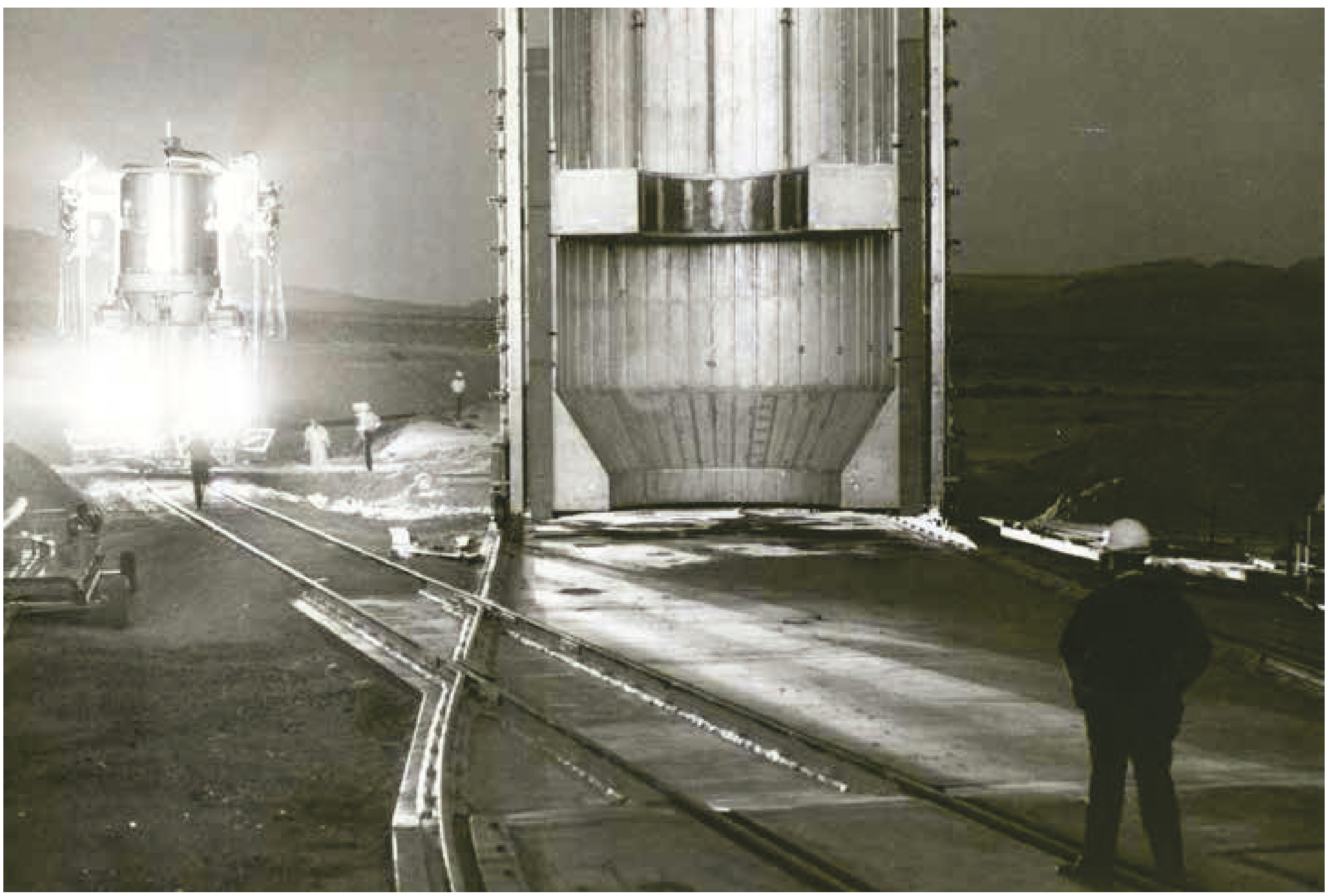
Regardless of the success of the Kiwi tests and tentative plans for use of a nuclear rocket by NASA, the Rover program began to fall victim to declining budgets and changing priorities in the early 1960s. More importantly, cost estimates for the nuclear rocket flight program continued to escalate. As a result, the planned flight demonstration was canceled in late 1963, which led to a redirection of NERVA away from the qualification of a specific engine system and toward a program of general nuclear rocket technology improvement. Then began a series of full-power reactor tests in early 1964 that continued to move the nuclear rocket concept down a path of development.

The shift in NERVA to a technology improvement program in 1964 resulted in the redefining of its program goals, including operating

NERVA engine mockup. The spheres at the top contained hydrogen which, after passing through the reactor (center), was discharged out the nozzle (bottom of picture). (Photo: LANL Flickr) for 60 minutes at full power; restarting at any point in the reactor's life cycle; demonstrating rapid temperature increases and decreases; cooling down using only liquid hydrogen; startup of the engine without an external power source; and determination of system operational margins, limits, and reliability.[17]

Major contractors involved in the NERVA program included the Rocketdyne Division of North American Aviation (later part of Boeing), which was responsible for building a liquid hydrogen turbopump and nozzle; Aerojet, responsible for a flow control system; ACF-Erco, responsible for manufacturing the pressure shell; and EG&G, Inc., which was responsible for producing instrumentation. Construction of the nuclear reactor was the responsibility of the Westinghouse Electric Corporation Astronuclear Laboratory.[17]

With program goals and the project team established, nuclear rocket engine testing began in September 1964 under the name Nuclear



The first ground experimental nuclear rocket engine (XE) assembly (left) is shown here in cold flow configuration, as it makes a late evening arrival at Engine Test Stand No. 1 at the Nuclear Rocket Development Station in Jackass Flats, Nevada. (Photo: grin.hq.nasa.gov)

Rocket Experimental (NERVA NRX). Over a period of three years, four tests were conducted (NRX-A2, NRX-A3, NRX-A5, and NRX-A6). The NRX test series led to testing of the first down-firing prototype nuclear rocket engine, XE-Prime.

From December 1968 through September 1969, XE-Prime was successfully operated over a period of 115 minutes with 28 separate restarts, thereby demonstrating the feasibility of an integrated 1,000-MWt nuclear rocket engine.

Phoebus 1A reactor at LANL, 1965. (Photo: LANL Flickr)

Phoebus, Pewee, and the Nuclear Furnace

As visions of space travel turned again to a manned trip to Mars (long a goal within NASA), a program was initiated to develop advanced reactors capable of power levels on the order of 5,000 MWt. Conducted in parallel with the NERVA program, the Phoebus and Pewee reactors were designed and tested by LASL for such operation. Phoebus, a 5,000-MWt prototype reactor, was first tested in 1965. By 1968, Phoebus' final version (the most powerful nuclear rocket ever built) ran at over 4,000 MWt for more than 12 minutes.[17] The Pewee reactor was a small test bed used to test full-size Phoebus and NRX fuel elements and other components, allowing components to be developed in parallel to reduce lead times and costs.

As restrictions on radioactive emissions began to tighten, the Nuclear furnace was built to allow testing without releasing radioactivity into the atmosphere. The furnace was a modular 44-megawatt reactor, where the core portion could be switched out for separate experiments.[17] The reactor effluent filters produced a hydrogen jet without detectable fission products.[19]

Accomplishments and the Face of Changing National Priorities

As the Rover program turned the corner on a new decade, it soon found itself facing a very different future. After the urgency of reaching the moon passed and the Apollo missions ended in 1972, it became clear that a manned Mars mission wouldn't be the next step. Due to changing priorities on national budgets, further development of the NERVA nuclear rocket was terminated in the fiscal year 1972 budget.

From 1955 to 1971, the United States spent approximately $3.5 billion (in 1960 dollars) on the Rover and NERVA programs[19] (compared with $19.4 billion spent on the Apollo program from 1960 through 1973[20]). During that period, 17 reactors, one nuclear safety reactor, and two ground experimental engines were developed and tested. The feasibility of a solid graphite reactor/nuclear rocket engine had been clearly established "...at temperature, pressure, power levels, and durations commensurate with today's [1991] propulsion system requirements..." The technology had also been demonstrated to an extent such that "…future nuclear propulsion development associated with new space exploration initiatives can be directed to incremental performance, reliability and lifetime improvements." In addition, the Rover program demonstrated a model by which two government agencies could effectively manage a major technology development program.[21]

100-MWt Kiwi-A reactors to the 4,000-MWt NERVA XE reactor through 20 different reactor tests.

Against the backdrop of such technical accomplishments, lessons had been learned that provided a foundation for future

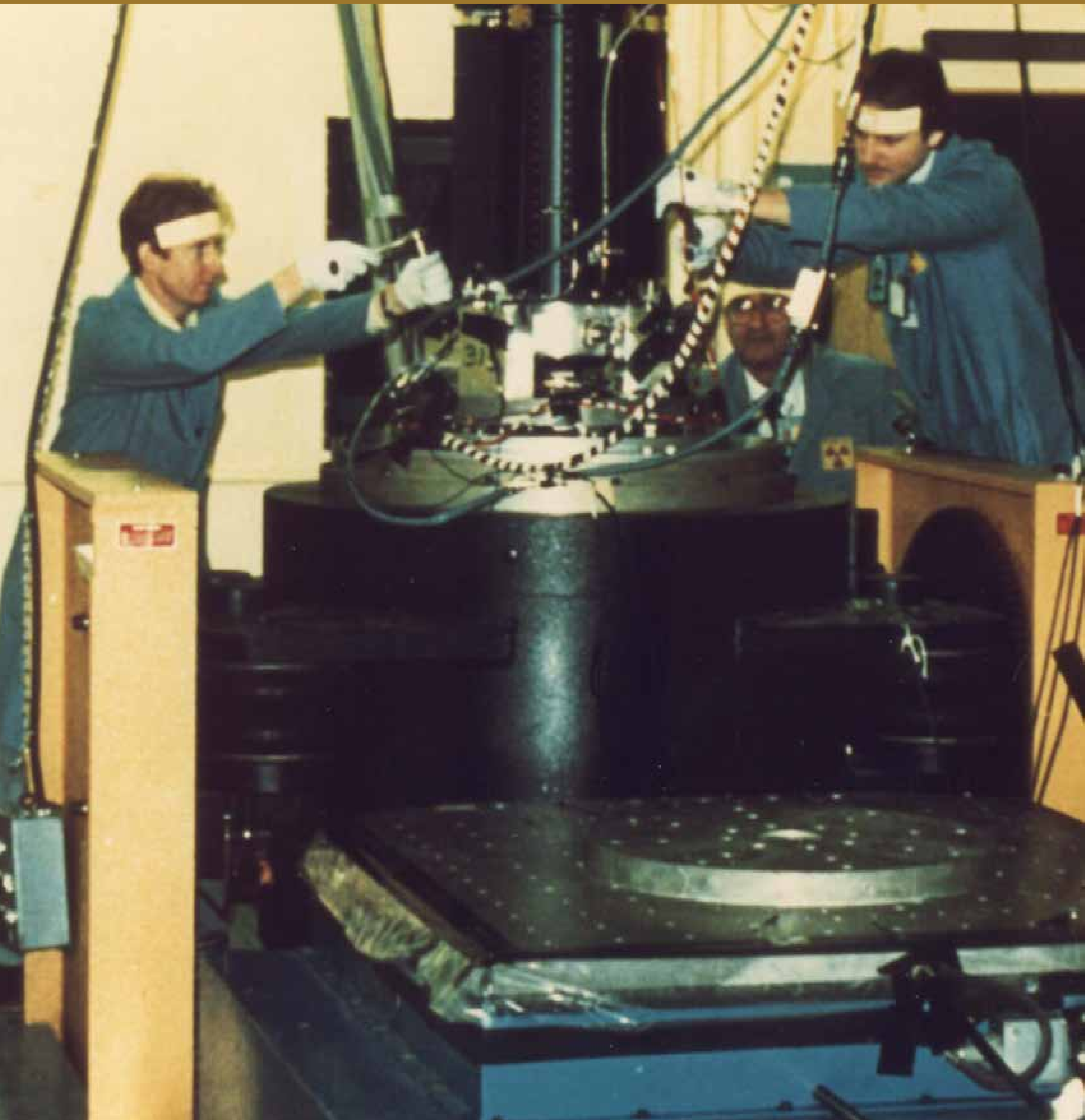
Against the backdrop of such technical accomplishments, lessons had been learned and provided a foundation for future development.

Looking Forward

As the first 30 years of space nuclear power drew to a close in the mid-1980s, DOE, NASA, and others had many reasons to celebrate. Thirty-five RTGs, ranging in power from the small 2.7-We SNAP-3B unit to the 157-We MHW-RTG, had been successfully launched into space to power lunar experiments and planetary orbiters, while other spacecraft were on their way to the end of the solar system. Multiple space RPS concepts had been developed and tested under the SNAP program, and one space nuclear reactor power system had been successfully placed into Earth's orbit. On the nuclear rocket front, the feasibility of nuclear thermal propulsion had been successfully demonstrated, evolving from initial testing of the

development. In addition, an entire infrastructure had been built across the DOE complex to support ongoing development, testing, and use of space nuclear systems. Most importantly, a new technical discipline had been defined, an industry established, and a foundation laid that would allow a new generation of space nuclear technologists to carry the torch of space nuclear power into another 30 years of testing, development, and accomplishments.

The evolution of RTG technology through the 1970s well represented the idea of taking something good and making it better. Looking back, however, we see that the best was yet to come.



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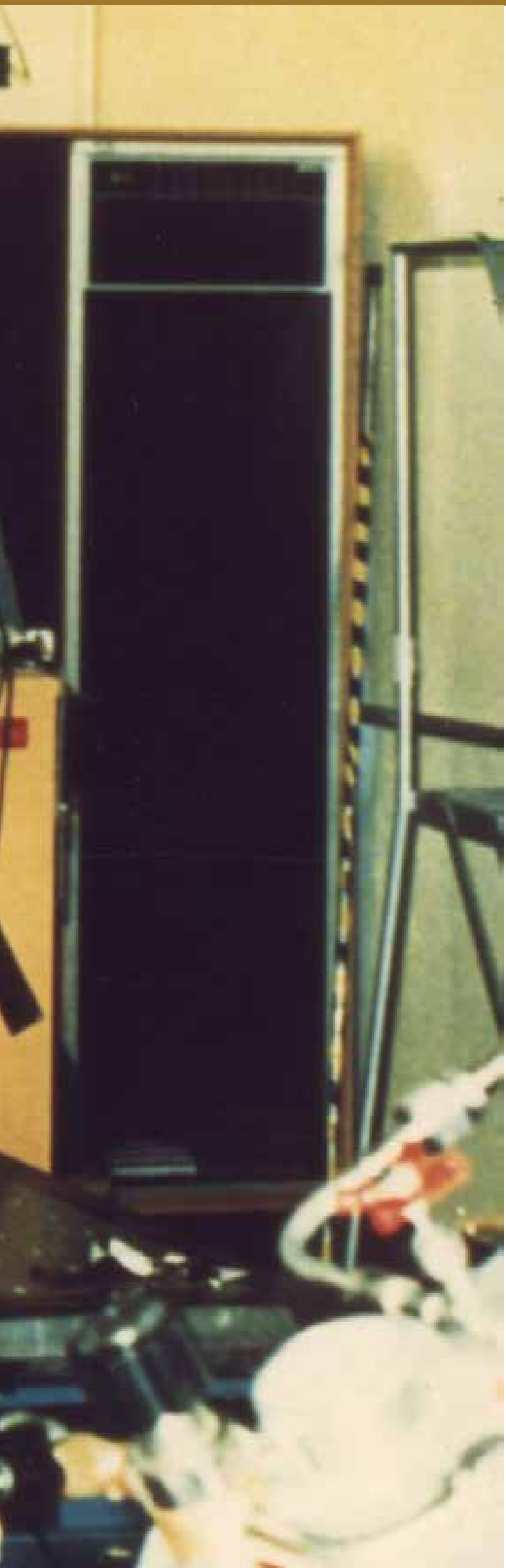
Galileo and Ulysses
The General Purpose Heat Source RTG



Following their conception in 1954, RTGs evolved from the small, 2.7-We SNAP-3B system in 1961 to the MHW-RTG unit that generated a nominal 157 We. Improvements were made in the fuel form, thermoelectrics, and safety aspects of these static power systems. The evolution of the "quiet technology" of the RTG through the 1970s well represented the idea of taking something good and making it better. Looking back, however, we see that the best was yet to come.[1]

At the end of a 12-year period during which DOE and NASA prepared for the parallel missions of Galileo and Ulysses, the pull of ingenuity and the push to look at the old ways of doing things in new, creative ways led to the development of the most powerful RTG ever to be used in space applications. The general-purpose heat source (GPHS)-RTG, as it came to be called, would prove to be the most efficient RTG ever built (as well as the unit with the highest specific power) and would power NASA missions for decades to come.

Powering New Missions

While the MHW-RTGs were performing as planned on their Earth-satellite and outer solar-system missions, DOE continued its efforts to advance RTG technology throughout the 1970s. Those efforts were centered largely on the development of advanced thermoelectric materials called selenides, which were to replace the silicon-germanium materials used in the MHW-RTG; a new modular heat source, the GPHS; and an improved MHW heat source that featured improved iridium-alloy fuel cladding and advanced graphitic materials for the aeroshell.[2, 3, 4]

The new GPHS was being developed at LANL for use in a wide range of power conversion systems, power levels, and space missions. With a focus that included improved safety, development plans for the new heat source included an extensive safety testing and qualification program.[5, 6]

While advances in heat source technology sought to improve safety, advances in thermoelectric materials sought to improve the overall efficiency by which thermal power was converted to useable electricity. To that end, Teledyne Energy Systems (TES) was working on advanced

The Galileo and Ulysses missions marked the beginning of new assembly and testing operations at Mound, circa 1985. (Photo: Mound Museum Association) power conversion technology using selenide-based thermoelectric materials under development at the 3M Corporation. Early laboratory-scale testing of the selenide materials indicated potential conversion efficiencies of at least 10 percent, which represented a hopeful improvement of approximately 50 percent above that of the silicon-germanium materials used in the MHW-RTG. Amidst such favorable expectations, DOE planned to develop a new RTG (called the selenide isotope generator [SIG]) that would eventually utilize the new selenide thermoelectric materials and the new GPHS.[7]

The first phase in developing the SIG would combine the selenide thermoelectrics with a MHW heat source for use on a mission that came to be called Galileo (initially called Jupiter Orbiter Probe), named after the 17th-century Italian astronomer who discovered four of Jupiter's moons. Long-term surveys of Jupiter would be made using an RTG-powered orbiter, while a smaller probe would collect atmospheric and other information about the gas giant during a one-time pass through its atmosphere.[8]

The next phase in SIG development would combine the selenide thermoelectrics with the new modular GPHS for use on a multi-national mission originally called the International Solar Polar Mission (ISPM). As conceived, the mission was a joint effort between NASA and the European Space Agency (ESA) to provide the first polar-orbital survey of the sun. Each agency would supply one spacecraft, both powered by RTGs supplied by DOE, to make scientific measurements above and below the ecliptic—the plane of Earth's orbit about the sun. Domestic budget pressures in the early 1980s resulted in cancellation of the NASA spacecraft; ESA continued the mission, and it was subsequently renamed Ulysses.[9]

Despite high hopes for the new selenide thermoelectric materials, by 1979, testing of prototypic selenide thermocouples had uncovered significant material-instability and conversion-efficiency issues. After considering its options against mission needs and schedules, DOE decided to abandon further development of the selenide materials and return to the proven silicon-germanium unicouples for the needed RTGs. For the Galileo mission, development of the MHW-RTGs continued but with the proven silicon-germanium thermoelectrics. For the ISPM mission, responsibilities for development of the RTG were subsequently contracted to GE and the new RTG was named (at least briefly) the ISPM, or Solar-Polar, RTG.[6]

With the broader set of mission uses, the ISPM-RTG was soon rebranded the GPHS-RTG, a name that would find its place in the annals of RTG history.

As the developmental success of the ISPM-RTG progressed, changing mission plans for Galileo, which included a desire for more power, eventually gave way to a decision to use the ISPM-RTG in lieu of the improved MHW-RTG. With the broader set of mission uses, the ISPM-RTG was soon rebranded the GPHS-RTG, a name that would find its place in the annals of RTG history.[7]

As the dust of program and mission planning settled, DOE was responsible for developing the new GPHS-RTG for use on the two missions. Ultimately, three flight-qualified GPHS-RTGs and one spare unit were needed. The new GPHS, around which the RTG was to be built, was still under development; safety testing and a final design, necessary to demonstrate acceptability for use in space, remained to be completed. In addition, the launch vehicles planned for launching the Galileo and Ulysses spacecraft into space were also still under development. On top of that, the production capability for the silicon germanium unicouples had to be re-established. Years later, the effort to develop the GPHS-RTG would aptly be referred to as a "mission of daring" by many of the individuals directly involved.[10]

As had been performed previously, DOE completed this mission using a small but diverse group of companies and national laboratories, a unique set of technical capabilities and assembly and test facilities, and a group of highly dedicated individuals committed to program success. An interagency agreement signed by DOE and NASA defined the overall roles and responsibilities of the respective agencies. Responsibility for development of the GPHS-RTG resided with the DOE Office of Special Applications.[11]

The General Purpose Heat Source

Initial design and development of the new GPHS resided with LANL but was later enhanced by GE and Fairchild. Design of the new heat source included several goals, one of which was the idea of modularity, in which individual modules could be combined to provide the amount of power required by a specific mission. Another goal was to develop a heat source that would be compatible with multiple static and dynamic power conversion systems. A high power density of at least 75 watts (thermal) per pound was also desired. In keeping with the intact re-entry safety philosophy adopted in the 1960s, the primary safety objective was to keep the fuel contained or immobilized to prevent inhalation or ingestion by people. Ultimately, mission planners had to be confident that the public would be protected in case of any foreseeable accident.[5,12]

The final GPHS design consisted of a rectangular-shaped carbon-carbon module into which the encapsulated fuel would be placed. The design included several protective features to guard against explosions, fires, impacts, projectiles, and the heat of Earth re-entry. These features included the fuel, iridium-alloy metal cladding, fine-weaved pierced fabric (FWPF), and a carbon-bonded, carbon-fiber sleeve component.

GPHS-RTG Development - Key Contractors

The systems contractor for the GPHS-RTG development effort was the Astrospace Division of GE (later incorporated into Lockheed-Martin). Program execution was widely distributed and involved numerous contractors and national laboratories:

System Contractors
- General Electric
- Teledyne Energy Systems

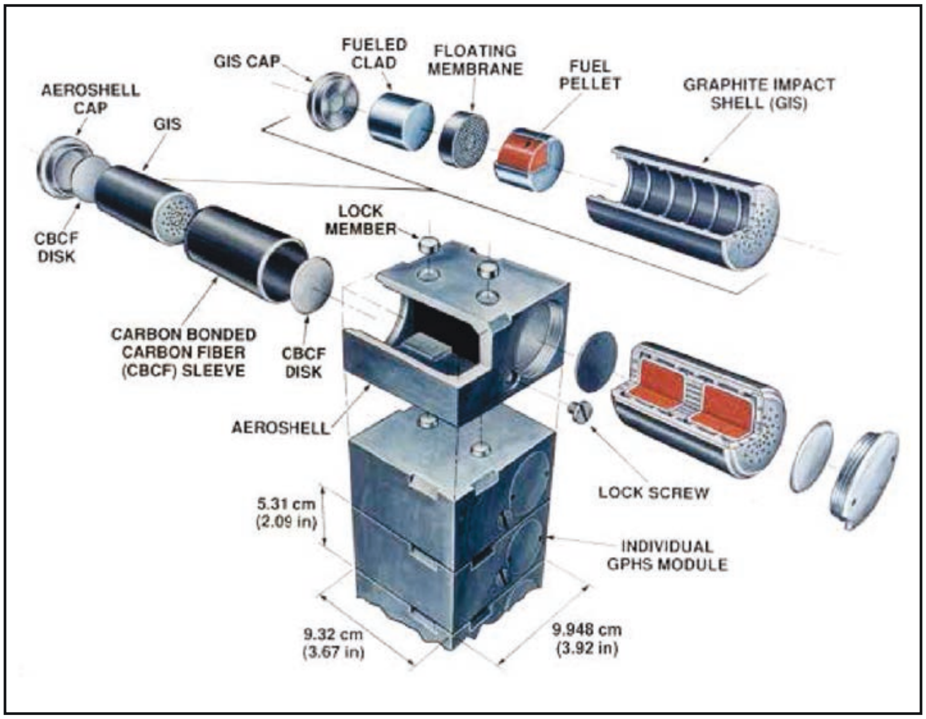
Technical Support
- Fairchild Space Company
- Battelle Columbus Laboratories

Technology
- Ames Laboratory
- General Electric

Safety Organizations
- Applied Physics Laboratory
- Los Alamos National Laboratory
- Naval Ocean Systems Center
- NUS Corporation

Heat Source Production and RTG Assembly/Testing
- Monsanto Research Corporation
- Oak Ridge National Laboratory
- Savannah River Laboratory
- Savannah River Plant

Reliability and Quality Assurance
- Sandia National Laboratories



Cutaway of the GPHS (Step-0). (Image: SNL)

The first protective feature was the fuel itself. The GPHS fuel pellet consisted of approximately 150 grams of plutonium oxide that produced roughly 62.5 watts of thermal power. As with previous RPS fuel, plutonium emits alpha radiation, which is easily shielded and can only become a health concern if it enters the body, such as through ingestion or inhalation. To minimize the risk, the plutonium oxide was produced in a ceramic form similar to the MHW ceramic fuel spheres. The ceramic fuel pellet is chemically stable, has a high melting and vaporization temperature, is highly insoluble, and tends to fracture into pieces generally too big to inhale.

The fuel pellet was encapsulated in a strong iridium alloy metal cladding, another protective feature. Developed at the DOE Y-12 Plant, and referred to as DOP-26, the cladding provided high material strength while retaining good ductility, a physical property that allows a metal to bend and stretch, without breaking under conditions of high strain. The iridium alloy is also chemically compatible with the plutonium oxide fuel and graphite components and has a high melting temperature. Its resistance to oxidation also provides for good post-impact protection. A small frit vent, welded into one end of the iridium cladding, allows helium gas produced from the radioactive decay of the plutonium fuel to escape while retaining the plutonium, thereby precluding the buildup of pressure that could crack or breach the cladding. The fuel clad set, commonly referred to as a fueled clad, has the shape of a cylinder with rounded edges and is approximately one inch long and one inch in diameter.

A third protective feature of the new heat source was the use of FWPF in several components, including impact shells and the GPHS module. The impact shells provide protection from projectiles and debris, and impacts on the ground. A final protective feature was the use of a carbon-bonded carbon-fiber sleeve component, which serves to protect the fueled clads against high temperatures associated with launch vehicle fuel fires and the heat that results during atmospheric re-entry, such as might occur following a failure in space. Fully assembled, a GPHS module containing four fueled clads weighed approximately 3.3 pounds (1.5 kilograms) and generated approximately 250 watts of thermal power.

The GPHS-RTG

As design and development of the new heat source progressed, so did the new power conversion unit. Developed by the GE Astrospace Division, the GPHS-RTG consisted of a structural housing inside of which 572 interconnected silicon-germanium thermoelectrics, called unicouples, converted heat into useable electricity. The housing in which the thermocouples were located was constructed of aluminum and designed to support a stack of 18 GPHS modules. The selection of aluminum for the housing was part of the overall safety design of the system, ensuring that it would readily melt if exposed to the high temperatures of re-entry, and that the GPHS modules would be released as individual units. Other design features included the use of eight heat rejection fins, electrical power connectors, and externally mounted cooling loops that could provide cooling for the RTG when located inside a confined area such as the space shuttle cargo bay.

As GE transitioned into production of the new power conversion system, it needed a production capability for silicon-germanium thermocouples. The production capability, originally established by Radio Corporation of America (RCA) in support of the Voyager and Lincoln Experimental Satellites-8 and -9 missions, had been shut down following these missions. Thus, GE had to re-establish a new production capability that duplicated the RCA process.

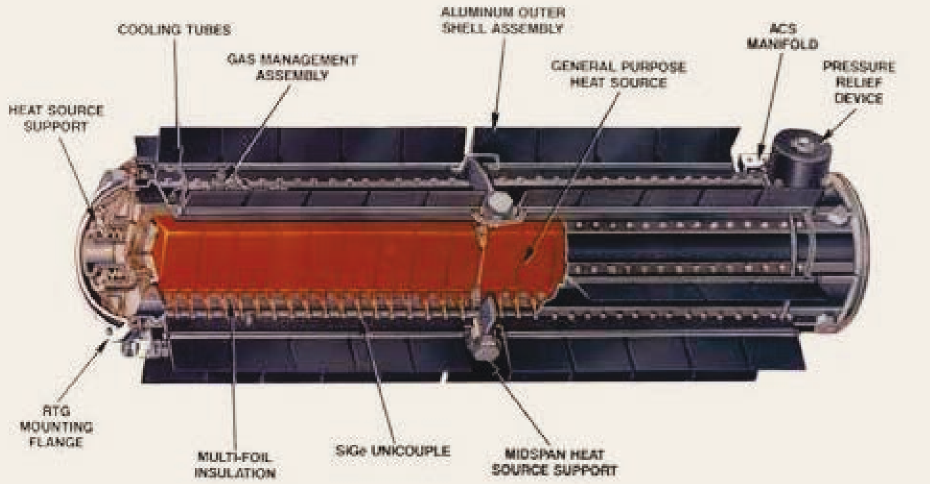
As design and development of the new heat source progressed, so did the new power conversion unit.

The process by which the small silicon-germanium thermoelectric elements had been made by RCA consisted of several steps, each of which had to be re-established.

Replication of the RCA process was not without its challenges. For example, it was discovered that the production practices employed by RCA personnel had embellished upon documented specifications and processes; as a result, the additional practices and other changes required incorporation into production

GPHS-RTG Specifications

The GPHS-RTG generated approximately 300 We from the nominal 4,400 watts of thermal heat generated by its 18 GPHS modules. Fully assembled, the GPHS-RTG was approximately 16 inches (0.4 meters) in diameter and 43 inches (1.1 meters) long, and weighed approximately 123 pounds (56 kilograms), resulting in a specific power of approximately 5.4 We per kilogram when first assembled. (Image: SNL)



procedures to improve process rigor and control.[13] For the four GPHS-RTGs planned for the Galileo and Ulysses missions, over 2,000 individual unicouples were eventually fabricated for use in the units. Additional unicouples were also produced for the engineering and qualification units used to demonstrate readiness of the RTG for flight use, as well as for an unfueled spare converter.

Along with re-establishing the production process for the unicouples, GE conducted a rigorous testing program to address all facets of the power conversion system and the fully assembled RTG. Testing was performed in a progressive manner, beginning with individual unicouples followed by 18-couple modules. The unicouple testing was followed by tests of full-scale component engineering test units for structural, thermal, and material properties, which demonstrated the design of an electrically heated engineering unit. Non-nuclear testing of the engineering unit included thermal and vibration tests to ensure the thermoelectrics and other components of the power conversion system would properly operate. Testing culminated with a nuclear-heated qualification unit, which served to verify that the GPHS-RTG would operate as designed and meet all mission requirements.[14]

Guided by Safety

Integral to the design and development of the GPHS-RTG was a rigorous safety testing program, conducted to determine how the heat source would respond to various postulated accident conditions that might occur during launch or once in orbit. For example, a launch vehicle explosion on the launch pad or during ascent might subject the RTG and its heat sources to high-pressure shock waves from liquid and solid fires, launch vehicle and spacecraft fragment impacts, and ground impacts onto steel, concrete, or sand. A late launch accident, such as one involving orbital or suborbital re-entry, might also subject the RTG and its heat sources to high temperatures and subsequent ground impacts. The modular design of the GPHS modules also ensured that the chances of impacts from spacecraft debris would be very low, if not impossible. Subsequent safety testing at LANL and SNL demonstrated the protective safety features of the GPHS module under a variety of postulated accident scenarios.[5, 15]

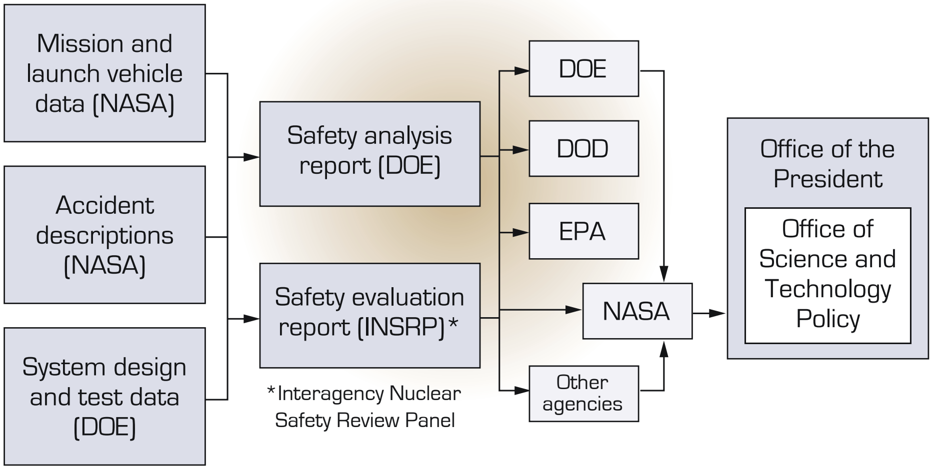
The testing was planned and conducted against a backdrop of evolving mission plans that centered on a new NASA launch vehicle. For the Galileo and Ulysses missions, NASA planned to launch the spacecraft aboard its new space transportation system (STS), which included the space shuttle. Once the shuttle reached its parking orbit, the spacecraft would be released from its cargo bay, and an upper-stage propulsion system would be used to propel the spacecraft towards its destination.

In the evolution of planning associated with the use of the new STS, which was then under development, a decision regarding the specific upper-stage launch vehicle to be used for Galileo and Ulysses changed frequently, alternating between a solid-fuel inertial upper stage and a Centaur rocket that was fueled with liquid hydrogen/liquid oxygen. Each upper-stage vehicle had unique hazards and characteristics that influenced development of the requisite safety analysis. As a result of ongoing changes regarding which upper-stage vehicle to use, a preliminary safety analysis was based on use of an inertial upper stage but was later revised to reflect a Centaur system. As discussed later in the chapter, this would not be the last change in the launch system to be used.[15]

While upper-stage vehicle planning perturbations were frustrating, tests were nonetheless devised to simulate a broad range of possible pressures, temperatures, and other environmental conditions. In a series of safety verification tests designed and carried out in the early 1980s, data and information were gathered for use in the safety and environmental analyses needed to support a launch decision.

The tests were planned and conducted using facilities and equipment at DOE sites (i.e., LANL and SNL). For example, launch vehicle explosions and the resulting overpressures were simulated using a shock tube at SNL. Impact tests were simulated using a rocket sled at SNL and the Isotope Fuels Impact Test Facility at LANL, which could accelerate heat source components to high velocities for impact against different materials, such as concrete and steel. Similarly, the SNL rocket sled used aluminum plates to simulate the impact of fragments or other debris that might be generated during an accident. Other tests studied the response of the GPHS module to a solid-rocket-propellant fire, as well as long-term exposure of heat source plutonium oxide fuel to aquatic and terrestrial environments.[15]

This testing demonstrated the robustness of the new heat source and provided information to support the safety analyses and review processes needed for launch approval. For example, fueled GPHS modules impacted against concrete at approximately 116 miles per hour (52 meters per second), its terminal velocity, which resulted in no fuel release. Impacts of fueled clads without the protection of the GPHS aeroshell against sand at velocities up to and including 560 miles per hour (250 meters per second) and against concrete up to



*Interagency Nuclear Safety Review Panel

A Formal and Exhaustive Safety Review Process

Federal agencies collaborate to complete two separate safety processes before the United States launches a spacecraft carrying nuclear material. The first is the production of an environmental impact statement (EIS) by the agency launching the spacecraft (with DOE support) incorporating public review. DOE produces a nuclear risk assessment that is used as input to the EIS. The second process is an independent safety evaluation by an ad-hoc Interagency Nuclear Safety Review Panel (INSRP) formed for the specific mission in question, which ends in an Executive Branch review that requires final launch approval by either the President directly or by the Director of the White House Office of Science and Technology Policy. To support this process, DOE prepares a detailed Safety Analysis Report that describes the potential launch accidents and the nuclear system response to these accidents and their associated probabilities. It also describes the mission, spacecraft, power system, and testing that has been completed to evaluate the risk of the release of nuclear material under various accident scenarios. The INSRP produces a Safety Evaluation Report that evaluates the DOE Safety Analysis Report. The two review processes are both comprehensive and detailed. The full process for RTG launch approval generally takes four to eight years.

134 miles per hour (60 meters per second) yielded similar results. No releases occurred as a result of explosion over pressure when tested, as did testing at over pressures up to 2,200 pounds per square inch (psi). At the conclusion of the safety testing, design, and development efforts, the new GPHS was finally ready for production and use.[15]

Production Takes Center Stage

The effort to produce the GPHS-RTGs and their heat sources was widely distributed and involved numerous DOE contractors and national laboratories. For example, the iridium-alloy raw materials used to fabricate the cladding and frit vents were produced at ORNL. Fabrication of the iridium cladding and frit vents was performed at the Mound Laboratory. Fabrication and encapsulation of the plutonium oxide fuel pellets was performed in the Plutonium Fuel Fabrication Facility at Savannah River Site (SRS). The encapsulated fuel pellets were then transferred to Mound, where they were encapsulated in the graphitic components during GPHS module assembly operations.

The Galileo and Ulysses missions brought new opportunities for the space nuclear power system workforce at Mound.

The Galileo and Ulysses missions brought new opportunities for the space nuclear power system workforce at Mound.

In the late 1970s, DOE decided to transfer RTG assembly and testing operations from its system contractors, GE and TES, to Mound. Although radioisotope heat source assembly and other related operations had been conducted at Mound for over 30 years, the new RTG assembly and testing work required that a facility, equipment, operations, and personnel be in place and ready to support the planned launch dates. The new operation was located in Building 50, the RTG Assembly and Testing Facility, which had been used for other activities since the early 1970s.

Modifications to accommodate the new RTG operations began in the early 1980s and were completed in 1983. Equipment was received and set up, procedures were developed, and workers were trained to accommodate the new assembly and testing operations.[16] It was a hectic time, and the pressure to have RTGs ready for the aggressive launch schedule meant long hours and work weeks for those involved. As Wayne Amos of Mound recalled years later, "We had technical problems which led to schedule issues and working 24 hours a day, seven days a week. But it was a good group and we all worked well together..."[17]

After months of preparation, training, and reviews, Mound finally put its new RTG assembly and testing capability to work. In April 1983, Mound received a GPHS-RTG qualification unit, designated Q-1, for fueling and testing. Assembly of the qualification unit was performed in the new Inert Atmosphere Assembly Chamber, where operators assembled the stack of 18 fueled GPHS modules and inserted the stack into the generator. The RTG was then sealed and backfilled with an inert gas, which served to protect the thermoelectrics from deleterious effects of atmospheric oxygen during storage and testing operations.

A technician works on the assembly of a nuclear generator. (Photo: DOE Flickr)

GPHS-RTG Identification

GPHS-RTGs are identified following a convention based on their status as either a **qualification** unit or a **flight** unit that has been certified by DOE as being ready for mission use. A qualification unit receives a Q designation, followed by a sequential number representing its assembly order. For example, a Q-1 designation means the unit is the first qualification unit for the GPHS-RTG design. Similarly, an F-1 designation means the unit is the first flight-certified version of the GPHS-RTG design.

Following assembly, the nuclear-fueled qualification unit was put through an extensive series of tests that checked the system for resistance to leaks, neutron- and gamma-radiation emission rates, and pressure decay. Vibration testing was performed using a shaker table, which simulated launch conditions. Long-term power testing was performed in a large vacuum chamber to simulate RTG performance in space.

Upon completion of the testing, a long-term life test was initiated to demonstrate the longevity of the power conversion system over a period of several years. Successful testing of the qualification unit provided assurance that the new GPHS-RTG would meet mission needs and verified the analytical models used to predict performance.[16]

Following successful completion of the RTG qualification and safety-testing programs, DOE and NASA were confident that the GPHS-RTG was ready for flight. In 1985, Mound completed the assembly and acceptance testing of four GPHS-RTGs – three for use in the Galileo and Ulysses missions and one spare unit. In January 1986, the four RTGs (designated F-1, F-3, F-4, and F-5) were transferred from Mound to the Kennedy Space Center (KSC) in preparation for the Galileo and Ulysses missions, which were scheduled to launch later that year. A fifth unit, F-2, had been prepared but inadvertent exposure to air during operational processing resulted in slight power degradation, and use of the unit was deferred to a later mission. DOE provided the GPHS-RTG units in time for the scheduled flights, and they were ready to power the next step in space exploration.

Launch Plans Put On Hold

Only days after the GPHS-RTGs arrived at KSC, the Space Shuttle Challenger exploded shortly after takeoff on January 28, 1986. Following the accident, all parts of the U.S. civil space program that depended on the space shuttle were put on hold, and investigations into the cause of the accident quickly ensued. The accident had major ramifications for the Galileo and Ulysses missions. First, the original 1986 launch dates for the missions were eventually moved to 1989 for Galileo and 1990 for Ulysses. The accident also prompted questions regarding the risks of launching nuclear payloads aboard the shuttle.[18] In addition, questions arose regarding the risks of the Centaur upper-stage launch vehicle, with its liquid hydrogen propellant, aboard the shuttle. Finally, the Challenger accident, coupled with the catastrophic failure of a Titan-34D rocket during launch in April 1986, led NASA to completely re-evaluate its launch vehicle failure modes and associated accident environments and probabilities.[19]

As investigations into the accidents progressed and plans developed to address the causes, the GPHS-RTGs, still at KSC, were connected to the Galileo and Ulysses spacecraft in a series of hot tests to ensure proper integration and operation with the spacecraft systems. After the integration work was completed, the RTGs were returned to Mound in 1986 for servicing, monitoring, and long-term safekeeping pending their final transfer to KSC for launch.

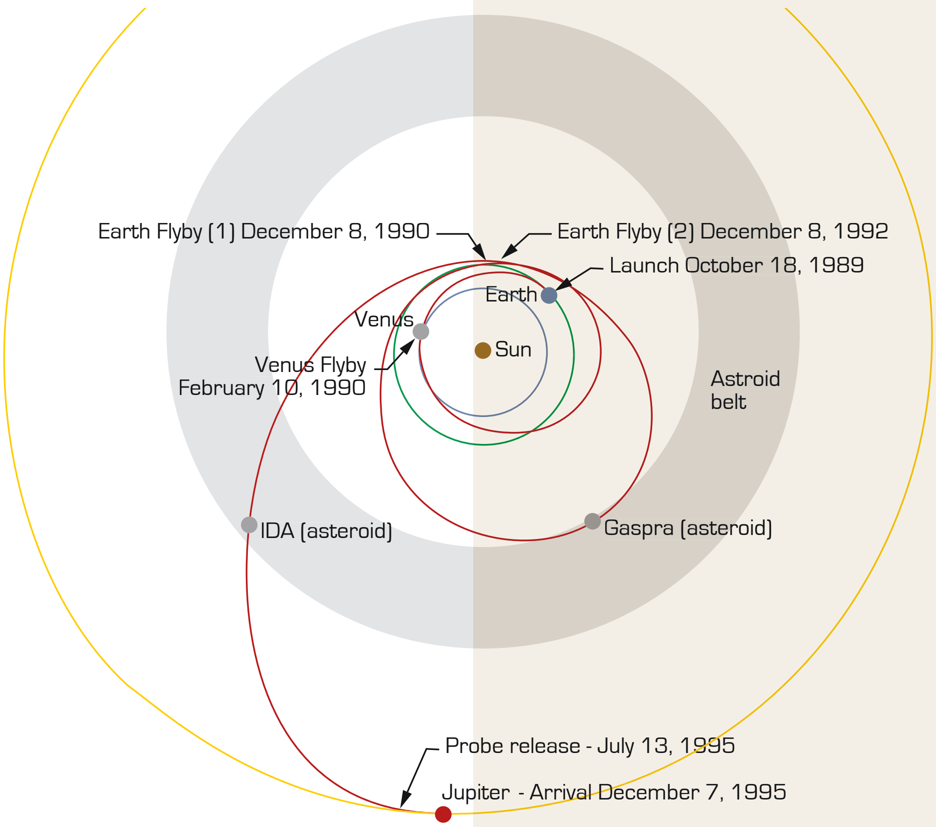
> Only days after the GPHS-RTGs arrived at KSC, the Space Shuttle Challenger exploded shortly after takeoff on January 28, 1986.

Against the backdrop of the Challenger accident and the risks associated with use of the Centaur rocket with its liquid-oxygen/liquid-hydrogen propellant, NASA Administrator James Fletcher announced, in June 1986, a decision to cancel the Centaur program. The decision ended the plans to use the Centaur rocket with the Galileo spacecraft. As a consequence, NASA subsequently decided to use a less energetic solid-fuel inertial upper stage (IUS) rocket for the Galileo and Ulysses missions. Because the IUS booster didn't have the power to send the spacecraft on a direct path to Jupiter, Galileo mission planners devised a new flight plan that included a Venus-Earth-Earth gravity assist (VEEGA) to set the spacecraft on its path to Jupiter. In the VEEGA maneuver, the gravity of the two planets would be used to increase spacecraft velocity and reduce travel time to Jupiter. The gravity-assist maneuver resulted in the need for additional re-entry safety tests and analyses.[9, 19] The results prompted iterative changes to the original Earth fly-by maneuvers and resulted in a slightly delayed arrival at Jupiter.

In addition to the need for the gravity-assist maneuver, the decision to use a solid-fuel upper stage resulted in the need for new tests and analyses to ensure the GPHS could contain its fuel under postulated accident conditions involving large pieces of the shuttle solid-rocket-booster. In a series of tests conducted at SNL, scientists simulated the interaction of large solid rocket booster fragments with a GPHS-RTG. Components used in the testing included the GPHS-RTG engineering unit that was being tested at Mound and GPHS modules containing fueled clads of uranium oxide used to simulate the plutonium oxide. In a series of three separate tests, solid-rocket-booster fragments were shot into sections of the GPHS-RTG at varying velocities and orientations to determine impact effects on the fueled clads.[19] The test results provided information for use in updated safety and environmental analyses. Jim Turi, retired from DOE, noted one special feature of the testing: "What is little known is that in testing the RTGs, we actually used some leftover pieces from the Challenger accident after the investigation was finished. We put pieces of the space shuttle on rocket sleds at Sandia and ran them into the RTGs…."[20]

Gravitational Assists

A gravitational assist is an essential tool for some interplanetary missions. It allows a spacecraft to change direction or speed by taking advantage of the gravitational pull of planets and moons. A gravitational assist is typically used when a spacecraft requires a large change in velocity, such as when traveling to the outer planets or even Mercury, as the technique enables the spacecraft to achieve velocities that are beyond the capability of its rockets. This enables missions that would not otherwise be possible, and also reduces the amount of fuel or time required for a trip. Use of a gravitational assist requires a high level of planning and navigational accuracy. With the planets, including Earth, in constant motion, a particular gravitational-assist maneuver may only be available within a short time period. The time period when a spacecraft can be launched that will allow it to successfully complete its mission is known as a launch window.



Galileo Venus-Earth-Earth gravitational assists. (Image adapted from NASA/JPL illustration)

When a spacecraft approaches the orbiting body that will provide the assist, the gravity of that body pulls the spacecraft towards it. Objects in orbit are not stationary, but travel at great velocity as they orbit around the sun. If the spacecraft approaches the moving planet from behind, it inherits some of the planet's velocity as it is pulled forward by gravity. Similarly, if the spacecraft approaches an oncoming planet from the front, it will be slowed. With careful planning and execution, the spacecraft will exit the gravitational influence of the planet in the proper direction and with the desired speed.

Mariner 10, launched in 1973, was the first spacecraft to use a gravitational assist when it traveled to Mercury. Pioneer II used a gravitation assist at Jupiter to reach Saturn, and Voyagers 1 and 2 used gravitational assists to explore the outer planets.

By 1989, DOE and NASA had updated the safety and environmental analyses to support the planned Galileo launches. The updated analyses reflected the use of a solid-fuel upper stage, the VEEGA, and the results from the large fragment tests, and concluded that the risks of launch with the GPHS-RTG onboard the shuttle were acceptably low. Reflecting upon the Challenger accident and its impact on the space nuclear program, Roy Zocher, one of the heat source designers from LANL, noted, "[T]hat accident…brought us to explore other possibilities in terms of accident environment, and so a good deal of the extensive safety testing originated as a result of the Challenger accident…."[21] With the new safety testing and review processes completed, Galileo and Ulysses were once again ready to fly, at least as far as DOE and NASA were concerned. Some within the public had a different opinion, however, and soon took the opportunity to make their voices heard.

In the months leading up to the Galileo launch, anti-nuclear groups like the Florida Coalition for Peace and Justice, the Foundation on Economic Trends, and the Christic Institute (a public interest law firm) began to express their opposition. Concerns were voiced over the possibility of accidents that could result in plutonium contamination of the space coast and other areas. The concerns culminated in protests at KSC and the filing of a first-ever lawsuit against NASA, which threatened to halt the Galileo launch. After hearing arguments from both sides of the case, the presiding judge ruled in favor of NASA. The Galileo mission was finally a go. After the launch of Galileo, the Ulysses mission would see similar concerns and protests. Although the protests and lawsuit didn't stop the launch, they did contribute to the establishment of pre-launch contingency planning. Such planning provides for response to radiological incidents in the unlikely event of a launch accident.[1, 9, 18]

The Launch and Discoveries of Galileo

After more than 10 years of development, testing, and preparations that spanned three presidential administrations, the Galileo spacecraft and its two GPHS-RTGs finally made their way to space aboard the Space Shuttle Atlantis (STS 34) when it was launched on October 18, 1989. For all involved, such launches produce an almost indescribable feeling of pride and sense of accomplishment, as described by Jim Turi: "…I can remember the first launch I was down there for, Galileo. I'm not a very emotional person but I actually had tears in my eyes when it got off the ground. It was just the excitement, the thrill, the adrenaline, the happiness. It was just amazing. It was just totally unexpected when it occurred."[20] Galileo was successfully deployed from the shuttle, once it reached orbit, and sent safely on its way to Jupiter via the gravity assists.

During the flyby of Earth in December 1990, Galileo provided the first photographs taken by an unmanned spacecraft of the Earth and moon together and confirmed the existence of a huge ancient impact basin in the southern part of the far side of the moon that had never been mapped. The first multispectral study of the moon showed evidence of more extensive lunar volcanism than previously thought.[22] On its six-year outbound journey to Jupiter, the spacecraft provided the first close-up observations of asteroids (Gaspra and Ida) and also recorded the collision of the Shoemaker–Levy comet with Jupiter.

A probe was released from the orbiter on July 13, 1995. Once released, it could no longer be commanded and followed its predetermined path for 147 days before entering the Jovian atmosphere. After the probe was released, the orbiter trajectory was altered to fly over the site where the probe encountered the planet so it could relay data from the probe back to Earth. The orbiter began circling Jupiter on December 7, 1995, becoming the first spacecraft to orbit an outer planet. On the same day, the probe, running on its life-limited 580-watt-hour batteries, entered the Jovian atmosphere to take direct measurements for the first time. For the next 22 months, the orbiter traveled between several moons, including those discovered by Galileo Galilei (Io, Europa, Ganymede, and Callisto), using their gravity to set its course and complete its primary mission. Although it was the fifth mission to observe Jupiter, the Galileo spacecraft was the first to enter orbit around the planet, and it changed mankind's understanding of Jupiter, its moons, and the outer solar system.

At the end of its planned eight-year (71,000-hour) mission in December 1997, the two GPHS-RTGs were still providing 482 We, well beyond the mission required 470 We. Even after the launch delay and the extended VEEGA route to Jupiter, the GPHS-RTGs produced sufficient power to enable NASA to extend the mission by several years, enabling the craft to ultimately complete 35 orbits of Jupiter. In February 2003, with the spacecraft running out of propellant, the flight team extracted the last scientific data from Galileo and sent the spacecraft into a collision with Jupiter on September 21, 2003. The planned collision eliminated the possibility of a crash on Europa that could have left contamination on the moon, which was understood to host an ocean important to the study of extraterrestrial life.[1, 10]

Artist's conception of the Galileo spacecraft. The GPHS-RTGs are located at the end of the booms on the back of the craft. (Photo: NASA.gov)

Although it was the fifth mission to observe Jupiter, the Galileo spacecraft was the first to enter orbit around the planet, and it changed mankind's understanding of Jupiter, its moons, and the outer solar system.

The Space Shuttle Atlantis—carrying the Galileo orbiter and atmospheric probe—lifts off from KSC. (Photo: NASA.gov)

Ulysses' Solar Odyssey

The launch of Ulysses went as smoothly as that of Galileo. The spacecraft, along with its GPHS-RTG, was launched on October 6, 1990, aboard the Space Shuttle Discovery (STS 41). A two-stage inertial upper stage and a payload assist module booster sent the spacecraft out of Earth's orbit on a direct 16-month trip to Jupiter, where the gravity of Jupiter was then used to shift the spacecraft trajectory out of the ecliptic plane of the planets and over the poles of the sun.[10]

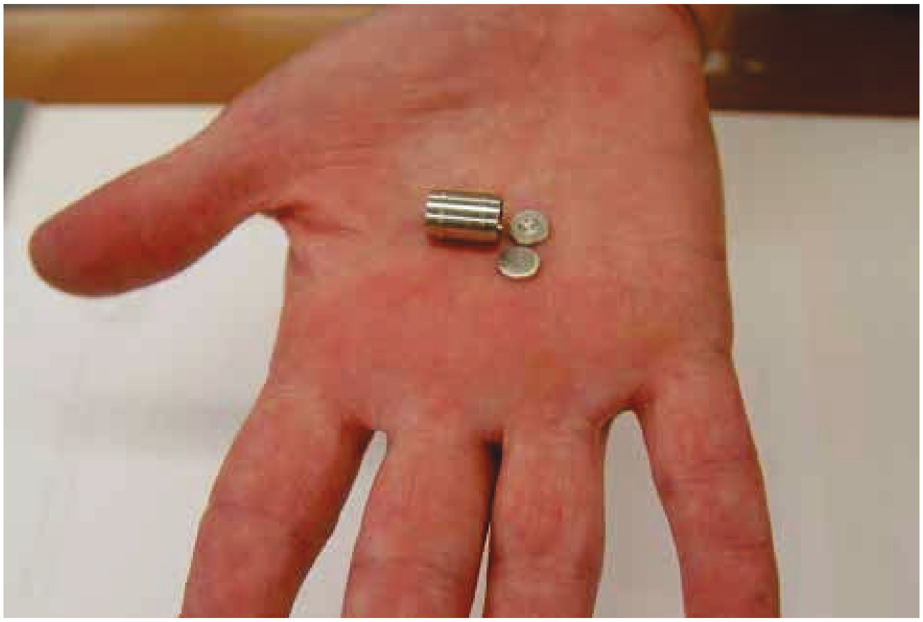
Ulysses studied the solar wind, a steady stream of particles ejected from the sun that produces a bubble in interstellar space called the heliosphere. Ulysses provided the first map of the heliosphere from the solar equator to a maximum latitudinal inclination of approximately 80 degrees (relative to the North and South Poles) during 1994 and 1995. The mission also improved the understanding of sunspot behavior, solar flares, solar x-rays, solar radio noise and plasma waves, the sun's magnetic field, cosmic rays, and both interstellar and interplanetary gas and dust. Having successfully accomplished its primary mission, Ulysses continued to operate on its second orbit of the sun to study the solar wind during the sun's maximum solar activity cycle.

At the end of its planned five-year (42,000-hour) mission in August 1995, the GPHS-RTG was still providing 248 We, slightly above the mission required 245 We. With the ongoing power provided by the RTG, the Ulysses mission was able to be extended several times. Ulysses started its third south polar pass in November 2006, and completed its third north polar pass in March 2009. On June 30, 2009, after 18 years of successful operation, electronic equipment problems and negligible thruster fuel precluded further operation of the spacecraft, resulting in termination of the Ulysses mission.

Radioisotope Heater Units

As the Galileo and Ulysses missions came to an end, this chapter would not be complete without mentioning one of the simplest but most unsung heroes of space nuclear technology: RHUs. RHUs are used to keep sensitive instruments at desired operating temperature without using electrical power and without producing the electromagnetic interference produced by electrical heaters. Bob Campbell, who worked at the Jet Propulsion Laboratory (JPL) during preparations for the Galileo and Ulysses missions, points out the benefit: "… [B]y using these RHUs just at certain places where they are needed… it completely saves having to run electric cables out, separate electric cables out to each one of these things, just to have an electric heater there. And then you are using the power supplied by the RTG to run all the way out there, to supply these instruments with heater power. So it's more draining on how much electrical power you're going to be able to use for the rest of the spacecraft. It's about 100 RHUs. That's a demand of 100 watts total. But now all of a sudden your RTG is going to spend 100 of its 300 watts… just to supply those heaters. So if you put the RHU there, that solves all the wiring difficulties. It… gives you an extra 100 watts saving on the RTG power that doesn't have to be used… for those little electrical heaters to heat up those units."[23]

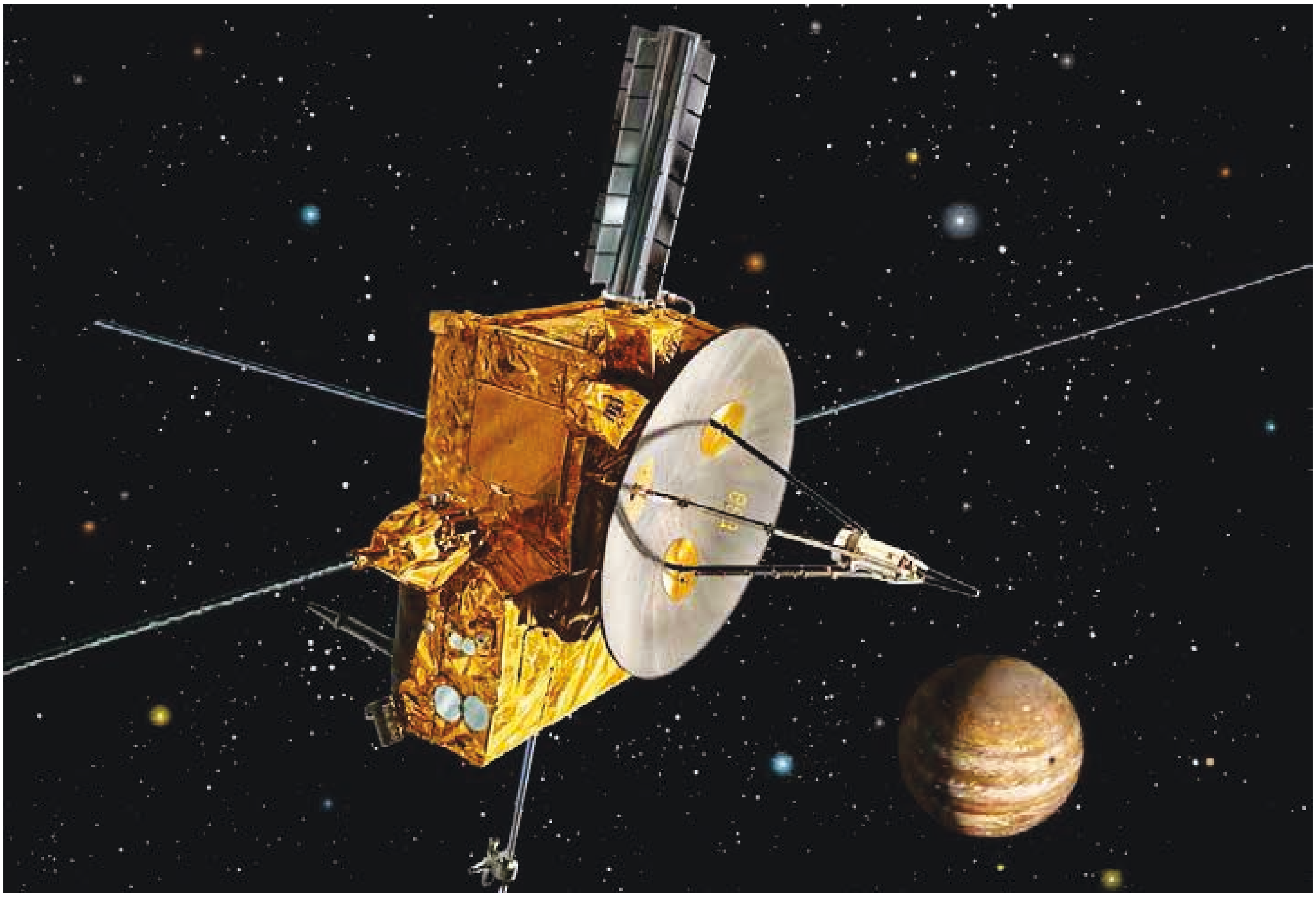
First used in the Apollo 11 mission in a configuration that produced 15 watts of thermal power, a smaller one-watt version was developed for use in the Pioneer program of the 1970s. The one-watt Pioneer RHU was subsequently modified for use on the Voyager 1 and Voyager 2 spacecraft launched in 1977. Fueled and encapsulated at Mound, the



Lightweight RHU components. (Photo: ORNL)

RHU produced its one watt of thermal power from approximately 0.01 pounds (2.7 grams) of plutonium oxide fuel. Similar to RTGs, the RHU was designed with several protective layers and other safety features to contain and/or immobilize the plutonium oxide fuel during accidents.[24]

In 1978, LANL began development of an improved version of the lower mass RHU for use on the Galileo orbiter and probe. The new heater unit, called a light-weight radioisotope heater unit (LWRHU), produced one watt of thermal power from approximately 0.01 pounds (2.7 grams) of plutonium oxide fuel similar to the GPHS-RTG. The LWRHU, however, was lighter (0.08 pounds versus 0.1 pounds [40 grams versus 57 grams]) and shorter (1.3 inches vesus 1.8 inches [32 millimeters versus 47 millimeters]) but somewhat larger in diameter (1 inch versus 0.9 inches [26 millimeters versus 22 millimeters]) than the RHU. The new LWRHU was designed with several safety-related features, including a ceramic plutonium oxide fuel pellet; platinum-rhodium alloy cladding with a frit vent in one end to allow the release of helium from the natural decay of



An artist's impression of the Ulysses spacecraft at Jupiter. (Image: NASA/European Space Agency) the plutonium (whereas the RHU was designed to contain helium); a pyrolytic graphite thermal insulator to keep the clad from melting in case of re-entry; and a FWPF aeroshell for re-entry protection (an improved material relative to that used in the RHU). Completely assembled, the LWRHU was a cylinder approximately 1.25 inches (3 centimeters) long and one inch (2.5 centimeters) in diameter, similar in size to a modern-day C-cell battery.[25]

The LWRHU development effort originally planned for design, testing, production, and delivery to be completed in 14 months; however, the postponement of the Galileo launch enabled development of a design with an increased safety margin and allowed for additional testing. The fuel containment capability of the new lightweight heater unit was evaluated in safety tests similar to those for the GPHS-RTG. The tests included overpressures, impact by aluminum alloy bullets, extended exposure to burning solid-fuel propellant, impact on a hard surface in various orientations at velocities greater than terminal, and immersion for nearly two years at a pressure equivalent to 6,000 meters of seawater.[25] Following the development and testing effort, assembly of 134 LWRHUs for the Galileo mission was completed at LANL in 1985; however, only 120 of the units were used on the spacecraft, with the remainder being set aside as spares.

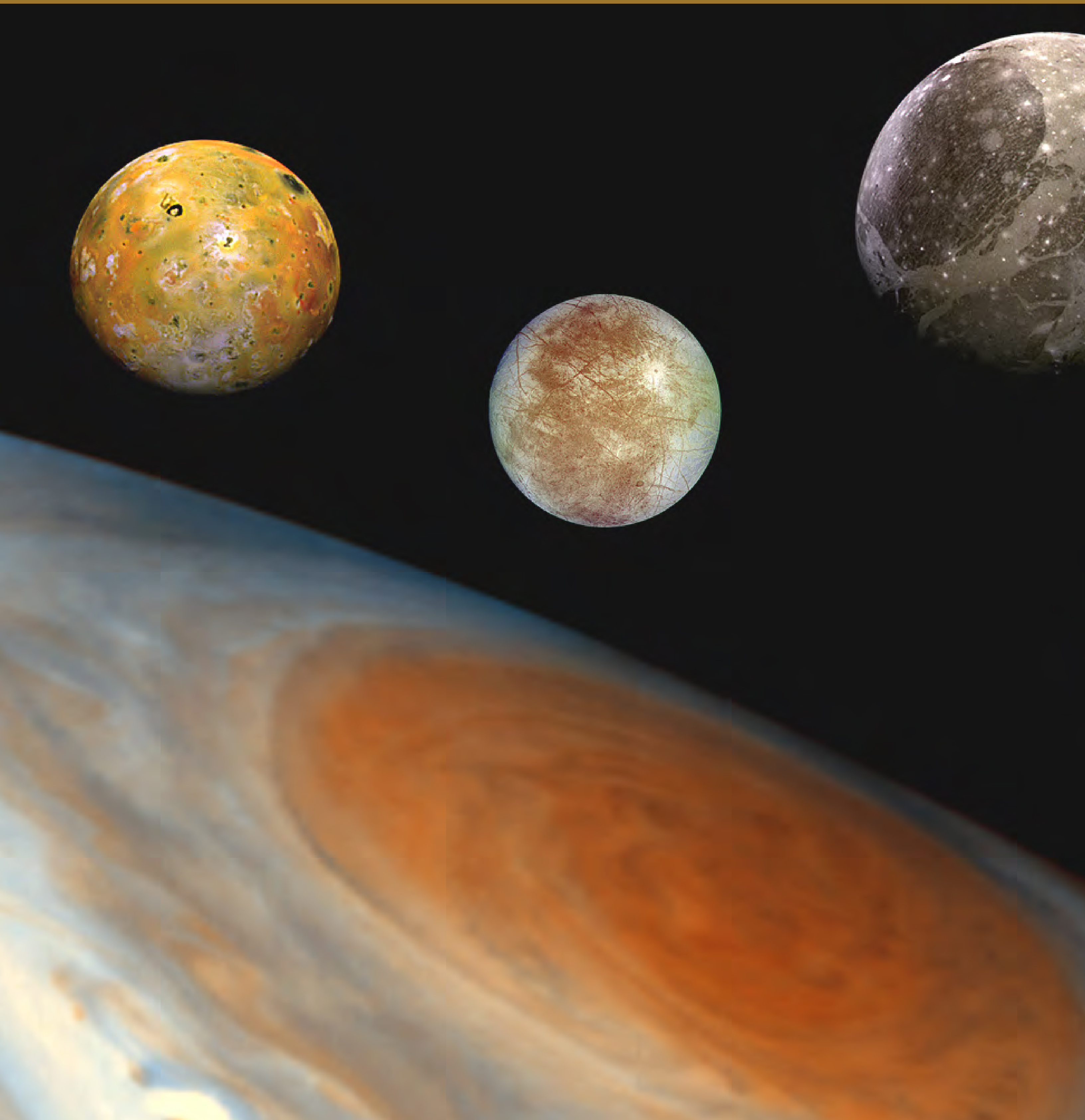
"When you look at the photos from the Galileo and Ulysses missions, people marvel at the pictures and the science... And you realize, you know, that couldn't have happened if it wasn't for these RTGs, and usually the RTGs aren't even mentioned.... But those who are in the community, we know, and... there's just an awful lot of pride... when you think about how you played a small part in these missions' successes and advancing science...that you helped make these missions successful, and I think that's why I and others just have a warm place in our heart for these programs. Let's face it, space exploration is still sexy and it will be for a long time, I think."

–Jim Turi, DOE

Looking Back

The success of the GPHS-RTG and LWRHU on the Galileo and Ulysses spacecraft closed another chapter in a long history of the quiet technology. The GPHS-RTGs extended mission life and provided the power necessary to transmit countless pictures, data, and other information that enhanced the understanding of our solar system. The LWRHUs provided heat that kept scientific instruments and other electronics warm (and functioning) in the coldness of deep space. And in both cases, with the GPHS-RTG and LWRHU, DOE had developed units that would power and heat NASA missions for decades to come.

The goals of these developmental efforts were (and still are) to improve efficiency and maximize electrical power output while minimizing power system weight, all the while striving for the highest level of safety during a host of highly energetic accident conditions.



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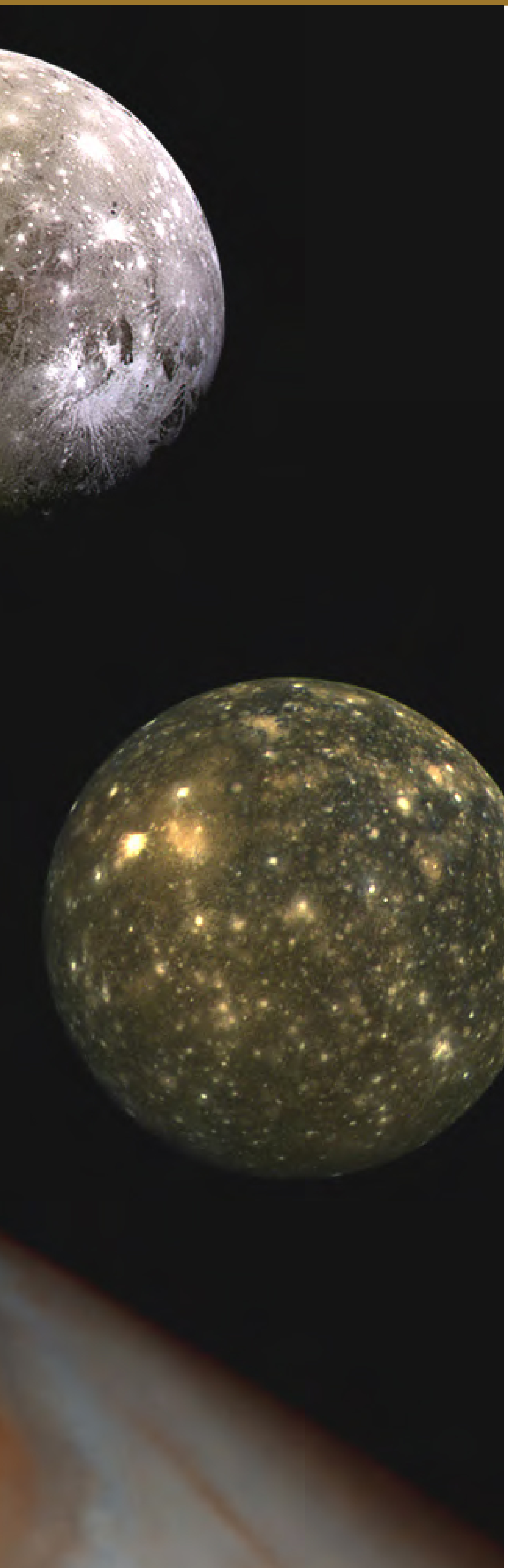
Advanced Isotope Power Systems
Expanding RPS Boundaries



As RTG technology continued its evolution through the 1970s and 1980s, development of advanced isotope power systems remained an important goal within DOE and NASA. The goals of these developmental efforts were (and still are) to improve efficiency while minimizing power system mass, all the while striving for the highest level of safety. With these goals in mind, the agencies sought to take advantage of advancements in materials, power conversion technologies, and fabrication and production techniques. In so doing, their efforts served to expand the knowledge base of RPS technology and provided a platform from which future development efforts might build.

A Modular RTG

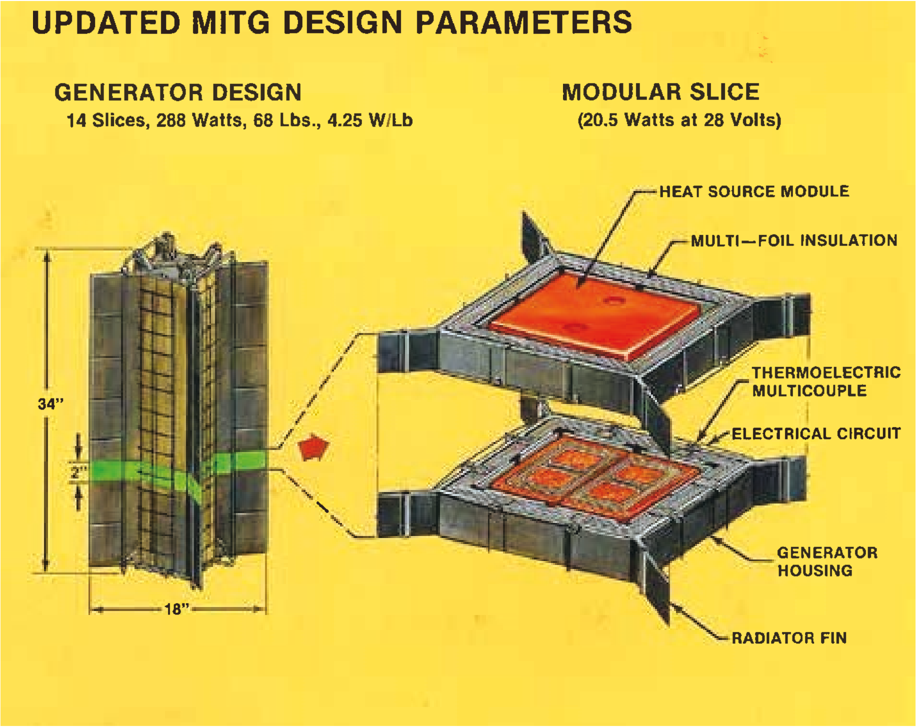
Throughout the 1980s, development and production of the new GPHS-RTG for the Galileo and Ulysses missions were the primary focus for DOE. With its modular heat source and improved power conversion system, the GPHS-RTG was a marked improvement over the MHW and SNAP-19 RTGs, especially in terms of specific power. Soon, however, RTG visionaries began to evaluate the viability of a variation of the design that would bring modularity to the converter level as well as the heat source level.

In 1980, DOE contracted with Fairchild Space and Electronics Company to develop and analyze a new RTG design based on advanced materials and fabrication techniques, as well as the new GPHS that was under development by LANL, Fairchild, and GE. The RTG concept subsequently developed by Fairchild was called the modular isotopic thermoelectric generator (MITG). As conceived, the MITG concept included a single GPHS module surrounded axially by eight multicouples, as well as a standardized section of thermal insulation, housing, radiator fins, and electrical circuit. With a projected electrical power output of approximately 20 watts, individual MITG units could be combined to create an RTG that would be scalable over a range of power levels. Power-level increments of less than 20 watts would be accommodated by adjusting the size of the heat rejection fins located on the outside of the generator housing.[1]

A composite of the Jovian system, including the edge of Jupiter with its Great Red Spot, and Jupiter's four largest moons, known as the Galilean satellites. From left to right, the moons shown are Io, Europa, Ganymede, and Callisto. The Jupiter, Io, Europa, and Ganymede images were obtained by the Galileo spacecraft and the Callisto portrait was obtained by the Voyager spacecraft. (Photo: NASA/JPL/DLR)

The cornerstone of the MITG was a thermoelectric concept called the multicouple. Developed by the Syncal Corporation, the multicouple concept consisted of an array of p- and n-type thermoelectric legs that were connected to a common hot shoe, or heat collector, and cold-shoe mounting stub. In addition to the multicouple concept, Syncal had also developed a modified silicon-germanium thermoelectric alloy that included a small amount of gallium phosphide. Early testing indicated that the presence of the gallium-phosphide additive would improve the efficiency of the thermoelectric material by reducing its thermal conductivity. The anticipated benefit of the MITG was improved power conversion efficiency over the unicouple design employed in the GPHS-RTG.

Based on an initial concept, an MITG consisting of 12 power modules would generate approximately 280 We, which was comparable to the electrical output of the GPHS-RTG and its 18 GPHS modules. Relative to system weight, the 12-module MITG would weigh roughly half of the GPHS-RTG. With such promising performance, fabrication and testing of the new thermoelectric materials and multicouples were performed during 1981 through 1983 to determine performance and viability under conditions that simulated operational temperatures of the GPHS-RTG.[1] Among other things, test engineers sought to determine the performance of the gallium-phosphide-doped silicon-germanium thermoelectric material relative to the standard silicon-germanium used in the GPHS-RTG and to estimate module lifetime through measurement of the degradation of individual multicouples. The testing would also serve to confirm adequacy of fabrication and manufacturing techniques associated with the thermoelectric materials and multicouples.



MITG converter unit concept. (Graphic developed by GE; provided by INL RPS Program)

Two test assemblies, each consisting of eight MITG multicouples positioned inside a prototypic section of the generator housing, were subsequently fabricated and tested. Multicouples made from the modified silicon-germanium were used in one test module, while standard silicon-germanium multicouples were used in the second test module. The test assemblies were heated electrically using a heater that was enclosed in an insulated graphite box having the same outer dimensions as a GPHS module.

The tests served their purpose, as a number of issues were subsequently identified. For example, crack formation was observed in the multicouples. Subsequent investigation revealed the cause of the cracking to be thermal stresses occurring at the joints of the thermocouple array and the hot and cold shoes. The multicouple was subsequently redesigned to incorporate stress-relief features at the problem areas.[2, 3] In addition to the stress-cracking problem, independent testing of the gallium-phosphide-doped silicon-germanium thermoelectric material, performed at DOE's request, revealed material efficiencies that were lower than those previously reported (although they were higher than those of the standard silicon germanium alloy). Lessons learned from the testing were incorporated into a revised MITG design as well as fabrication and manufacturing processes. With improvements underway, DOE decided to test the MITG technology in a ground demonstration system as part of a follow-on modular (MOD) RTG development program (MOD-RTG). The MITG program ended in September 1983.[4]

MOD-RTG

Managed for DOE by GE, the goal of the MOD-RTG program was to develop a ground demonstration system to test the modular RTG concept. Beginning in October 1983, a three-year plan was developed to fabricate and test an electrically heated MOD-RTG demonstration unit based on six GPHS converter units.[5] By mid-1985, GE (with the help of Fairchild) had completed a reference flight design and a ground demonstration system design. With a single thermoelectric multicouple device designed to produce 19 We from one GPHS module, the reference design consisted of 18 GPHS modules and 144 thermoelectric multicouples to produce 340 We.[6] With a projected specific power of approximately 7.9 We/kilogram (based on a weight of approximately 42 kilograms [92 pounds]), the MOD-RTG reference flight design was significantly higher than the 5.4 We/kilogram GPHS-RTG. Fabrication of a ground demonstration system began in the summer of 1985.

Although initially optimistic, the MOD-RTG project soon found itself facing problems similar to the MITG effort. Multicouple testing revealed continued performance issues, including mechanical and electrical shorting problems, material issues associated with the gallium phosphide, and thermoelectric degradation faster than expected. In its attempt to address the thermoelectric issues, DOE suspended fabrication of the ground demonstration system in mid-1986. Efforts to address the multicouple performance issues stretched into a multi-year task and were the primary focus of project efforts through 1992 when the project was finally terminated. In spite of the difficulties encountered and technical challenges that remained at the time of project termination, the nine-year MOD-RTG effort did see some significant accomplishments, including the development of reproducible manufacturing processes for multicouple fabrication, resolution of mechanical and electrical-shorting problems that had been identified early in the project, and an understanding of the degradation mechanisms associated with the multicouples. Although follow-on work was recommended, DOE priorities shifted to production of the GPHS-RTGs for the Cassini mission slated for flight in 1997.[7]

Taking Energy From Heat

Thermodynamic cycles are the basis for many common technologies, including refrigeration, car engines, and aircraft jet engines. A thermodynamic cycle is a process that manipulates the temperature, pressure, and volume of a working fluid to either convert heat into energy or use energy to remove heat. Each cycle has its own intricacies but shares four common processes: compression, heat addition, expansion, and heat removal (cooling). Three thermodynamic cycles are of key interest to the space program due to their high efficiency and compatibility with various energy sources (e.g., solar and nuclear).

Rankine—Often used in steam power plants where water is boiled to produce superheated steam, which is expanded through a turbine to produce electricity; the steam is condensed back into water and pumped to the boiler to restart the cycle. For space applications, different working fluids (e.g., mercury, potassium, toluene) are considered based on design criteria that include weight and system operating temperatures and pressures. The fact that Rankine uses a two-phase (liquid and gas) operation creates engineering challenges that must be addressed in the low and zero gravity of space. However, because phase changes are an efficient way to transfer heat, Rankine cycles are typically the lowest mass option for high-power space applications.

Brayton—Jet engines and power-producing gas turbines often use this cycle. A working gas is compressed, heated to increase its pressure, and expanded through a turbine to produce electricity. The turbine is attached to the compressor to power the pressurization step. In a jet engine, the hot air is rejected to the atmosphere and fresh air is taken in. In a power plant, the waste heat can be used in a boiler to create steam for use in a Rankine cycle; such use is referred to as a combined cycle. Brayton engines in space must use a closed system and recycle their working gas (typically helium and/or xenon), which must be cooled before re-entering the compressor.

Stirling—As with other cycles, the working gas is compressed, heat is added, the gas is expanded, and heat is removed to restart the process. A variety of Stirling-engine types exist. The ones most recently investigated for potential space use are known as free-piston Stirling engines. In this configuration, the engine is a cylinder with one end exposed to a heat source and the other kept at a lower temperature using a heat exchanger. A displacer piston inside the cylinder moves gas between hot and cold spaces and is thermodynamically coupled to a power piston. The pressure changes caused by the addition and removal of heat at the two ends of the cylinder cause the two pistons to oscillate. The power piston can be used to drive a linear alternator to generate electricity from this motion. For the small Stirling engines that have been most recently developed for potential RPS use, these oscillations are extremely fast, on the order of 50 to 100 cycles per second, and with a piston stroke of just a few millimeters.

Dynamic Isotope Power Systems

Unlike static systems, such as the RTG, dynamic RPSs include a power conversion technology that uses moving parts to convert heat into useable electricity. Such systems typically employ the Brayton, Rankine, or Stirling thermodynamic cycles. Whereas the power conversion efficiency of an RTG may be on the order of five to seven percent, the conversion efficiency of a dynamic isotope power system (DIPS) may be 25 percent or higher, thereby producing three to four times the amount of electrical power per unit mass of radioisotope fuel.

Research into dynamic conversion systems for space applications began in the mid-1950s under the SNAP program conducted by AEC. For example, under the SNAP-1 program, an electrical heat source was used with a mercury-based Rankine power conversion unit to produce 470 We from the 13-pound (6-kilogram) system.[8] Development of mercury-based Rankine power conversion systems continued under the SNAP-2 and SNAP-8 reactor programs, in which the power conversion system was coupled with a metal-hydride nuclear reactor as the heat source to produce 3 and 30 kWe, respectively.[9] In this configuration, material and corrosion problems associated with the use of the liquid metal mercury eventually resulted in the substitution of organic fluids in the Rankine-based systems.[10] Early development work on closed Brayton cycle power conversion systems included a unit designed for a power output of two to 10 kWe developed at the NASA Lewis Research Center (now known as the John H. Glenn Research Center at Lewis Field, or more commonly referred to as the Glenn Research Center [GRC]).[11]

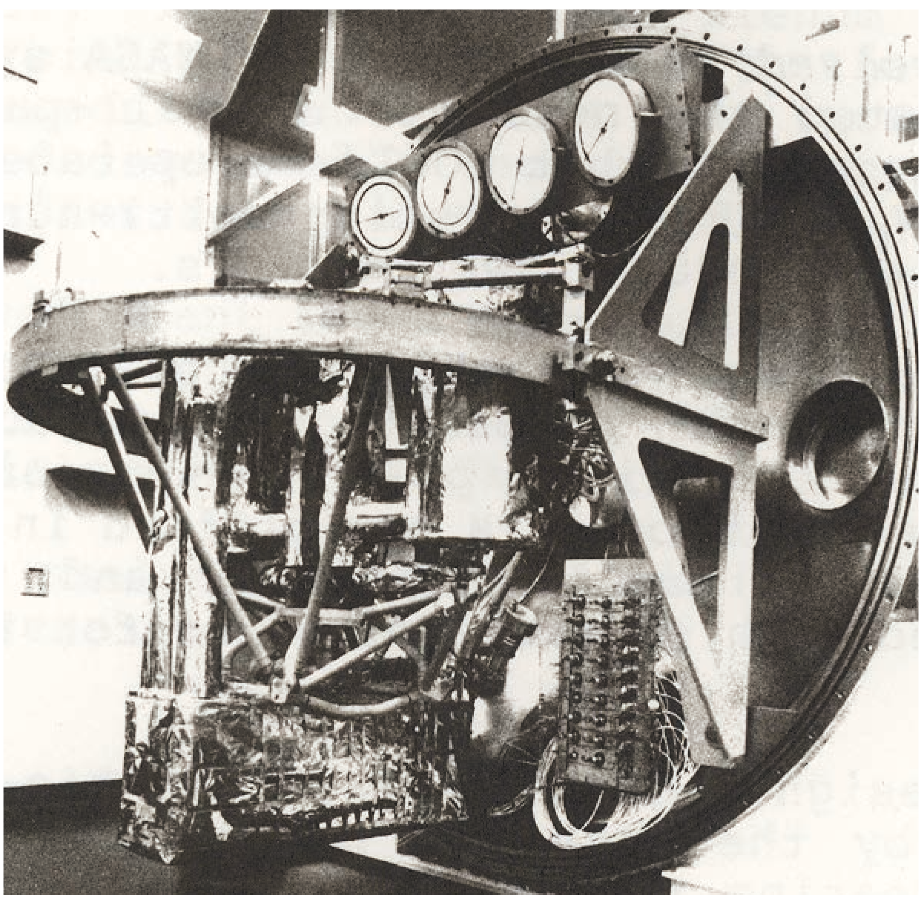
Recognizing that dynamic conversion was the next logical progression in space nuclear power system technology, DOE and NASA initiated a program in 1975 to develop a system capable of producing 1.3 kWe from a system weighing 450 pounds (204 kilograms). Two technologies were selected for development, testing, and evaluation. The Sundstrand Corporation developed an organic Rankine cycle, referred to as the Kilowatt Isotope Power System (KIPS), while the Garrett Corporation developed a closed Brayton cycle, referred to as the Brayton Isotope Power System (BIPS). Both contractors incorporated the MHW heat source into their design; however, testing was performed using electric heaters.

The KIPS concept consisted of three MHW heat source assemblies that would heat and boil an organic working fluid, thereby generating a vapor that drove a turbine. An alternator mounted directly to the turbine shaft was used to generate electrical power. After the vapor exited the turbine, it would pass through a regenerator where a portion of the remaining heat in the vapor was used to preheat the working fluid that was entering the heat source assembly. The vapor then passed through a condenser where it was liquefied and pumped to the point necessary to complete the cycle. The heat rejection system consisted of a barrel-shaped radiator through which the condensed liquid passed and excess heat would be rejected to space. An overall system efficiency of approximately 18 percent was anticipated from a 475-pound (216-kilogram) unit based on an electrical output of 1.3 kWe from the heat input of three 2.4-kilowatt (7.2 kilowatts total) MHW heat sources.[12]

The BIPS concept utilized two MHW heat sources to heat a helium-xenon working gas which, in turn, drove a mini-Brayton rotating unit—the rotating unit included a turbine, alternator, and compressor. Similar to the KIPS, the alternator mounted directly to the turbine shaft was used to generate electrical power. After the working gas exited the turbine, it passed through a recuperator where a portion of the remaining heat in the working gas was used to preheat the gas that was entering the heat source assembly.

Strategic Defense Initiative

In March 1983, the Reagan Administration proposed the SDI and directed the Secretary of Defense to engage in space-based nuclear deterrence. The SDI was conceived to intercept and destroy strategic ballistic missiles and was to be implemented by a new SDI organization. The mission of the new defense agency was to research sophisticated surveillance, sensing, orbital transfer vehicles (to move satellites between orbits), and intercept systems and weapons platforms with electrical power requirements ranging from hundreds of kilowatts to hundreds of megawatts.



Brayton Isotope Power System workhorse loop. (Image: NASA)

The gas was then passed through a compressor and routed back to the system to complete the cycle. Based on system studies, an overall system efficiency of approximately 27 percent was anticipated from a 460-pound (208-kilogram) unit based on an electrical output of 1.3 kWe from the heat input of two 2.4 kilowatts (4.8 kilowatts total) MHW heat sources.[13]

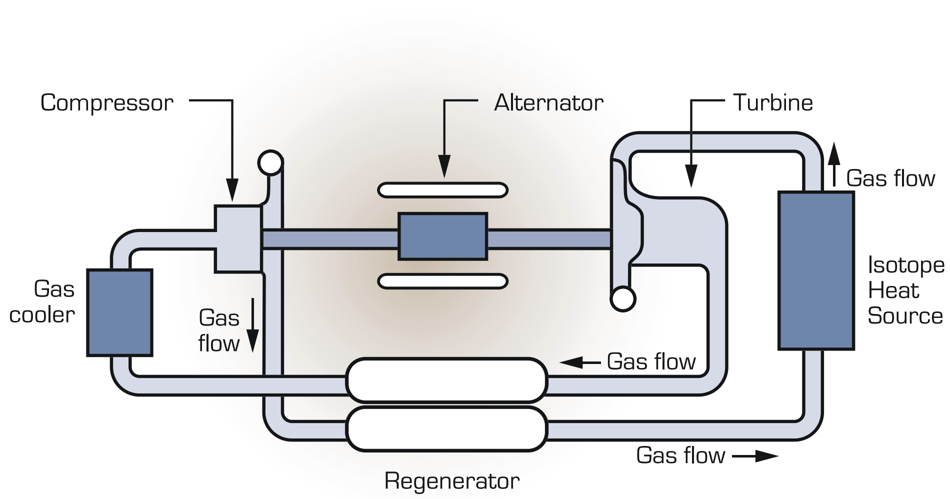
Although both contractors successfully developed a flight system conceptual design and a prototypic ground demonstration unit for testing, the Sundstrand organic Rankine system (KIPS) was selected for further development. When the program was discontinued in September 1980 due to the absence of a near-term mission, the Sundstrand system had operated for over 11,000 hours at a full output design power of 1.3 kWe and an overall system efficiency of 18.5 percent.[10]

The DIPS Program

Against the backdrop of the 1983 Strategic Defense Initiative (SDI), a DIPS technology demonstration program was initiated in 1987 as a joint DOE/DoD effort to develop a power system for the Boost Surveillance and Tracking System. The tracking system was conceived to provide early detection of enemy ballistic-missile launches during the first few minutes following launch, a time referred to as the boost phase.[11]

The Boost Surveillance and Tracking System was expected to require an electrical load of 6 kW, a seven-year lifetime, and 98 percent reliability. Following an evaluation of three candidate space nuclear power system technologies (thermionic, reactor, and DIPS), DIPS was selected for further development. The overall objectives of the DIPS technology demonstration program included fabrication and demonstration of a dynamic power system that could be scalable over a range of one to 10 kWe, life testing of an electrically heated qualification unit to demonstrate reliability of seven to 10 years, and resolution of all significant technological issues. The planned DIPS was also to be configured to use the latest heat source technology—the GPHS.[14] For comparison, a 6-kWe DIPS would be equivalent to 20 GPHS-RTGs.

Under contract to DOE, Rocketdyne (then a division of Rockwell International) was selected to lead the effort to design, build, and test a prototypic power system through the point of flight readiness. Following an evaluation of Brayton and Rankine technologies, the closed Brayton cycle power system previously under development by the Garrett Corporation was recommended to



Graphic depicting a generic DIPS. (Image adapted from "The Dynamic Isotope Power System: Technology Status and Demonstration Program," Gary L. Bennett and James J. Lombardo, 1988)

How a Dynamic Isotope Power System Works

A DIPS consists of a radioisotope heat source, a power conversion system consisting of turbine alternator compressor on a common shaft, a heat exchanger and gas cooler, a heat rejection system, and associated piping, valves, and control systems. During system operation, a working fluid (e.g., xenon-helium gas mixture for a Brayton cycle and organic liquid for a Rankine cycle) exits the heat source assembly at a very high temperature and is piped to the power conversion system. As the hot working fluid flows through the turbine, the turbine-alternator-compressor shaft rotates, resulting in the generation of electricity by the alternator. After passing through the turbine, the working fluid is routed through a heat exchanger and cooler, after which it is pumped back to the heat source via the compressor. Excess heat from the gas cooler is transferred to a heat rejection system via a cooling loop. The electricity generated by a DIPS is then "conditioned" for use in powering on-board electrical equipment or an ion propulsion system.

DOE for development. Following DOE concurrence, a Rockwell Garrett team designed a modular closed Brayton system with an anticipated power output of 2.5 kWe and an operating life of over 10 years.[11] Although ground testing of the Brayton system never materialized (the program developing the Boost Surveillance and Tracking System decided against use of DIPS in favor of a non-isotope technology),[15] the DIPS technology was soon connected to other space applications.

In 1989, President George H. W. Bush announced his Space Exploration Initiative (SEI). The SEI had ambitious goals of returning humans to the moon within a decade and sending a manned crew to Mars by 2019. Within a year of the announcement, DOE and NASA had penned a memorandum of understanding that established a general framework by which the two agencies would cooperate on matters concerning information exchange and research and development activities under SEI.[16]

While development of DIPS and other potential SEI power technology concepts began to grow, they soon came face-to-face with the reality that SEI lacked Congressional support and funding, largely due to its immense 20- to 30-year, $500 billion price tag.

With the new NASA-DOE agreement, potential applications for a Brayton system soon shifted from the SDI effort to space-based exploration. Under the DIPS Demonstration Program, dynamic power system concepts were developed to meet new missions and power levels for the exploration of space. For example, the closed Brayton cycle system was identified for possible use in planetary surface applications requiring 0.2 to 20 kWe.[17] For a mission conceived to establish a manned outpost on the moon, a 2.5-We Brayton design was compared to other dynamic power system technologies, both nuclear and non-nuclear.[18] In both concepts, planners assumed the use of a fueled GPHS module, the mainstay of DOE heat sources since its development for the Galileo and Ulysses missions.

While development of DIPS and other potential SEI power technology concepts began to grow, they soon came face-to-face with the reality that SEI lacked Congressional support and funding, largely due to its immense 20- to 30-year, $500-billion price tag. In the absence of the needed support, the lofty human-exploration goals of SEI were soon abandoned and the DIPS Demonstration Program was brought to a close.[19]

Stirling Radioisotope Generators

By the mid-1990s, the need for an advanced radioisotope power system was becoming increasingly important to DOE and NASA. The importance lay in the fact that the agencies had been faced with a limited inventory of plutonium-238 for over a decade following the shutdown of the K-Reactor at SRS in 1988.[c] Soon, interest in another dynamic power conversion system based on Stirling technology began to gain ground within DOE and NASA. That interest had been fostered by years of Stirling technology research, including experience gained during development of the SP-100 space reactor power system.

c. See Chapter 10, Infrastructure Inroads. The K-Reactor had provided for production of plutonium-238 for over 30 years. With its shut down, DOE lost its sole production capability for the heat source isotope.

Stirling Engine Origins

Invention of the Stirling engine is generally attributed to Robert Stirling, a Scottish minister who invented the first practical closed-cycle air engine in 1816. Initially developed as a competitor for the steam engine in the 1800s, kinematic Stirling systems developed in the early- to mid-1900s were used in portable and marine generators and in various automotive and locomotive applications. In 1974, William Beale invented the free-piston Stirling engine, which found subsequent application in RPS concepts developed by DOE and NASA beginning in the mid-1990s.

The Stirling Technology Company, later named Infinia, was based in Kennewick, Washington, and had been working under contract to DOE to develop a 55-We Stirling engine called the technology demonstration convertor (TDC).[d] Following initial development and fabrication of multiple demonstration engines, the TDC was subjected to an extensive three-month evaluation that included testing for dynamic launch load capabilities, characterization of electromagnetic fields, and performance tests that measured parameters such as power output, system efficiency, and temperature. The purpose of the DOE-sponsored evaluation, which began in late 1999, was to assess the technology readiness of the Stirling convertor relative to viability for a mission with a December 2004 launch date and its readiness for flight development. To support the evaluation, DOE tapped into the space nuclear power system expertise of NASA, Lockheed-Martin, Orbital Sciences Corporation, and others. At the conclusion of the three-month evaluation, the 55-We TDC won the support of the evaluation team as well as technology decision-makers within NASA and DOE, and follow-on development soon commenced.[20]

With the favorable results of the 55-We TDC assessment, DOE soon turned its efforts to development of a Stirling radioisotope generator (SRG). Following development of conceptual designs during a contract downselect phase, development of an SRG formally commenced in May 2002, when DOE selected Lockheed-Martin to serve as system integrator under a new project to develop an SRG capable of producing 110 We. Lockheed-Martin was responsible for the overall design, integration, and qualification of the planned Stirling power system, eventually dubbed the SRG-110. The SRG-110 concept included use of the 55-We TDC under development by Infinia, which was responsible for convertor development, including design, fabrication, and testing. Technical expertise and support for development of the Stirling power system were provided by GRC. With a contract and project team in place, plans were laid to bring a flight-qualified Stirling RPS to fruition.[21]

As design of the Stirling generator progressed, fabrication and testing of TDCs continued in an effort to address manufacturability, performance, life, and reliability criteria. Much of the testing to support technology development, including convertor performance tests, thermal vacuum tests, materials studies, alternator testing, and structural-dynamics testing, was performed at the GRC.[22] Such testing provided opportunities to address technical issues and refine the convertor design and supported overall integration with the Lockheed SRG design.[23]

By the end of 2005, Lockheed had designed a Stirling power system that could operate in the vacuum of deep space and on the surface of Mars. The SRG-110 design consisted of a beryllium housing that contained two free-piston Stirling engines

d. The NASA Stirling technology community uses the term "convertor" rather than "converter" when referring to Stirling power conversion. That convention is reflected throughout this document as appropriate.

(i.e., convertors), two GPHS modules, thermal insulation, and various support components. An electronic controller and other miscellaneous components were mounted on the outside of the housing, as were several fins that served to reject residual heat that wasn't converted to useable electricity. Each closed cycle free-piston Stirling engine would convert the heat from the GPHS module into reciprocating motion, which was subsequently converted to useable electricity through use of a linear alternator. Each TDC was designed to produce approximately 60 watts of (alternating current) electrical power, which was converted into a direct current power level of approximately 55 watts. The SRG-110 design, using the Infinia convertors, resulted in a system specific power of approximately 3.5 We/kilogram and a system-efficiency of approximately 23 percent.[21, 24]

With the SRG design in place, fabrication of an engineering unit generator, a complete system prototype built to test the ability to meet flight requirements, was nearing completion in 2005. Design, fabrication, and testing of a qualification unit had also begun and was scheduled to be complete by the end of 2006. However, cost overruns and the lack of a specific mission resulted in a decision to cancel further development of the SRG-110 system in 2006.[25]

While the specific power of approximately 3.5 We/kg for the SRG-110 was consistent with the objective to use plutonium-238 more efficiently, the 5.4-We/kilogram specific power of the GPHS-RTG suggested there might also be room for improvement to the specific power. To continue the advancement of RPSs, NASA and GRC issued a research announcement in 2002, the focus of which was radioisotope power conversion technology. One of the technologies subsequently selected for a three-year development and demonstration project included a free-piston Stirling engine concept developed by Sunpower, Incorporated.[26]

> To continue the advancement of RPSs, NASA and GRC had issued a research announcement in 2002, the focus of which was radioisotope power conversion technology.

Under a 2003 NASA contract, a Sunpower-led team pursued development of the advanced Stirling convertor (ASC). Over the course of three years, Sunpower developed a convertor design with an estimated electrical power output of 80 We (alternating current), a conversion efficiency of greater than 30 percent, and a convertor-specific power of greater than 90 We/kilogram. In the context of a Stirling generator system, the specific power was projected by GRC to be approximately 8 We/kilogram, more than double that provided by the TDC-based SRG-110 system and much better than the GPHS-RTG. An early ASC test model had also successfully passed vibration testing without power degradation or convertor failure.[27]

In light of such potential, NASA requested that DOE complete fabrication (already in progress) and testing of the SRG-110 engineering unit, utilizing early generation ASCs in place of TDCs to better understand the potential of the new technology. Completed in 2008, the effort was originally planned to be the end of the project; however, renewed interest in Stirling systems combined with favorable generator test results led to a new flight development effort called the Advanced Stirling Radioisotope Generator (ASRG) project.[24, 25]

Under the new ASRG project, Lockheed-Martin continued to serve as system integrator, under contract to DOE, and held the responsibility for design, fabrication, and testing of the ASRG. Sunpower was responsible for design, fabrication, and testing of the Stirling convertor. GRC provided technical support and testing capabilities for the Sunpower convertors, just as they had for the Infinia technology demonstration convertors.

Although initial development and testing of the Sunpower ASC was encouraging, its readiness for flight use remained a distant target as technical questions and challenges remained to be resolved. For example, designers needed to demonstrate a 17-year life for the convertor heater head, the portion of the Stirling convertor that interfaced directly with the GPHS module and had to be able to withstand prolonged exposure to high operating temperatures. To increase the temperature ratio of the system and its overall conversion efficiency, developers of Stirling convertors sought to maximize the temperature difference between the hot and cold ends of the convertor.

Technical issues that had been under investigation and/or closed for the Infinia design had to be revisited for the ASC. In addition, the development and testing of the ASC included development of heater heads fabricated of Inconel 718 and MarM-247, two superalloys selected for operation at temperatures of 650 degrees Celsius (°C) and 850°C, respectively. Although operating at the higher temperature would offer improved conversion efficiency, testing revealed ongoing materials issues at the higher temperature. For instance, convertor designers had to revisit the possibility of the permeation of helium, the convertor working fluid, through this new heater-head material operating at a higher temperature. If helium losses due to permeation were too high, operational performance of the Stirling convertor would be reduced, thereby lowering the power output of the system. For this reason, a special permeability testing apparatus had to be designed and fabricated to address the permeability question. Another area that had to be revisited was organic materials, which were present in the convertor for uses such as electrical insulation and structural bonding in the linear alternator. The materials selected for use in the ASC were different than those used in the TDC, and it was necessary to understand how they would perform under the planned operating temperatures as well as in the presence of radiation, primarily from possible space environments (e.g., the Jovian system) but also originating from the plutonium oxide fuel. These and other key technical questions had to be resolved as they arose to demonstrate the feasibility, longevity, and reliability of the conversion system for space use.[28]

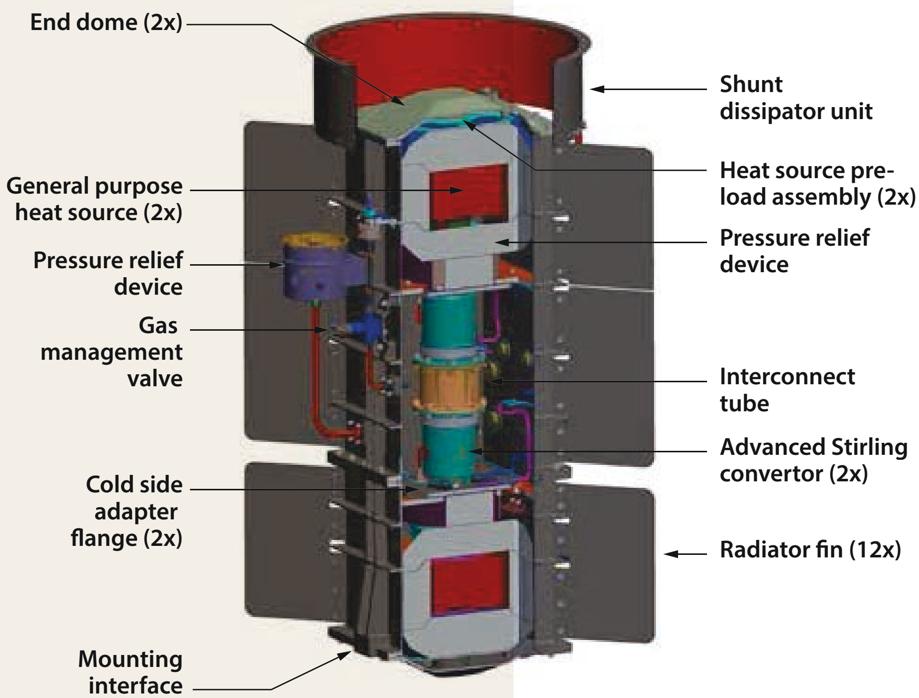
Lockheed-Martin, developers of the Stirling generator system, faced a similar set of questions and challenges in their effort to develop, qualify, and integrate the yet-to-be-demonstrated convertor into the new ASRG. Between 2008 and 2010, Sunpower fabricated numerous convertors of varying materials for a series of long-life reliability tests performed at the GRC Stirling Research Laboratory. System-level testing of the ASRG engineering unit, including vibration, shock, and thermal vacuum tests that simulated launch and space environments, was completed by Lockheed in 2008. The engineering unit was subsequently transferred to GRC and placed under long-term operation.[29] By 2011, the ASRG had projected performance capabilities of approximately 130 We using a little more than 2.2 pounds (one kilogram) of plutonium oxide fuel. The resulting system power conversion efficiency of approximately 27 percent would be achieved from a unit expected to weigh no more than 70 pounds (32 kilograms).[30]

How an ASRG Works

An ASRG produces electricity by converting heat to motion inside the engine, and then converting the motion into electricity that is useable by the spacecraft. Inside the ASRG is a device known as the Advanced Stirling Convertor (ASC), which contains an oscillating piston and a companion displacer sealed inside a closed cylinder and suspended in helium gas. The displacer and piston move back and forth in response to pressure changes between the hot side, heated by the plutonium fuel, and a passive cooler at the other end. The steady alternating expansion and contraction of gas within this Stirling heat cycle drives the magnetized piston back and forth through a coil of wire, with the magnet and coil forming a device known as a linear alternator (also inside the ASC), as movement occurs approximately 100 times per second to generate an alternating current of electricity in accordance with Faraday's Law (a property of physics).

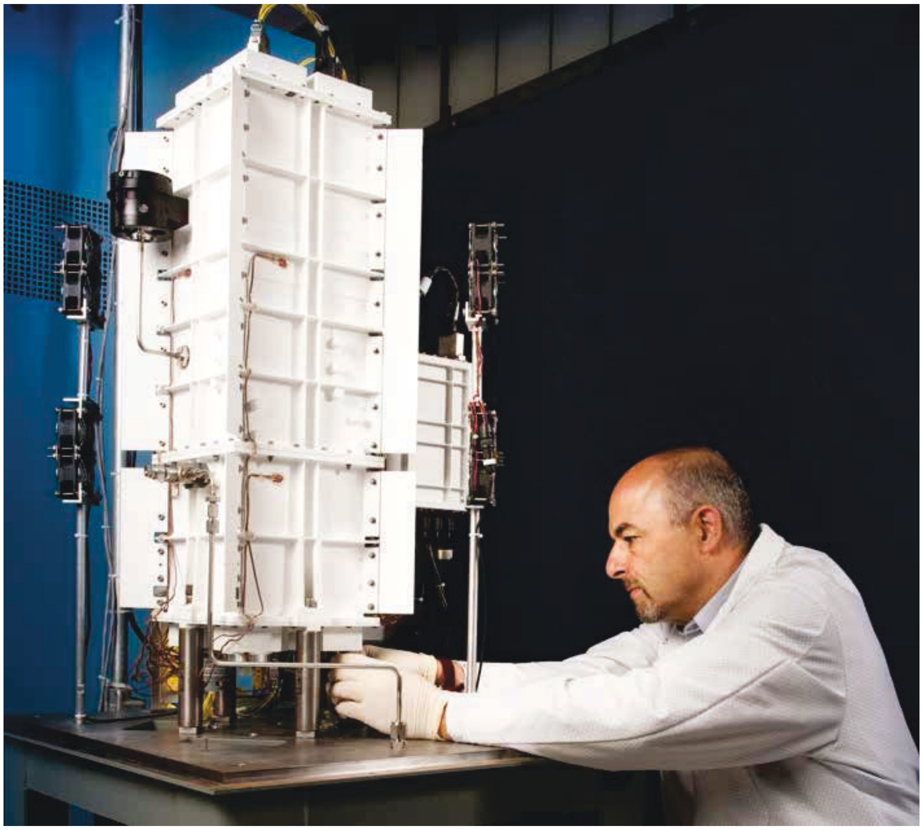
Each ASRG contains two ASCs. The ASCs are aligned end-to-end in the middle of the generator, which serves to cancel out their vibration when their motion is synchronized. The helium gas inside each convertor functions as a hydrostatic bearing, which prevents the displacer and piston from rubbing against the walls of the cylinder to minimize the potential for physical wear.

The ASRG also includes a controller, connected to the ASRG housing by electrical cables, that is designed to synchronize the two pistons, provide ASRG-related data to the spacecraft, and transform the alternating-current power produced by the generator into approximately 130 watts of direct-current power at a voltage useable by the spacecraft (Adapted from NASA Fact Sheet - Advanced Stirling Radioisotope Generator, 2013).



As development of the ASRG progressed, NASA decided in 2011 that the ASRG development schedule should be consistent with supporting a future mission to be launched as early as January 2016; the decision added substantial schedule risk to the project. [31] Due to the cost limits associated with Discovery missions, NASA also intended to provide the ASRG to the mission as government-furnished equipment.

In 2011, the ASRG design was subjected to a final design review that served to confirm system adequacy relative to specified performance and operational requirements.[32] The review led to technical questions that required additional investigation and reviews that continued into 2012. Although many of the technical questions were addressed during this period, the time needed for their resolution raised concerns relative to the ability to provide a flight-qualified unit in the 2016 timeframe.[33] At the same time, the remaining unresolved technical challenges, such as material-properties issues with critical components and nuclear launch safety concerns related to the housing design, continued to impact the project cost and schedule. While ASRG supporters remained hopeful that a near-term mission was still viable, those hopes began to fade in August 2012 when NASA selected a solar-powered Mars lander over two ASRG-powered missions for a 2017 Discovery-class planetary science mission. ASRG developers immediately began looking to the next Discovery-class planetary mission as an opportunity to demonstrate the new RPS in a space application.[34]



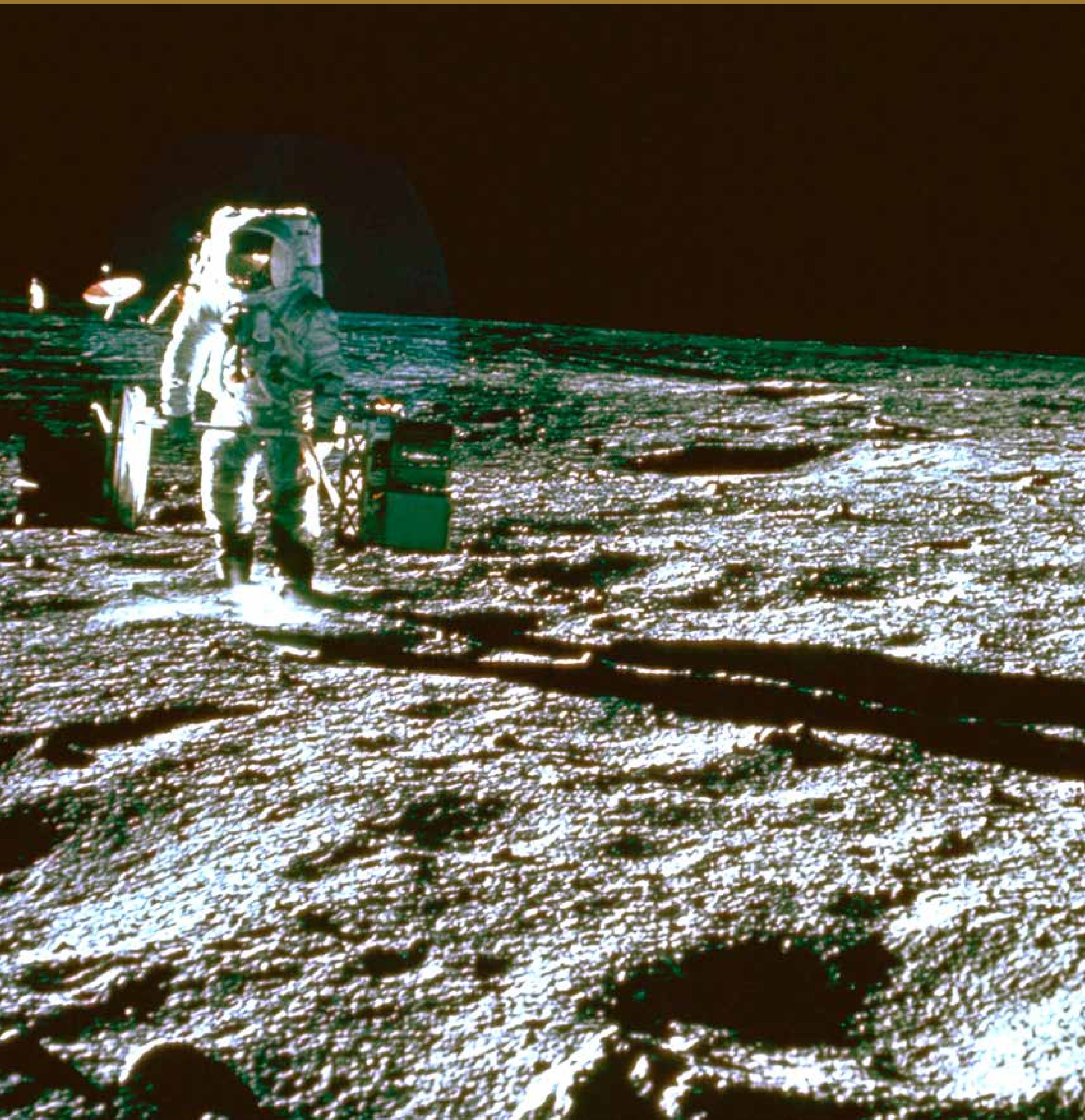
Testing of an unfueled ASRG at NASA's GRC. (Photo: NASA)

In November 2013, any glimmer of hope for a near-term ASRG flight was lost when NASA announced that it had directed DOE to discontinue further work on ASRG flight units—citing budgetary constraints and a favorable plutonium-238 inventory outlook resulting from a new project approved to restart production of the heat source isotope.[35] After nearly 14 years of development, use of an SRG in space would have to wait.

Looking to the Future

Over the years, DOE and NASA have invested substantial time and money to advance RPS technology, particularly in the area of dynamic power systems. Although the focus was largely on Brayton, Rankine, and Stirling dynamic systems, other efforts have been undertaken to develop technologies, such as the Alkali Metal Thermal-to Electric-Converter.[36] More recently, research into new thermoelectric materials (i.e., skutterudites) is showing promise for application in power conversion technology. All of these efforts have contributed to the space nuclear power system body of knowledge, providing an ever-larger base from which future development efforts can build.

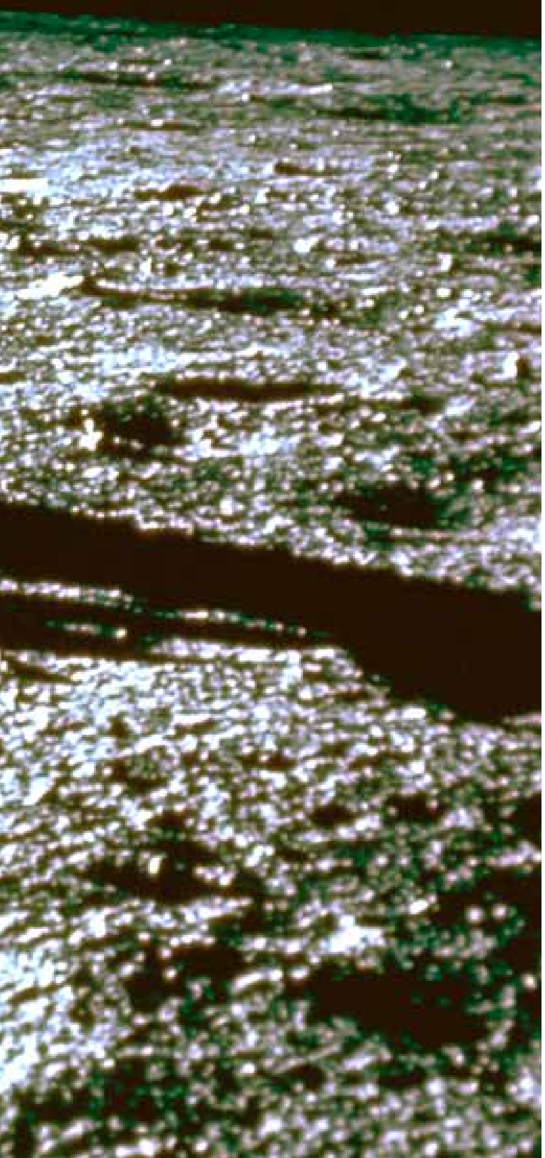
Until the day when new missions rekindled interest in space nuclear reactor technology, much of the 1970s was devoted to simply keeping the technology alive.



4

Reactors Redux

Space Nuclear Reactor Interlude



Following termination of the NERVA nuclear rocket program and other space reactor research in 1973, the remainder of the decade was a dry time for space nuclear reactor technology development. Changing national priorities and reduced Federal budgets hampered further research through much of the decade. At the same time, there were still strong incentives for use of space nuclear reactors. Apollo-era projects provided a solid foundation to build upon, and reactors had capabilities unmatched by competing technologies like solar power. The greater power, compactness, and robustness of the technology could help the United States keep tabs on potential enemies, enable more civilian uses of satellites, and dramatically accelerate exploration of the outer solar system. Until the day when new missions rekindled interest in space nuclear reactor technology, much of the 1970s was devoted to simply keeping the technology alive.

Space Reactor Revival

Although space reactor research in the United States was defunded in 1973, a smaller space nuclear power program continued to operate with the majority of funding directed toward RPS development. During a hearing before the Joint Committee on Atomic Energy in March 1973, David Gabriel, Director of the Space Nuclear Systems Division at AEC, noted that space reactor research was terminated because of budget priorities and the lack of near term NASA missions requiring the power levels afforded by space nuclear reactors: "These projected [mission] delays, along with the budget priorities, led to the decision that the distant payoffs did not warrant continued funding of high-powered nuclear propulsion or reactor power systems."[1]

Despite the end of large-scale space reactor development, the years that followed saw a small but ongoing effort to maintain the viability of space reactor technology.[2] In addition, some space power energy conversion technologies found new life in ground-based power and transportation programs only to be resurrected years later in new space reactor programs. One example was the Thermionic Energy Conversion for Applied Research and Technology program, which researched the use of thermionic conversion to produce electricity using heat recovered

Apollo astronaut on the moon. Apollo-era projects provided a solid foundation to build upon, and reactors had capabilities unmatched by competing technologies like solar power. (Photo: NASA) from coal-fired central power stations. In 1975, NASA broadened the program to include high temperature out-of-core nuclear thermionic power systems for future space applications.[3]

In 1973, AEC, DoD, and NASA formed an ad hoc group "…to evaluate the future DoD needs in space power and to indicate the possibility of meeting those needs with space [nuclear] power systems."[2] The group's final report, issued in March 1974, recommended preserving the reactor technology developed under the SNAP program and stimulating "a focused space power program for earlier payoffs on DoD missions."[2]

The focused space power program began to take shape in 1975 when DoD and the newly-formed ERDA, the successor agency to AEC, established a Space Nuclear Applications Steering Group. Chaired by George P. Dix, former head of the AEC space nuclear safety program,[4] the group was tasked to establish effective management and communication channels between the agencies in order "to encourage a proper development program for space nuclear energy systems."[2] In concert with the steering group, DoD and ERDA also established a space nuclear power working group in early 1976. The working group was tasked to study future DoD space power requirements to determine which applications would best be served by nuclear power systems and to recommend a space power technology development program.[5]

In August 1976, DoD Steering Group Chairman A.E. Vossberg sent a letter to Richard W. Roberts, ERDA's Assistant Administrator for Nuclear Energy, stating, "In our continuing effort to ensure that future space power requirements of the DoD can be met on a timely basis, I wish to call your attention to the growing likelihood of need for space nuclear reactor systems in the 10 to 100 kW electric range in the late 1980s and beyond."[2]

By 1977, the Steering Group had identified several DoD missions with power requirements up to 100 kWe. Comparing reactors to their main space competition, solar-battery power, the group found that for military missions, solar panels coupled with batteries were competitive with nuclear in the range of 25 to 50 kWe; nuclear power was judged to be superior above power levels of 50 kWe. With several potential DoD missions needing 25 kWe or more, particularly a space-based radar system planned by the Air Force, the case for a renewed space reactor development program continued to gain traction, as noted by the Steering Group in January 1977:

"*Although the Steering Group has been unable to identify any approved and budgeted DoD missions (requiring greater than 3 kWe)… a reactor power supply is presently the only candidate spacecraft power option for future high power applications. This fact, combined with data on space reactor power capabilities outside the U.S., the enhanced military capability provided by having sufficient power to operate on-orbit equipment such as radar, and future threats to our space defense posture afforded by similar high power capabilities in the hands of adversaries, has led the Steering Group to recommend that a reactor power development program be initiated by the U.S. following intensive preparatory studies to define the reactor power system and its requirements.*"[2]

Additional support for a renewed space reactor development program was provided by the space power system working group when it recommended a "modest technology and experimental program to provide a solid basis from which to develop space reactors."[5] The recommendations soon bore fruit.

Space Electric Power Supply Program

In 1977, DoD and ERDA initiated a joint technology-screening study to evaluate existing space reactor power system technologies and develop a space reactor power system concept for further development. The study was performed by LASL under a new Space Electric Power Supply program.[6,7] With the advent of the planned Space Transportation System, or space shuttle (under development since 1972) a new era of space use and exploration was expected to open up and, along with it, larger space-based systems that would require higher power, thereby giving impetus to the new space reactor efforts.[8]

> With the advent of the planned Space Transportation System, or space shuttle (under development since 1972) a new era of space use and exploration was expected to open up.

Although the technology screening study was initiated under ERDA, it would be completed under a new Federal agency. Only 20 months after the formation of ERDA, its almost 9,000 employees were consolidated into the newly created DOE, which combined ERDA with other energy-related Federal organizations. George Dix became the Director of Safety and Environmental Operations within the new Federal agency[4] and Bernard Rock became the Director of the Office of Space Nuclear Projects. The Space Electric Power Supply program continued under the Nuclear Energy Programs group within the Assistant Secretary of Energy Technology organization in the new DOE.[7]

The screening study included the identification of several DoD missions that could require power levels up to 100 kWe, such as satellites and space-based radar, many of which were expected to be needed by the early 1990s. DoD required a seven-year lifetime and 95 percent reliability, preferring designs that would degrade only gradually and avoid the potential for a single fault to cause the whole system to fail (such a failure is often referred to as a single-point failure). The reactor had to be able to operate in Earth's natural radiation fields, and radiation created by the system had to be limited both in rate and amount delivered over the mission lifetime. The reactor was also expected to meet all regulations of NASA, DoD, DOE, and the National Range Commanders in charge of the sites where the system would be launched.[5]

In addition to the potential DoD missions, studies by Grumman and McDonnell Douglas identified commercial industrial-scale low-earth-orbit missions that were likely to require a space nuclear power system. One mission envisioned a construction site in space to build solar- or nuclear-powered satellites that would send energy to Earth. Another was a low-gravity manufacturing facility. The studies also proposed a civilian version of the military's new GPS and scientific missions focused toward the stars and planets.[5] For NASA, potential applications included communication and surveillance systems, electronic mail, and advanced television antenna systems for which five to 220 kWe was expected, and planetary exploration missions requiring even higher power levels.

Based on a target power level of 10 to 100 kWe, LASL developed 135 reactor power plant combinations that reflected a suite of reactor designs, electric-power-conversion technologies, and heat rejection systems. The reactor designs included heat pipe, gas-cooled, and liquid-metal concepts, while fuel types included uranium carbide, uranium oxide, and uranium nitride. Several power conversion technologies were evaluated, including static (thermoelectric and thermionic) and dynamic (Brayton, potassium Rankine, and Stirling) systems. Heat rejection options included heat pipes, pumped fluid with fin radiators, and pumped fluid with heat pipe radiators. After consideration against criteria that included weight, size, reliability, safety, and development cost and time, LASL recommended a technology development program based on a concept consisting of a heat pipe solid-core reactor with thermoelectric power conversion, and a heat pipe radiator.[5]

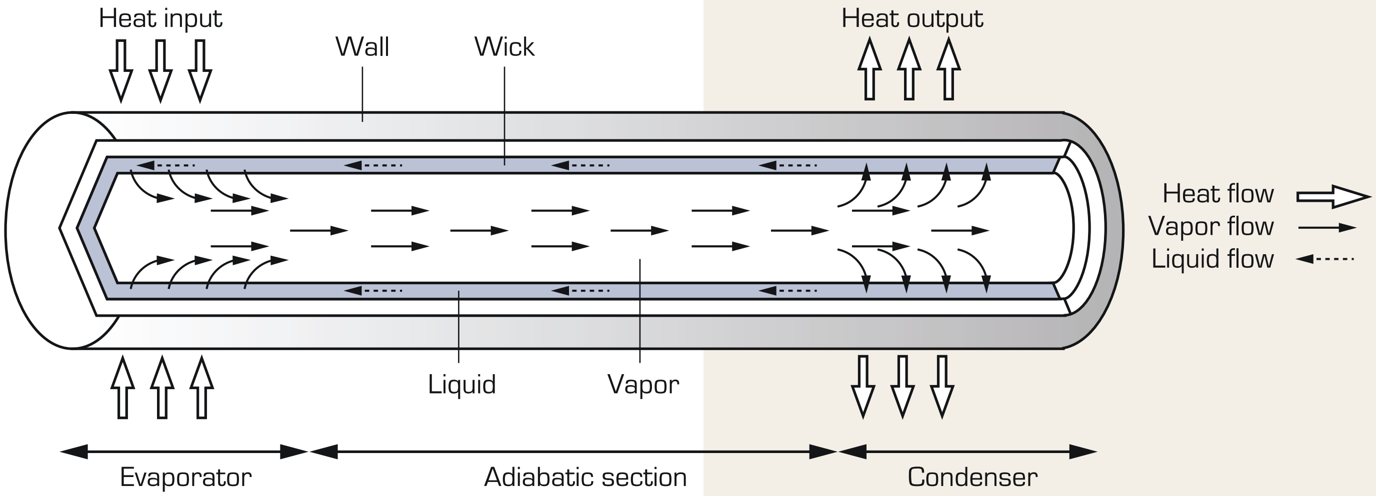
As the LASL technology study progressed, an accident involving a Russian space reactor power system provided a somber reminder of the importance of incorporating safety into all aspects of space nuclear power system design. In January 1978, a malfunction aboard a Russian satellite (Cosmos 954), which was powered by a nuclear reactor, resulted in its failure to boost into a higher orbit. Upon re-entry, the reactor disintegrated in the upper atmosphere (per its design) resulting in radioactive debris being scattered over a 48,000-square mile (124,000-square kilometers) area of northern Canada. A joint response by Canada and the United States managed to find approximately 0.1 percent of the reactor core.[9, 10] The event raised international policy questions regarding the use of nuclear reactors in space and led to the creation of a United Nations working group to address the topic. It also motivated President Jimmy Carter to propose a joint U.S.-Soviet ban on nuclear reactors in Earth's orbit if a fail-safe mechanism to prevent radioactive material from entering the atmosphere could not be implemented; however, the ban was not accepted by the Soviet Union.[11]

While the Cosmos 954 accident had broad visibility, it also provided a context for discussion of safety as it pertained to the LASL space

A joint response team from the United States and Canada, dressed in specially designed arctic clothing, search for Cosmos 954 radioactive debris with hand-held radiation detectors. (Photo: DOE/NV1198) reactor technology assessment effort then underway. David Buden, a key member of the LASL space reactor technology assessment team, noted that "safety has been and continues to be a major concern of U.S. scientists involved in using reactors in space."[12] Safety was built into space reactor designs through a combination of engineering design, analysis, and testing. For example, the use of reactor safety features such as backup control rods, where only one would be unlocked at a time, served to prevent inadvertent operation. Reactor design also included measures to prevent inadvertent criticality when immersed in water. The long-standing emphasis on safety was, and would continue to be, a

Heat Pipe Technology

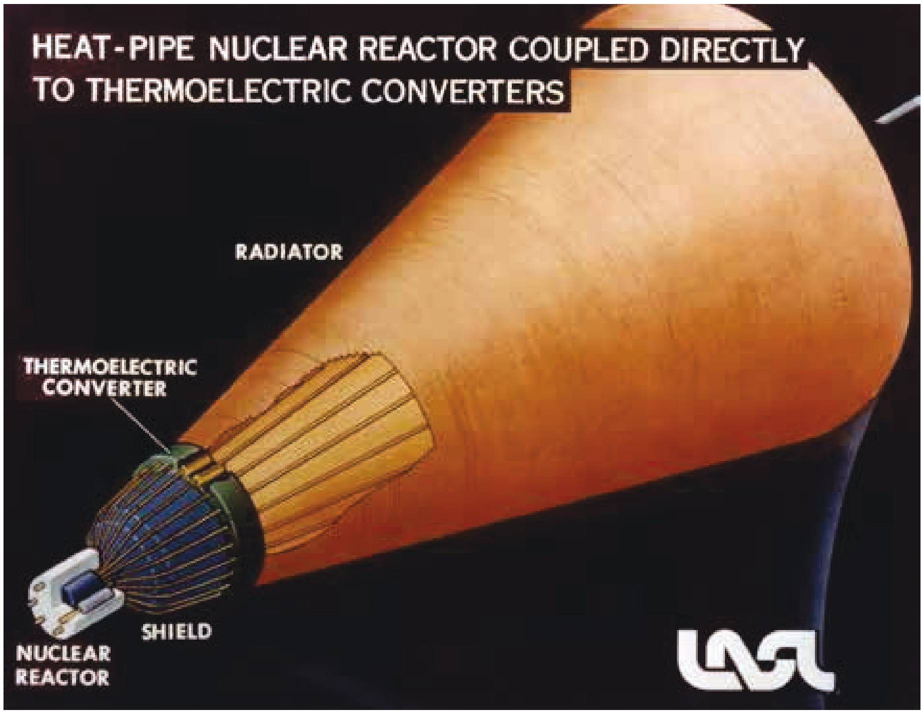
A heat pipe is a highly efficient way of transferring heat from one location to another. It is a sealed tube containing a low-pressure working fluid (e.g., sodium or lithium) matched to the preferred system-operating temperature. The fluid evaporates at the heated end of the tube and condenses at the cooler end, releasing its heat and wicking back toward the hot end of the tube by capillary action. For the SPAR reactor concept, the heat pipes, integral to the reactor core, would extend beyond the core and traverse the reactor shielding, where they would then connect with the thermoelectric power conversion system. Because there are no moving parts (only the working fluid moves), heat pipes are highly reliable. The heat pipe was developed in 1963 by LANL physicist George Grover, and it was first implemented in the NERVA program. NASA continued to develop heat pipe technology through the 1960s. Today heat pipes are routinely used to cool electronics on geostationary communication satellites.[13]
(Image adapted from "Space Nuclear Power," Joseph A. Angelo, Jr. and David Buden, Orbit Book Company, 1985)



fundamental aspect of U.S. space reactor power system development, including the space reactor work being performed at LASL.

Space Power Advanced Reactor

In late 1979, DOE initiated a five-year program to develop the technology base of the heat-pipe reactor power system recommended by LASL. With funding of $2 million per year, the goal was to develop a space reactor system capable of producing 10 to 100 kWe. The LASL heat pipe reactor power system concept was subsequently named SPAR.[14,15] Concurrent with the DOE activities, NASA also began funding work on heat pipe and power conversion development, both at LASL and their own facilities. In early 1980, DOE and NASA joined with DoD to create a steering committee and space reactor working group to bring some unity to the DOE-funded SPAR effort and NASA's own space reactor work (the groups worked together until 1981).[2]



Concept of a heat pipe nuclear reactor coupled directly to thermoelectric converters. The heat pipes extend from the reactor core (bottom left of image) and carry heat to the thermoelectric converter. Excess heat not converted to electricity is transferred to the radiator via a second set of heat pipes. (Image: LANL)

By 1981, an initial design for SPAR had been developed. The reactor was being designed to produce a nominal 1,200 kW of thermal power while operating at 1,500 Kelvin. The reactor design incorporated a core of 90 uranium oxide sodium-filled heat pipe fuel element modules. The heat pipes would remove thermal energy from the reactor core and transfer it to the thermoelectric power conversion system. For compatibility with the space shuttle power system, the mass would be less than 4,210 pounds (1,910 kilograms).[16]

The core was to be surrounded by a neutron reflector of beryllium or beryllium oxide, which would control reactor operation. As with the NERVA program, rotating drums were to be used for power control; each drum would contain a boron carbide sector that could be rotated in and out of the reactor to control reactivity. Redundant instrumentation and electronics would increase reliability, which was considered as important as safety, and the reactor had to keep operating even if some components failed.

For the thermoelectric power conversion system, LASL planned to use an improved version of the silicon-germanium thermoelectric materials used in the MHW-RTGs that powered the Voyagers 1 and 2 spacecraft; the improved silicon-germanium material, then under development by DOE, contained gallium phosphide and offered the potential for higher conversion efficiency. Excess heat would be radiated to space through the use of a heat pipe radiator system. A shadow radiation shield design was also drawn from the earlier SNAP and Rover reactors. Because the reactor was to be used in space where there is no air to deflect neutrons and gamma rays around the shield, weight could be reduced by placing the reactor and payload at opposite ends of the spacecraft with shielding in between, instead of shielding the whole reactor.

By 1982, the SPAR technology development program had evolved into a broad testing, experimental, and analytical program centered on the reactor, heat pipes, thermoelectric materials, and shielding. For example, predictions of neutron behavior in the reactor core were experimentally checked using a critical assembly. Analyses were also performed to demonstrate the reactor would remain safely sub-critical in the event of immersion in water. Fuel development focused on production processes for the uranium oxide fuel and in-reactor testing to verify fuel performance and heat transfer characteristics. Development of the molybdenum heat pipes included materials testing, wick design development, development of processes to bend the heat pipes, and performance testing for compatibility with working fluids. For the power conversion system, activities focused on development of silicon-germanium thermoelectric modules (i.e., panels) that would interface with the heat rejection system heat pipes.[17,18]

Excess heat would be radiated to space through the use of a heat pipe radiator system.

Because the space shuttle was to be the primary method of launching systems into space, reactor power system designers also had to ensure that the spacecraft and its reactor power system would fit in the shuttle cargo bay, a cylinder 60 feet (18.3 meters) long and 15 feet (4.6 meters) in diameter. When an upper stage launch vehicle was factored into the spacecraft configuration, the available room in the shuttle could be reduced to 42 feet (12.8 meters) long and 14 feet (4.3 meters) in diameter.[19]

Reagan National Space Policy

In July 1982, President Ronald Reagan announced his National Space Policy, which was intended to strengthen U.S. security, expand private-sector investment, and increase exploitation of resources and international cooperation. The 1982 policy established the space shuttle as a major factor in the U.S. program and called on NASA to continue exploring the "requirements, operational concepts, and technology" needed to support permanent space facilities – a space station.[20]

Defining Roles and Goals: Establishing Cooperation

As the technology effort progressed, the future of its funding soon came into question. During the formulation of its fiscal year 1982 budget, DOE was directed by the Office of Management and Budget to reduce its funding for space reactor development to $1 million, thereby putting DoD and NASA on the hook to fund the shortfall. Although DoD opted out of funding, NASA agreed to support the project and work with DOE toward a joint technology verification phase; NASA mission models had indicated that 100 kWe was suitable for both outer-planetary and earth-orbital missions. Because of the budgetary constraints at DOE, NASA also assumed responsibility for development of the power conversion subsystem while DOE retained responsibility for development of the reactor subsystem, with funding support from NASA.[15] The arrangement marked a change from previous joint NASA-DOE approaches under which DOE was solely responsible for funding reactor technology development.[3]

Shortly after NASA became a co-sponsor of the SPAR technology development program, it was named the Space Nuclear Reactor Power Systems Technology Program and the SPAR reactor was renamed SP-100 (for Space Power 100 kWe).[2, 15] The SPAR reactor design was also refined to ensure its compatibility with the space shuttle and to raise its temperature and energy density.[21] The new program goals were similar to those outlined for the original SPAR design and included full-power operation at 100 kWe for seven years, with an overall system life of 10 years, and no single-point failures.[2]

Although the technology development program had shifted to support NASA, groups within DoD continued to maintain an interest in a space reactor power system.

Although the technology development program had shifted to support NASA, groups within DoD continued to maintain an interest in a space reactor power system. In addition to its attractiveness for space-based radar, surveillance, communications, electric propulsion, and jammers, such systems offered other benefits, as noted by Gordon L. Chipman, DOE Deputy Assistant Secretary for Breeder Reactor Programs (and oversaw its Office of Space Reactor Projects):

"*[N]uclear power enhances survivability against nuclear attack, laser attack, and antisatellite attack. It also makes it practical to provide the payload with high power, which enhances survivability by permitting higher orbits, more ground links, harder electronics, smaller antennas, and mobile ground receivers. Nuclear power also provides the spacecraft with an improved field of view and improved pointing accuracy and permits undegraded operation in the Van Allen radiation belts.*"[15]

With the continued interest in space power reactors, DOE separated its Office of Space Nuclear Projects into an Office of Special Applications focused on RPS technology and an Office of Space Reactor Projects.[22]

The National Research Council Lends a Hand

In the months that followed the conception of the DOE NASA SP-100 reactor, the agencies began working with the Defense Advanced Research Projects Agency (DARPA) to establish a joint program for development of a 100-kWe space reactor system. Disagreements over management, organization, and program goals soon led to tension. For a short time in late 1982, NASA began working with DARPA under a project called the Technology for Advanced Space Power program, leaving DOE to continue work on technology for the SP-100 reactor.[21]

As the three agencies struggled to find common ground, the Departments of the Army, Navy, and Air Force; DARPA; and NASA sponsored the National Research Council in October 1982 to assess the state-of-the-art advanced nuclear power systems with possible aerospace applications in the area of propulsion, including shielding and safety problems. The Council was also asked to describe research gaps and areas of uncertainty in space nuclear power system technology and to make recommendations for future development efforts. To accomplish its task, the committee responsible for the assessment organized a symposium on advanced reactor concepts in November 1982. The symposium offered an opportunity for experts throughout the space nuclear power community to discuss space power technology concepts, safety, research and development issues, and mission requirements for both space reactor power and propulsion systems. It also provided the basis upon which the committee developed its assessment and recommendations for future space nuclear power technology development efforts.[23]

Failure to act would mean a higher bill later for a crash program or simply not having the needed technology at all.

Space Nuclear Power Symposiums

In the fall of 1982, a small group of government, industry, and academic representatives, including University of New Mexico professors Dr. Mohamed El-Genk and Dr. David Woodall, decided to hold an annual symposium on space nuclear power systems due to growing interest in such systems within the Federal government. The first symposium, held in 1983, was enthusiastically received by the space nuclear power community. Though initially small, the annual symposium briefly rose to prominence several years later. After a decade of obscurity, limited funding, and slow development, space nuclear reactors were again on the front burner of U.S. space power research.

In its final report, the space nuclear power assessment committee noted that a government-wide joint space reactor power system program was appropriate because both the military and civilian agencies had future power needs that could only be met with reactors. Failure to act would mean a higher bill later for a crash program or simply not having the needed technology at all. The report also included assessments of several items that had been cause for earlier frustration and tension among the agencies, including funding and research program goals, and provided an assessment of the LASL heat pipe reactor.[24]

The report accurately described a chicken-and-egg dilemma that DoD, NASA, and DOE had been facing in deciding whether and how to proceed:

"Most research and development managers would like to be in a situation in which a user (with resources) can specify with precision a requirement that can serve as the target for a technical development effort. However, experienced technical managers recognize that such a linear situation rarely obtains [sic], especially in circumstances in which long lead times and expensive development efforts are required. Prudent program managers are reluctant to risk or expose large scale resources

to achieve stated requirements until the viability of the technology is sufficiently well established to provide a reasonable prospect that the requirement can be met at estimated costs. On the other hand, major resources for research and development programs cannot be easily justified to those who control funds unless a firm requirement exists. The inevitable result of such a situation is no action unless research and development programs can be launched and pursued with a realistic acceptance of the uncertainty…"[25]

The report also weighed in on the question of which agencies should pay for the needed research and development:

"Potential Air Force and NASA users are loath to adopt a requirement prior to demonstration of the technology from a concern about… a large development bill, perhaps in the range of $500 million to $1 billion. Yet most managers of space systems programs recognize that the future… points toward nuclear power…The military users should recognize that someone will need to bear the research and development cost for the operational capability they will require. Accordingly, these users should recognize that the desired capability will not be forthcoming unless they are more supportive of these initial research and development efforts."[26]

On the subject of the DOE-NASA SP-100 reactor, the report noted that the LASL design was of high quality but "not sufficiently unique or demonstrably superior to alternative concepts to justify selection of this approach."[27] The report identified several areas that still required significant development before a full ground test could be pursued, most notably in the heat pipes (fabrication, performance, and longevity), reactor (fuel behavior and actuator performance), and high-temperature thermoelectric performance. For these reasons, the committee urged that alternative concepts "be brought to a stage in which they can be evaluated relative to the SP-100 on a similar basis."

In light of its assessment, the final report recommended a research and development program be funded at a level of $10 to $15 million per year to develop a 100-kWe space power reactor as a generic multi-use development, not tied to a specific mission. The recommendation came with a warning: *"The major lesson from this history is the importance of approximately matching the research and development effort to the process of emergence of a firm requirement. The committee seeks to avoid a massive research and development program that never meets the needs or resource availability of military or civil space users."*[28]

In February 1983, DOE, NASA, and DARPA finally came together and signed a tri-agency memorandum of agreement to take action along the lines of the National Research Council recommendations.[29] The agreement called for the three agencies to assess and advance the technology for 100-kWe and multi-megawatt (MMW) space nuclear power systems, provide engineering development and production systems for users, and ensure nuclear safety. Under the new agreement, the agencies carried the DOE-NASA SP-100 name into a new space reactor development program that would be the largest since the days of Rover/NERVA.

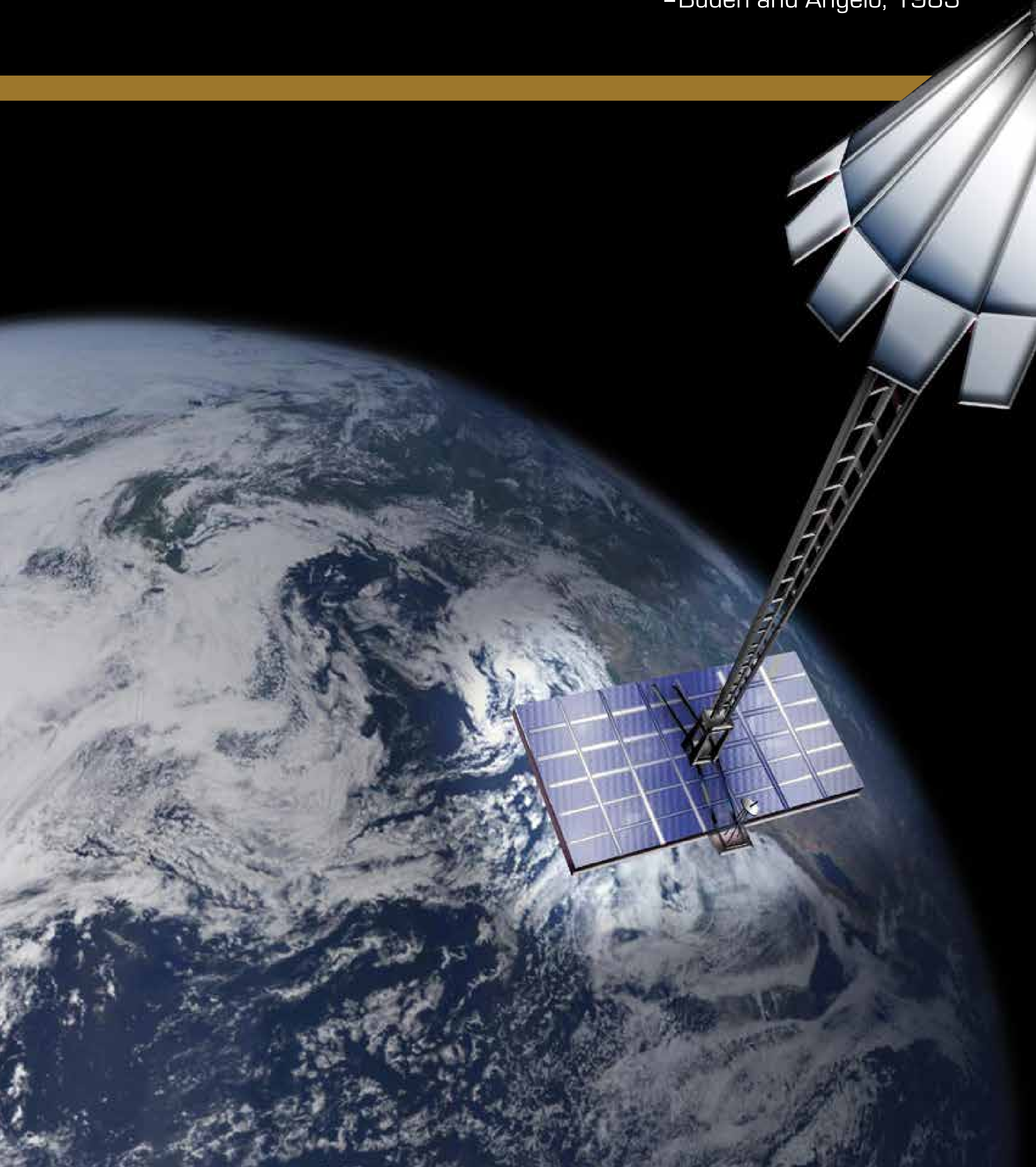
"The committee seeks to avoid a massive research and development program that never meets the needs or resource availability of military or civil space users."[28]

The Interlude Gives Way

The 10-year period that followed the termination of the Rover/NERVA program seemingly served as an interlude for U.S. space reactor development. Efforts were aimed at keeping the technology moving forward. Although seemingly buried, the prospects of power and other benefits afforded by a space reactor power system brought about a renewed development effort focused on a heat pipe reactor that served to expand the base on which future space reactor work could build. The desire for space reactor power also provided the impetus by which the broader space nuclear power system technical community was brought together to share technology status, concepts, and information. That gathering gave rise to what would become a decade-long annual event that eventually expanded to include international partners. At its conclusion in 1983, the interlude had given way to the SP-100 program, a new movement in the concerto of space reactor power system development (discussed in Chapter 5). As for the LASL heat pipe reactor system concept, it was carried into the technology assessment phase of the new SP-100 program but eventually was set aside in favor of other technologies.

"The successful test flights of the Space Shuttle mark the start of a new era – an era of routine manned access into cislunar space."

–Buden and Angelo, 1983



5

The SP-100 Program
A 100-KWe Space Reactor

In the 10 years following termination of the Rover/NERVA program, the domestic space reactor program had maintained a tepid pulse through occasional funding for technology reviews and limited development efforts. As the country turned the corner on the 1980s, that pulse began to quicken as talk of missions requiring higher-power systems became more common within the walls of DoD and NASA. In 1981, talk turned to optimism as DOE, DoD, and NASA sought common ground on plans to undertake a new space reactor development program. That optimism became reality when the agencies signed a tri-party agreement in February 1983 (as discussed in Chapter 4) to jointly pursue development of technology for a space nuclear reactor power system capable of producing electrical power in the range of tens of kilowatts to 1,000 kilowatts. The new SP-100 program, as it was called, was a successor to the late 1970s space reactor development effort undertaken at LANL under the SPAR/SP-100 moniker and opened a new chapter in the history of U.S. space reactor development.

Gearing up for Success

The SP-100 program was planned as a three-phase effort to be conducted over a period of 10 years. Phase I (1983 through 1985) would involve technology assessment and advancement, and would culminate in a ground-test-phase decision. If warranted, Phase II (1986 through 1989) would involve development and ground testing of a reactor power system prototype, while Phase III (1990-1993) would involve flight qualification of the power system.[1]

The 1983 tri-party agreement provided the general framework under which DOE, NASA, and DARPA worked together during Phase I to select a space reactor power system concept. Overall programmatic direction and policy were provided by a tri-agency senior-level steering committee. Technical direction and integration of project activities were provided by a project office established at the JPL and led by Vincent Truscello, with assistance from LANL and the NASA Lewis Research Center.[2]

Artist's concept of a space nuclear power reactor orbiting above Earth. (Image: NASA)

To support the technology assessment and development activities during Phase I, a generic set of performance criteria were established for the planned SP-100 system. The criteria included a power output of 100 kWe; a design lifetime of 10 years, with seven years at full power; a maximum system mass of 6,600 pounds (3,000 kilograms); and a maximum length of 20 feet (6.1 meters). The length criterion was associated with the space shuttle cargo bay, which was to be used to launch the space reactor into orbit. The power system would also need to be scalable to higher or lower power levels without major design changes.[2] Although generic in nature, the power system criteria provided broad targets for evaluation and design of candidate SP-100 power system concepts.

With the assistance of three contractors (GA Technologies, Rockwell, and GE), JPL was responsible to review candidate power system concepts and recommend one concept that could meet expected civilian and military mission requirements. Research to advance nuclear technology, such as fuels and materials research, was performed at DOE laboratories, including LANL, ORNL, and Argonne National Laboratory-West (ANL-W). The DOE Energy Technology Engineering Center, located in Los Angeles, California, performed support test-facility work.[3] The Lewis Research Center provided support in areas of mission analysis, with particular emphasis on space shuttle missions and development of technologies such as energy conversion, thermal management, and space power materials and structures under an advanced technology program.[4] safety-evaluation program was established to ensure the reactor system concepts and the technology supporting those concepts would not result in designs that would lead to unacceptable nuclear safety risks. Phase I also included an effort to evaluate candidate DOE sites for reactor-power-system ground testing suitability.[2]

Linking the SP-100 power system to a specific mission was crucial for justifying the program and establishing design goals. Such linkage was also a necessity to ensure long-term funding and support.

Missions, Power Systems, and Technology

With funding of approximately $15 million per year, Phase I of the SP-100 program consisted of three core tasks: (1) definition of potential DoD and NASA missions that might require nuclear power, (2) evaluation of reactor power system concepts that could meet mission requirements, and (3) technology advancement (including testing and analyses) to address areas of technical uncertainty. Of primary concern from the outset was the need to ensure nuclear safety was properly addressed throughout the entire program, including Phase I. Therefore, a

Linking the SP-100 power system to a specific mission was crucial for justifying the program and establishing design goals. Such linkage was also a necessity to ensure long-term funding and support. Indeed, history had shown that while previous space reactor development efforts, such as the Rover/NERVA program, had demonstrated a high measure of technical success, the absence of a definitive mission could preclude ever going operational.[5] To that end, review groups were established by DoD and NASA to perform mission analyses and requirement studies early in the first phase. Workshops provided an avenue to discuss mission needs in the context of technology and power requirements.[6] Several generic missions were eventually identified. DoD anticipated power demands up to 100 kWe for robust surveillance systems, survivable communications with anti-jamming capabilities, and electric propulsion systems for orbital transfer and space-based weapons applications. NASA anticipated nuclear electric propulsion and power needs up to 50 kWe for uses such as interplanetary missions, an Earth-orbiting tug, and manned space stations and planetary bases.[7]

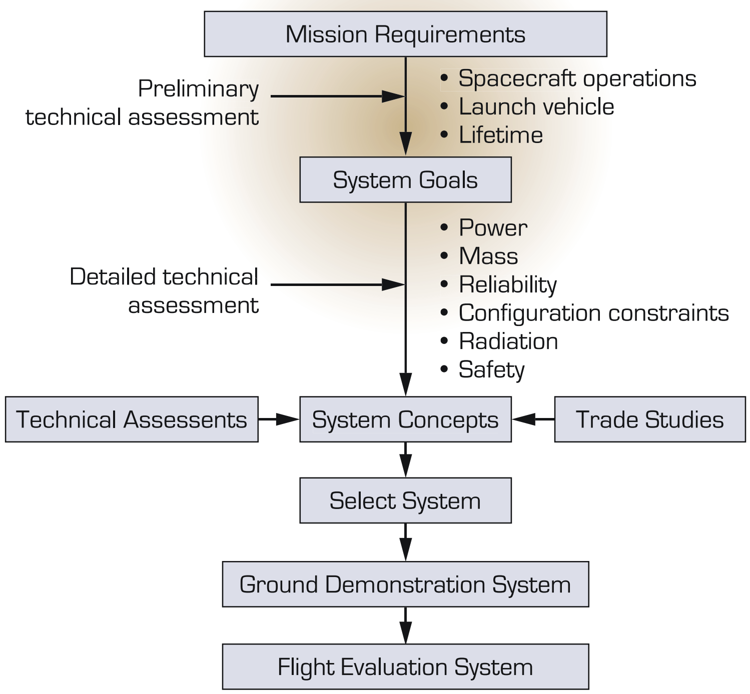
In the area of technology development, Phase I activities focused on a broad range of testing and experiments to advance technology that was common to multiple reactor systems or had applications beyond the SP-100 program. For example, in-core reactor-life testing of thermionic diodes was initiated to demonstrate the potential for a seven-year life. Research was initiated in high-temperature thermoelectric materials. Compatibility testing of reactor construction materials and reactor coolants was conducted. Fabrication and life testing of refractory metal heat pipes was also initiated. LANL re-established a production capability for uranium nitride fuel elements, lost since the SNAP-50 program in the 1960s, and continued efforts to demonstrate a fabrication capability for refractory metal fuel pins.[2] In the area of power-conversion technology, the Lewis Research Center initiated a Space Power Demonstrator Engine project to demonstrate the feasibility of a 25-kWe free piston Stirling engine for possible use with the SP-100 system.[8]

As technology development and mission analysis progressed, so did the development and evaluation

Cold War Concerns

Throughout much of the 1980s, Russian space nuclear activities continued to be a source of military and international concern, which provided impetus for the SP-100 program. Soviet surveillance satellites were designed to detach from their reactor power sources at the end of their missions, after which the reactor was to be boosted into a higher orbit, delaying re-entry for hundreds of years while fission products decayed to a safe level. In early 1983, the reactor from the Russian Cosmos 1402 spy satellite, launched in August 1982, separated from the satellite but the booster rocket failed to fire. As a result, the reactor reentered Earth's atmosphere in February 1983 over the South Atlantic Ocean.[9] Although not as serious as the re-entry of Cosmos 954 over Canada in 1978, at least in terms of response and cleanup, the event highlighted concerns about Russian space reactor technology, as noted by Mr. Herman Roser of DOE, during an address to the National Research Council on June 15, 1983:

"While the nuclear Navy is an outstanding example of the use of nuclear reactors to achieve defense energy security, we have not fared as well in our [space] reactor programs… On space reactors, we lag the Soviets by 10 years… Two Soviet nuclear-powered satellites were over the Falklands [during the war between Great Britain and Argentina] according to Defense Daily. My people were involved in two Soviet space emergencies: the Cosmos 954 reactor emergency in Canada in 1978, and the recent Cosmos 1402 reactor re-entry this January. It requires only a little imagination to be concerned with what the Soviets are doing in space today and what they will be capable of doing in the future, with their advantages in space nuclear power, given their possession of hardened multi-hundred kilowatt or megawatt nuclear reactors in orbit."[10]



Basic steps in development of a space nuclear power system. (Adapted from "Outlook for Space Nuclear Power Development," G. L. Chipman, Jr., 1982)

of reactor power system concepts. By early 1984, preliminary assessments had been completed that provided a broad evaluation of the suitability and performance of reactor technologies in the areas of nuclear fuels, refractory alloys, and other materials for high-temperature applications; fast and moderated cores and gas- and liquid-metal-cooled reactor types; heat pipe, thermoelectric, and thermionic static power conversion; as well as dynamic conversion systems, nuclear safety, and nuclear radiation and shielding. Three promising reactor-power-system concepts were selected for further evaluation: (1) a high-temperature liquid-metal-cooled pin-element fast reactor with out-of-core thermoelectric conversion, (2) an

Technology Pros and Cons

Several factors made space reactor power systems attractive for both civilian and military applications in the early 1980s (several of which still apply today). For example, at electrical power levels above approximately 25 kWe, the power-to-mass ratio of a space reactor system could be considerably higher than its solar/battery system cousins. A space reactor power system could also be used for deep-space applications without orientation to the sun. The relatively low cross-section configuration offered enhanced survival in radiation fields, reduced drag in orbit, a smaller detectable cross section, and enhanced maneuverability and hardenability. Nuclear power sources are also hardened against radiation by design to protect the power processing and control systems.

Conversely, solar cells suffer radiation damage over a period of years, making them unreliable for long-term missions where radiation is high (Jupiter's radiation belts hold the same threat for NASA's spacecraft). The performance of photovoltaic panels available at the time also degraded rapidly in so-called low-intensity, low-temperature conditions found far from the sun. From a military perspective, solar panels had been shown to be vulnerable to the after-effects of nuclear explosions, which send charged particles into orbit in Earth's Van Allen radiation belt.[11, 12]

in-core thermionic fast reactor power system, and (3) a low-temperature pin-element reactor with Stirling power conversion. In August 1985, following a detailed systems study of the power system concepts, the fast reactor thermoelectric power conversion system was selected for follow-on development during Phase II.[7]

Although the thermoelectric technology offered lower power-conversion efficiency than the thermionic and Stirling technologies, it represented the lowest technical risk of the three options due to the technology having been successfully used in RTGs for several decades. For this reason, the Interagency Steering Committee selected the thermoelectric reactor power system for further engineering development and ground testing based, in part, on the judgment that it was the only technology that could be ready for flight system development by the end of fiscal year 1991 at a cost of less than $500 million. Other factors that influenced the decision included operating life and weight. Robert Wiley, who worked on the SP-100 for the Strategic Defense Initiative Organization (SDIO), which replaced DARPA in directing the SP-100 program beginning in Phase II, recalled, "One of the key things that drove the decision was that Bill Wright [of DARPA] in particular was adamant… [that] mass was the key. And in order to find an actual application, the unit had to be relatively lightweight."[13] After three years and a cost of approximately $51 million, Phase I was completed in September 1985.[14]

The design power level was subsequently returned to 100 kWe approximately one year later.[15]

While the power-level decision introduced questions of technical feasibility, the thermoelectric choice was not unanimously supported and divisions began

The Air Force people, for the most part, were adamant that thermionics was the right answer.

Separate Directions

Concurrent with the decision to proceed with the thermoelectric-based reactor power system, the Interagency Steering Committee decided to increase the ground-test power level from 100 kWe to 300 kWe to meet evolving DoD needs, based primarily on an Air Force recommendation.[12] The decision introduced a small problem for developers of the reactor power system—the higher power level was technically incompatible with the capabilities of the thermoelectric system. In spite of the technical incompatibility, program inertia and the political risk associated with going back to another round of technology selection kept the program moving forward.

forming in the program. "The Air Force people, for the most part, were adamant that thermionics was the right answer. They were very unhappy about the decision to go thermoelectric…and so some were actually contemplating filing a formal dissent to their decision but they opted not to do that…" noted Wiley.[13] After much discussion with the thermionics advocates, DOE and SDIO initiated an in-core thermionics development program called the Thermionic Fuel Element (TFE) Verification Program.[e] NASA also started another program to develop a high-temperature Stirling engine that would be able to produce five times the output of the thermoelectric converter with the SP-100 reactor. Despite the original intent to focus

e. The TFE Verification Program is discussed in detail in Chapter 7, Thermionics Revisited.

on a single technology in Phase II, development would proceed down independent technology branches.[16]

Ground Testing Plans Take Root

With selection of a reactor power system completed, the SP-100 program turned its focus to the rigorous engineering and testing activities needed to develop the system for flight qualification. The general framework and plan for the second phase of the program was defined in a new tri-agency agreement that identified agency-specific roles and responsibilities, an overarching management structure, and a six-year funding plan totaling approximately $500 million, with ground testing to be completed by the end of fiscal year 1991. With a planned launch date of 1996, optimism in the SP-100 program was riding high.[17]

While overall program direction remained with the Tri-Agency Steering Committee during the ground-engineering and test phase, each agency now took on specific responsibilities. DOE provided much of the funding and was responsible for development and testing of the reactor power system, including selection and preparation of a reactor test facility. NASA and DoD continued mission analysis; however, most of the potential mission emphasis and planned user agency program funding remained with DoD. NASA also continued development of non-nuclear systems, such as power conversion and power conditioning, but at relatively modest funding levels under its SP-100 advanced

What Makes a Good Space Power Plant (Adapted from "Nuclear Reactors for Space Power")[18]

Factors that must be considered by designers of space nuclear power plants vary but always include those shown in the table below. The factors are all interdependent and often one can be improved most effectively only at the expense of the others. For example, system weight can be significantly reduced by raising the operating temperature of the reactor power system; however, power system equipment might deteriorate more quickly at higher temperatures. At this point, the designer may step in with trade-offs, such as how much weight-saving must be traded for one additional month of operational life? Ideally, this balancing act would result in a low-weight, low-cost, ultra-safe, and highly reliable power plant. In a practical world, however, compromises are usually needed in the process of power system optimization.

Desirable factor	What it means
Low Weight	The power plant's specific mass (mass per unit of power) should be as low as possible.
Reliability	The probability should be high that the power plant will run for the specified length of time (usually several years), with little or no human attention, in the presence of meteoroids, high vacuum, and the other hazards of space.
Nuclear Safety	Under no predictable circumstances should the crew or Earth's populace be endangered by radioactivity.
Compatibility	Power plant characteristics must not require unreasonable restrictions on spacecraft design or operation.
Availability	The power plant must be ready when the rocket and/or payload are ready for launching.

technology program. Project management functions remained at JPL/LANL.[17] conversion system utilized silicon-germanium/gallium-phosphide thermoelectric materials assembled in thermoelectric modules to produce a nominal 100 kWe. A portion of the excess heat that wasn't converted to useable electricity would be removed from the system using a series of heat pipes (through which the lithium reactor coolant flowed) connected to radiators. After passage through the radiator pipes, the cooled lithium was returned to the reactor core. The overall length was approximately 40 feet (12 meters), including the reactor system, the energy conversion assembly, and the heat rejection system. A radiation shield would minimize the dose at the payload (approximately 82 feet [25 meters] from the reactor), while a heat shield would protect the reactor in the event of re-entry. An auxiliary cooling loop was designed to remove heat in case the primary system lost its coolant.[7, 19, 20, 21]

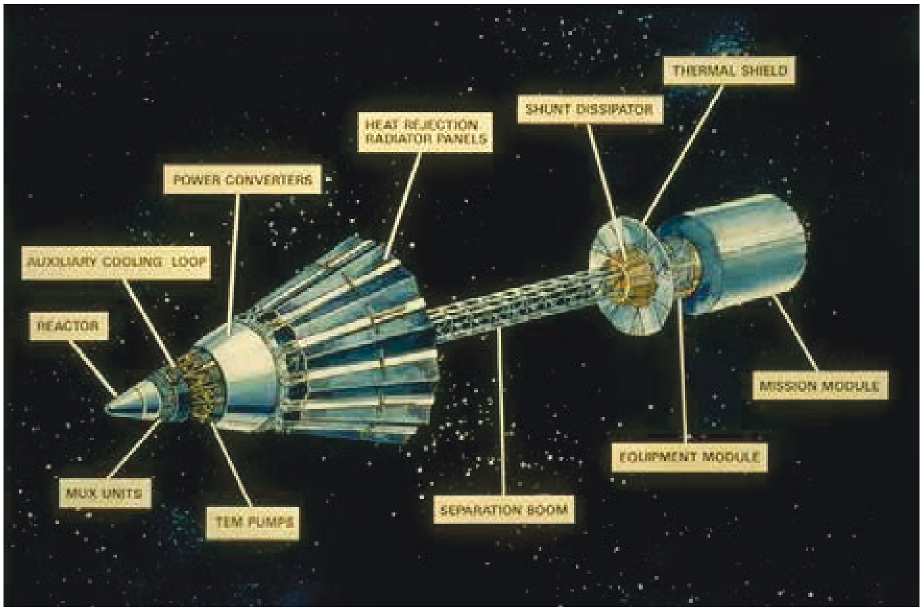
In the absence of a specific mission, a reference flight system design was developed that could be scaled upward or downward.

In the absence of a specific mission, a reference flight system (RFS) design was developed that could be scaled upward or downward to accommodate the broad range of power levels for the SP-100 system. The flight system was designed to support an earth-orbit military mission and provided the basis for design and development of the ground-based systems and facilities that would be needed to test the reactor power system.

At the heart of the RFS was a lithium-cooled pin-element fast reactor with uranium nitride fuel. The reactor, which was about the size of a five-gallon bucket, would generate 2.4 MWt at a temperature of approximately 1,350 Kelvin. The heat generated in the reactor core would be transferred to the thermoelectric power conversion system via a series of pipes through which the lithium-metal coolant was moved using an electromagnetic pumping system. The power

Ground testing of the SP-100 reactor power system was planned to be conducted at the Hanford Engineering Development Laboratory (later renamed the Hanford site) near Richland, Washington. DOE selected Hanford, which was managed by Westinghouse, in November 1985 based on an evaluation that included five candidate sites. The selection of Hanford was due in part to the availability of the decommissioned Plutonium Recycle Test Reactor (PRTR) facility. Having been defueled after its decommissioning in 1969, the remaining containment building and other facilities and equipment provided an ideal location for the planned operational, performance, and reliability tests on the SP-100 reactor system and its major components. In 1986, DOE initiated the safety and environmental evaluations needed to modify and upgrade the containment structure and other supporting facilities for the planned nuclear assembly test. Planned modifications included installation of a large vacuum chamber for testing the reactor system components in a near-space environment. Phase II testing would culminate in a "nuclear assembly test" designed to check operation of the SP-100 reactor, primary heat transport (cooling) loop, and the radiation shield.[19]

In addition to Hanford, DOE had at its fingertips in the mid-1980s a nuclear infrastructure that had



Artist's concept of the SP-100 reactor power system and space craft. (Image: Smithsonian Institute)

been developed over a period of several decades, dating back to the Manhattan project. Second to none, the infrastructure included a cadre of national laboratories such as LANL, SNL, ORNL, and ANL-W. Engineering and reactor expertise had been developed at locations such as the Idaho National Laboratory (INL; formerly the National Reactor Testing Station) and the Hanford reservation. Private industry partners in nuclear research and development included GE, Westinghouse, Rockwell, and Aerojet. At the heart of this unique national resource was a very

Academic vs. Practical Reactors

Admiral Hyman Rickover, known as the father of America's nuclear Navy, described two types of reactors, which he divided into academic and practical:

"… An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development is required. It will use 'off-the-shelf' components. (8) The reactor is in the study phase. It is not being built now.

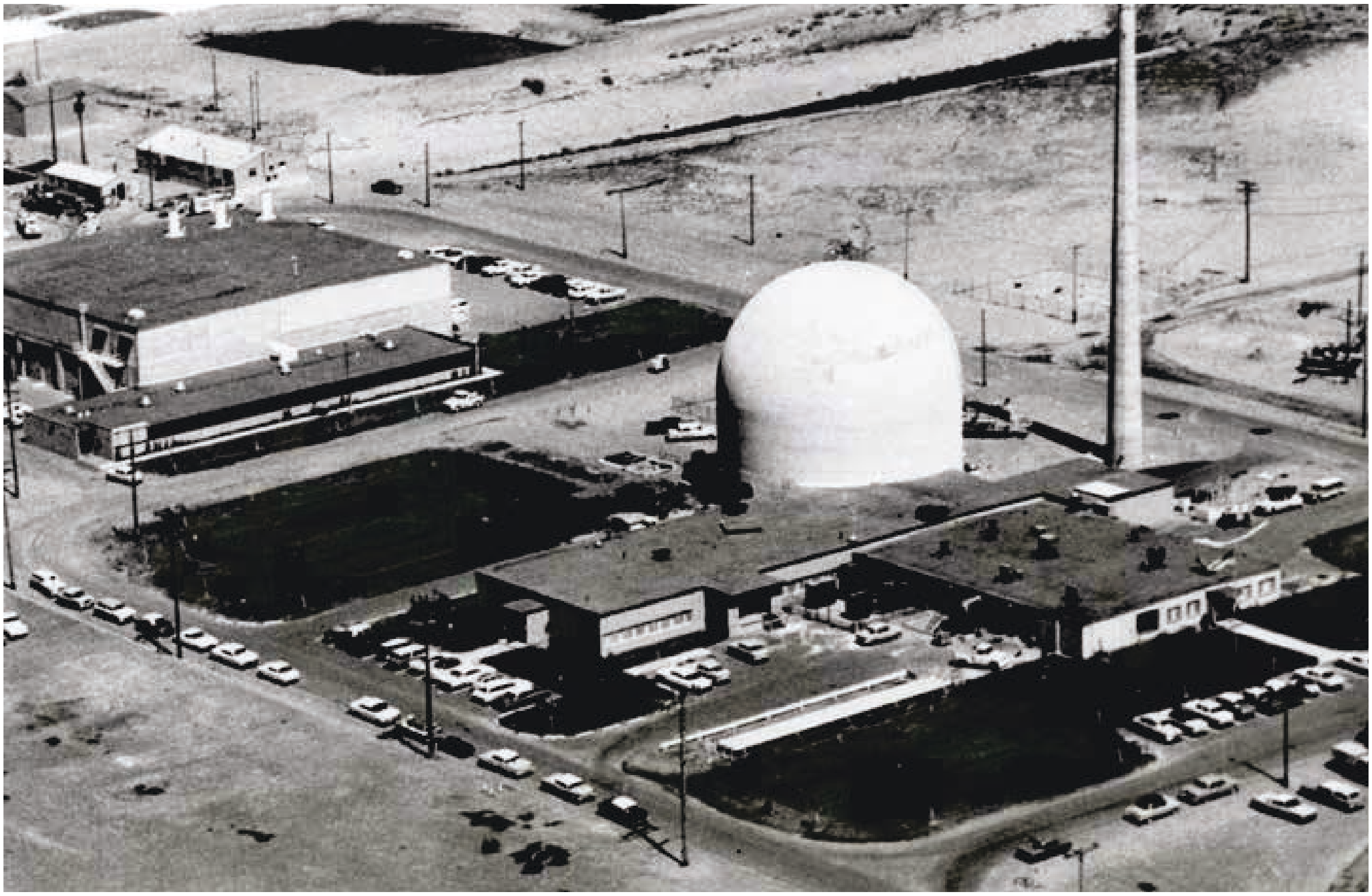
… a practical reactor plant can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It is requiring an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated…

The academic-reactor designer is … free to luxuriate in elegant ideas, the practical shortcomings of which can be relegated to the category of mere technical details. The practical-reactor designer must live with these same technical details. Although recalcitrant and awkward, they must be solved and cannot be put off until tomorrow. Their solutions require manpower, time, and money… For a large part, those involved with the academic reactors have more inclination and time to present their ideas… Since they are innocently unaware of the… difficulties of their plans, they speak with great facility and confidence. Those involved with practical reactors, humbled by their experiences, speak less and worry more…".[22]

capable workforce described as "a large and diversified population of technical experts with interest and experience in advanced nuclear power systems…waiting to be reengaged and redirected in a new effort to put nuclear power to work in space."[23] This resource, which had been primed by the preliminary feasibility work of Phase I, was ready for the challenge posed by the second phase of the new space reactor program.

SP-100 Technology Moves Forward

To facilitate engineering development, the reactor power system design and development work was separated into a logical set of individual subsystems. Major subsystems included the reactor system, power conversion system, heat rejection system, instrumentation and control systems, the shield system, and mechanical and structural systems. Each subsystem performed a specific function. For example, the reactor subsystem provided the source of heat from which the power conversion subsystem, consisting of the thermoelectric cells and related components, converted the heat into useable electricity. The instrumentation and control subsystem ensured proper operation and safety of the reactor. The shield subsystem protected the spacecraft



PRTR at Hanford circa 1964. Following its decommissioning in 1969, the containment structure would later be considered as a test structure for the SP-100 space reactor. (Photo: DOE Flickr) payload from the undesirable effects of the intense neutron and gamma radiation emanating from the reactor once it was started in orbit. Each subsystem had to be integrated and work together for proper operation of the reactor power system. Designers also had to ensure that each subsystem and their respective components would meet requirements associated with launch and operation in space, such as temperature limits, pressure limits, and shock and vibration limits, as well as applicable safety requirements for launch and operation of the nuclear power system. Designs were verified through analysis, testing, and/or experiments.

As the reactor power system design progressed, another equally important task focused on development of the fabrication and manufacturing processes needed to build, assemble, and test the various components and parts of the SP-100 system. In some cases, several different processes were needed for a single component. For example, production of the reactor fuel pellet required a specification that identified the exact chemical makeup of the uranium nitride feedstock that would subsequently be pressed into a fuel pellet. A process for producing the fuel pellet from the feed material had to be developed. Another production process was established for encasing the fuel pellet inside its metal cladding cocoon, which consisted of an inner metal liner encased in the outer metal cladding. Inspection and measurement of the clad pellets ensured they met dimensional requirements for placement inside a fuel element, the structural component that held multiple fuel pellets and formed the basic building block of the reactor core. The fuel pellet was but a microcosm of the overall set of fabrication and production processes that were developed for the SP-100 space reactor program.

In addition to the design and fabrication processes, a rigorous testing program was established that served to verify the design of the components, subsystems, and overall reactor power system. Experiments that verified nuclear physics calculations and other related parameters for the SP-100 reactor core were set up and performed using the Zero Power Physics Reactor (ZPPR) located at ANL-W.[24] Nuclear testing of fuel components (i.e., fuel pellets and cladding materials) was conducted using several facilities within the DOE infrastructure. The Experimental Breeder Reactor–II (EBR-II), operated by ANL-W, and the Fast Flux Test Facility (FFTF), located at Hanford, provided unique testing capabilities in which fuel pellets and cladding materials were subjected to high temperatures and radiation levels for several months to several years. Such irradiation testing provided fuel designers with information pertaining to material degradation and other criteria, which was needed to verify that the fuel would last the required seven-year lifetime at the expected reactor operating temperature. The uranium nitride fuel and niobium-alloy fuel pin developed by LANL was eventually demonstrated at fuel burnups equivalent to a life of seven years at cladding temperatures that exceeded the system design temperature.

Relative to the power conversion system, GE focused its efforts on developing a thermoelectric cell with a power density 16 times greater than the power units successfully used in the RTGs that powered the Galileo and Ulysses spacecraft. Integral to the GE effort was the use of coating materials on the external surface of the thermoelectric cell to help improve overall structural integrity in support of a seven-year operating life at full power.

The major effort associated with the heat transport system was development of a thermoelectric electromagnetic pump by which the liquid lithium would be pumped through the primary and secondary reactor coolant loops. The pump was self-actuating, receiving its power from the current produced by thermoelectric cells located between the primary and secondary coolant loops that passed through the pump.

Closely related to pump development was the need to ensure the lithium coolant (in solid form before system operation) was thawed in a manner that would allow the pump to operate as designed. In addition to demonstrating assembly techniques, the project team validated its hydraulic and electromagnetic performance through a series of pump tests. Testing of the pump and other major SP-100 subsystems, such as the thermoelectric power conversion and heat rejection systems, was performed using a non-nuclear heat source similar to what was done with the GPHS-RTG.

Tensions Mount

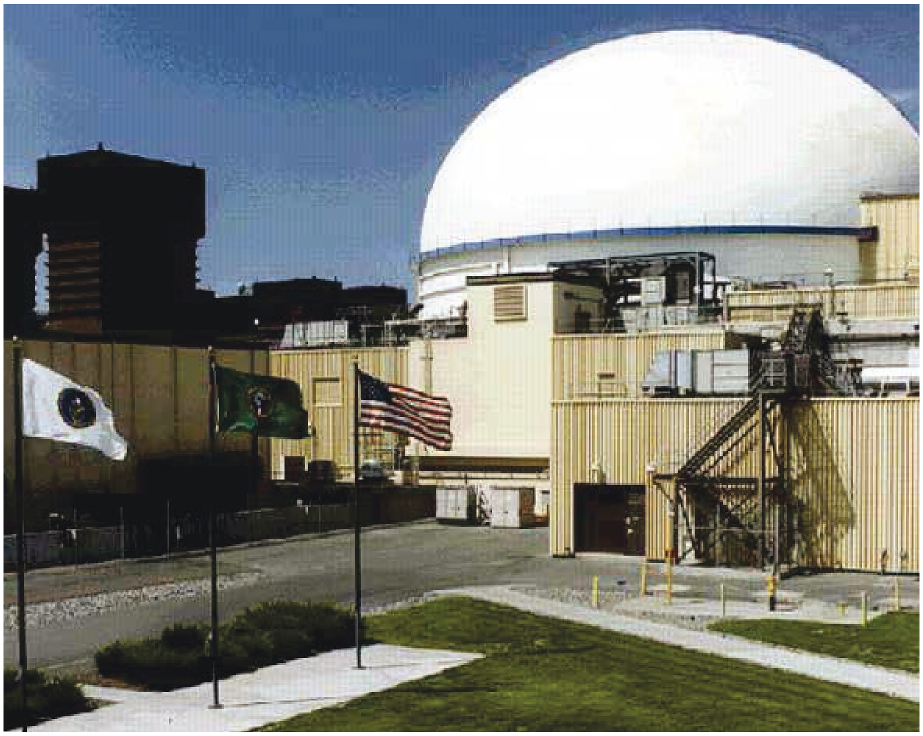
While significant technical progress was made during the first several years of Phase II, financial clouds began to form over the SP-100 program in 1986. Spurred by the Graham-Rudman-Hollings Deficit Reduction Act of 1985, the Federal government began a broad tightening of its fiscal belt. The fiscal tightening translated into reduced funding for all Federal agencies, and the SP-100 program was hit particularly hard. During the first four years of Phase II (1986-1989), the agencies received and/or contributed only $260 million of the approximately $450 million planned per the Phase II tri-agency agreement. At the agency level, the funding levels equated to $160 million of $210 million planned for DOE (a 25 percent reduction), $82 million of $220 million planned by SDIO (a 60 percent reduction), and $19.9 million of the $16 million planned for NASA. The situation didn't improve in 1990 or 1991, as appropriations continued to lag the funding plan. In addition to reduced funding levels for the agencies, the SP-100 program experienced significant cost growth due to ongoing technical issues, thereby worsening the fiscal outlook for the program.[25]

In the wake of the eroding financial picture, major program changes soon followed. The ground engineering system and technology development activities were delayed, shifting the planned completion date from 1992 to 1994, and then later from 1994 to 2002. The tri-agency agreement was updated more than once to reflect the changing funding and schedule realities.[25] As a result of the funding problems and schedule delays, frustration began to mount, particularly within SDIO, the primary mission organization and source of the major SP-100 program funding reductions.

SP-100 core mockup in the ZPPR at ANL-W. (Photo: INL)

As the reality of funding cuts and schedule delays were taking their toll on the SP-100 program, efforts to tie the SP-100 power system to a specific mission continued. In 1989, potential Air Force missions resulted in the development of various "hardened" designs capable of providing 10 to 40 kWe and meeting military reactor goals that included hostile threat survival.[26]

DoD interest in lower-power systems continued into 1990, when the Air Force signed five one-year design contracts to identify key technology issues for several 40-kWe reactor designs: (1) STAR-C, (2) Heat Pipe Thermionics, (3) the Small Externally-Fueled Heat Pipe Thermionic Reactor, (4) the Moderated Heat Pipe Thermionic Reactor, and (5) the Space Power Advanced Core Element Reactor, a derivative of a Soviet design that had become available as a result of the economic and political decline that transpired in the former Soviet Union in the late 1980s.[27] The Soviet Union had developed thermionic technology in its space reactor program over a period of several decades. One particular thermionic reactor concept, dubbed TOPAZ-II by the United States, caught the attention of SDIO in 1989. With significant interest in the Russian technology and hopes of gaining decades of Russian development at a fraction of the cost for a comparable domestic technology development program, a deal was subsequently brokered that eventually brought TOPAZ-II technology to the United States (at least temporarily).[f]



The FFTF was a 400-megawatt thermal, liquid metal (sodium) cooled reactor. The white dome in the background is the containment building that holds the reactor vessel. (LANL Flickr)

At NASA, interest in the SP-100 system was strengthened in light of the SEI announced by President George Bush in July 1989. SEI brought a renewed vision for the future of space exploration that included manned missions to the moon as well as to Mars by 2019. Mission planners at NASA and DOE soon began looking anew at nuclear propulsion concepts for the out-year manned mission to Mars and nuclear electric power for a planned lunar outpost.

f. The TOPAZ-II reactor is discussed more fully in Chapter 7, Thermionics Revisited.

Changes on the Horizon

Although interest in an SP-100 power system continued, by 1991 the SP-100 program was facing a mounting wall of uncertainty regarding its future. Inadequate funding continued to adversely affect testing and development plans. Mission requirements remained a moving target, shifting frequently within DoD and then NASA. And tensions were high between the agencies, and even higher within some agencies.

In November 1991, SDIO announced it would no longer support the SP-100 program in order to pursue the Russian thermionic technology. The announcement raised new concerns that acquisition of the Russian reactors would undermine the SP-100 program by redirecting government funding for space reactor power system development to SDIO. It also left the Air Force as the only DoD entity with a stake in the SP-100 program.[28]

With the pullout by SDIO, the question of mission purpose for the SP-100 program resurfaced. At the request of Secretary of Energy James Watkins, the Office of Management and Budget subsequently reviewed the beleaguered SP-100 program. By the time of the review, the SP-100 team was looking to ground test the reactor power system in 2004 at a cost of approximately $1.8 billion, representing a 10-year schedule slip and $1.3 billion overrun. Although a number of possible missions had been identified, the review found no firm civilian mission requirements for the space reactor system. To address the growing schedule and cost for the SP-100 system, the agencies were subsequently asked to develop planning options to facilitate a more-competitive, lower-cost, faster-paced, and flexible program for developing space reactor power systems for potential DoD/NASA use in the early to mid-2000s.[28]

Shortly after the Office of Management and Budget review, the program came under further scrutiny during a Congressional hearing in March 1992. The hearing chairman, Representative Howard Wolpe, started the hearing on a dire note:

"This is a program in crisis... After 10 years and the expenditure of $400 million, the SP-100 has yet to be chosen for a firm mission, by either DoD or NASA. And no firm missions appear to be on the horizon. The original program cost estimate has soared, and the project schedule has dramatically slipped. One of the SP-100's sponsors, the Department of Defense, recently withdrew financial support, citing dissatisfaction with program management, high costs, long lead time, and the desire to buy a TOPAZ reactor from the Russians... This program is in serious trouble...".[29]

Testimony was given by representatives from all three agencies, including William Young from the DOE Office of Nuclear Energy (DOE-NE); Dr. Robert Rosen, Deputy Associate Administrator for Aeronautics and Space Technology at NASA; and Col. Simon "Pete" Worden of SDIO. Testimony was also provided by the General Accounting Office and Steven Aftergood of the Federation of American Scientists. Through the course of the hearing, the merits of the SP-100 program were discussed and debated. Agency, management, and organizational issues, tensions, and frustrations were aired. The lack of a specific mission was noted, raising questions as to whether the SP-100 program had become an ongoing research and development program. Questions also arose as to who should pay for such an effort. Since DOE and DoD had provided the vast majority of funding for the SP-100 program, NASA was chided for trying to get something for nothing (or at least very little). On the topic of technology, SDIO presented its case for pulling out of the SP-100 program in favor of the Russian thermionic reactor technology. The SP-100 program was at times pitted against the new SDIO program in spite of many unknowns regarding the foreign technology.

When all was said and done, skepticism regarding efforts to reduce the cost and shorten the program schedule remained. The hearing was closed with the same tone with which it had opened, "SDIO… has pulled out of the SP-100 program. If current-year funding were to continue, the program would have an annual budget of about $50 million to fund a $1.5 billion program… it will take about 50 years to complete the program at that rate. That clearly is not an option… I think it is time, very frankly, to terminate this project."[30]

When all was said and done, skepticism regarding efforts to reduce the cost and shorten the program schedule remained.

Regardless of the issues raised during the hearing, the SP-100 program continued to move forward. In response to the Office of Management and Budget request, DOE, NASA, and DoD developed a planning options study that recommended a space reactor power system program that would launch a prototype reactor by 2000.[27] In conjunction with development of the planning option study, DOE and NASA began evaluating options for a significantly less expensive SP-100 system that could be launched in the 1990s. The agencies focused their efforts on technology to support systems in the 5 to 15 kWe power range. Cost and schedule savings could also be achieved by using the qualification system as the flight system. Seven conceptual design options and three launch date opportunities were developed. Four options used prototypic ground-flight system components for a 15-kWe system for launch in either 1997 or 1999, depending on system details. The remaining options used RTG thermoelectrics to accommodate a 1996 launch date. All of the options proposed elimination of the full-scale ground test to reduce costs. Previously considered a radical approach, elimination of full-power ground testing began to make sense based on economics and engineering benefits, which included the powerful analytical capabilities of the day.[26]

In late 1992, DOE and NASA undertook another effort to define options for a small (5 to 20 kWe) space nuclear reactor program for space-science and planetary-surface applications and a high-performance propulsion system for piloted and cargo missions to Mars. The DOE/NASA team put forth a plan centered on a 1998 launch using existing infrastructure to fulfill NASA scientific and exploration objectives that could not be met by other power systems. The 1998 flight was based on development of a 500-kWt SP-100 reactor coupled with a 20-kWe closed Brayton cycle power conversion subsystem. In response to this recommendation, DOE redirected the program and initiated a system design activity. A design review confirmed that the closed Brayton cycle design approach was feasible for an early mission. No major closed Brayton cycle development issues were identified, although normal engineering development would be required.[26]

In the area of technology development, the generic flight system design was also updated in 1992. The updated design demonstrated that a 100-kWe system with a mass of no more than 10,000 pounds (4,600 kilograms) was achievable. Researchers identified a thaw concept that utilized an auxiliary cooling loop to allow the reactor to restart after shutdown, and engineers completed development of fabrication techniques for the reactor, fuel, and fuel pins. GE continued development of the assembly process for the thermoelectric cells. Two test loops containing high-temperature lithium coolant demonstrated welding and fabrication techniques for refractory niobium alloys. Tests showed that the reactor design underwent lithium thaw with minimal stress.[31]

By 1993, the agencies were working under the presidential administration of William (Bill) Clinton. The Clinton Administration had a new set of priorities that didn't include nuclear power research and development. The SP-100 program had been attempting to modify its testing and development plans to better match anticipated missions. In early fiscal year 1993, however, it became increasingly clear that an early closed Brayton cycle-based SP-100 mission was unlikely, which led to a decision to generate a 20-kWe thermoelectric design with the rationale that with additional development time, the design would be more competitive in terms of mass and lifetime capability. As with the closed Brayton cycle design, requirements were based on a five-year nuclear electric propulsion interplanetary or asteroid mission.[26] The final system redesign, however, received no more support than any of the earlier efforts. As discussed in Chapter 3, SEI lacked Congressional support and funding, and the hoped for missions never materialized.

Orderly Shutdown

Despite efforts to accommodate Congressional concerns, the Clinton Administration showed no inclination to support the SP-100 space reactor program, and it was scheduled for termination in fiscal year 1994; funding of $16.9 million was provided for closeout activities. Including the amount for closeout activities, approximately $520 million had been spent on the SP-100 program.

Although the SP-100 space reactor power system was never fully developed, the program achieved several accomplishments and took notable efforts to preserve the technology for future researchers. The reactor fuel had successfully demonstrated low swelling and lifetimes exceeding the seven-year requirement. LANL had fabricated, inspected, and accepted sufficient uranium nitride fuel pellets for a 100-kWe space reactor. Thermoelectric-cell and power-converter technology overcame major technical hurdles, with demonstrated power densities approximately 16 times greater than GPHS-RTG technology. The reactor actuator assembly, the only SP-100 device with moving parts, had been successfully developed and tested at prototypic temperatures (800 Kelvin) in a hard vacuum. A prototype self-powered electromagnetic pump capable of pumping two separate liquid metal loops simultaneously had been produced, deriving its power from the hot liquid. Low-cost heat pipes were life-tested at prototypic temperature, showing long-term stability. As part of the closeout activities, equipment was distributed to government laboratories, universities, and industry. In addition, key fabrication-process documentation, work records, and other program-related documents were placed in government repository storage.[32]

During the course of the program, a number of technologies had also been successfully developed, including those with additional applications outside of the space program. The requirements for the SP-100 to operate at high temperatures in a vacuum for 10 years had resulted in technology developments in the areas of high-conductivity heat transfer, self-lubricating bearings, stress-relieving components, self-energized pumps, compact heat exchangers, bonding of ceramics to metals, high-temperature electric coils, electrical insulators, thermometers, high-temperature motors, and generators.[32]

Because many of these components had potential commercial uses, with permission from DOE, the SP-100 project office at JPL began an aggressive project late in 1993 to find commercial applications for fabrication processes, devices, and components developed during the SP-100 program.

> During the course of the program, a number of technologies had also been successfully developed, including those with additional applications outside of the space program.

Over 100 companies expressed interest in the technology transfer prospects that included self-lubricating ball bearings for the space shuttle, electric motors for aircraft activators, and the use of the gas-separator concept to remove gases from liquids in the manufacture of syrup for soft drinks.[32, 33]

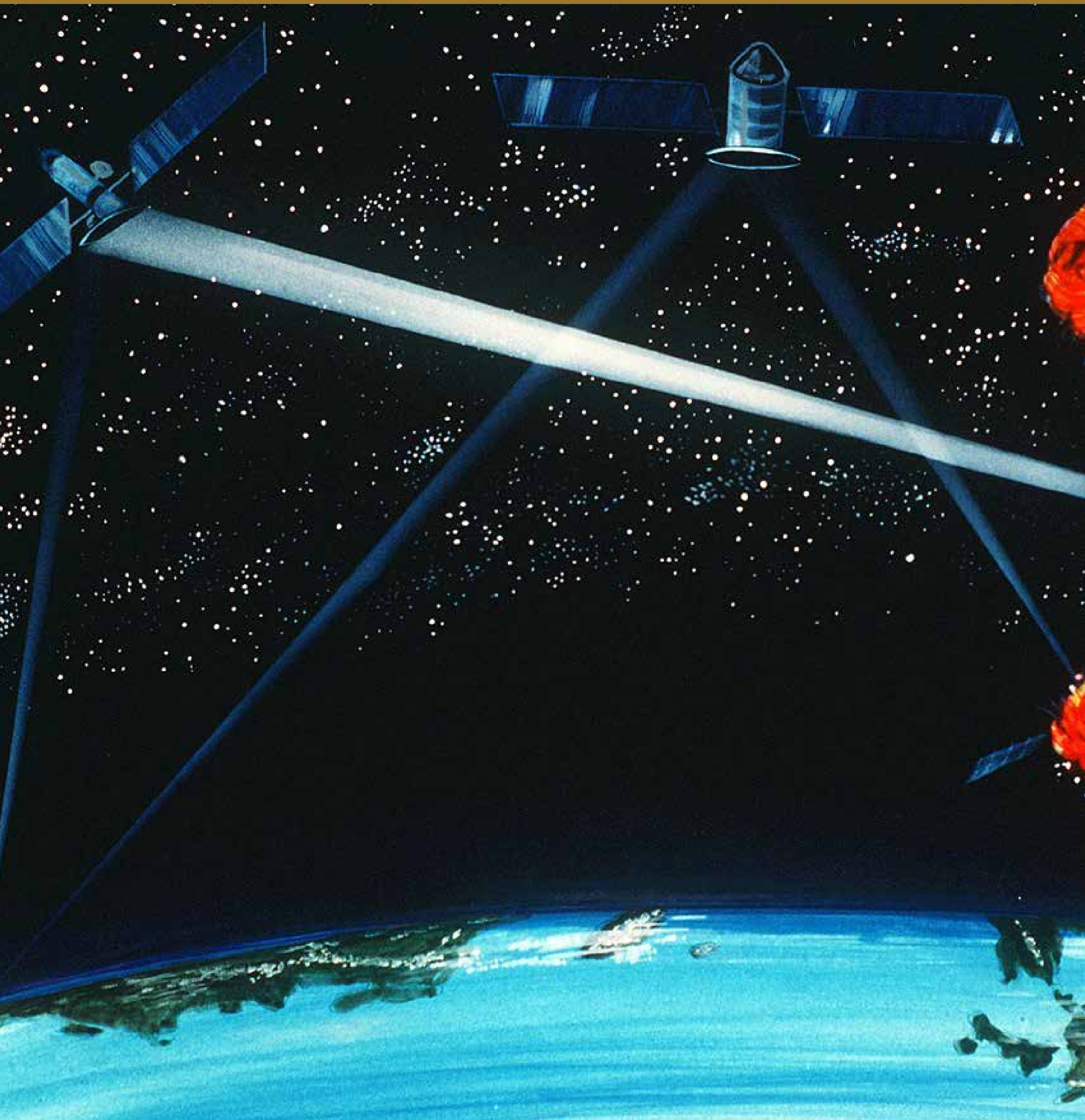
Experimental Breeder Reactor-II at Idaho National Laboratory. (Photo: Idaho National Laboratory Flickr)

Looking Back

With the end of the SP-100 program, the latest chapter in U.S. space reactor history came to a close. Although the proposed reactor system was never fully developed, many advancements were made in space reactor system technology and other supporting areas. The vision of repeating the success of the SNAP-10A launch 30 years earlier finally faded, succumbing to the weight of inadequate funding, lack of missions, and a changing political landscape that questioned the very need for ongoing nuclear research and development.

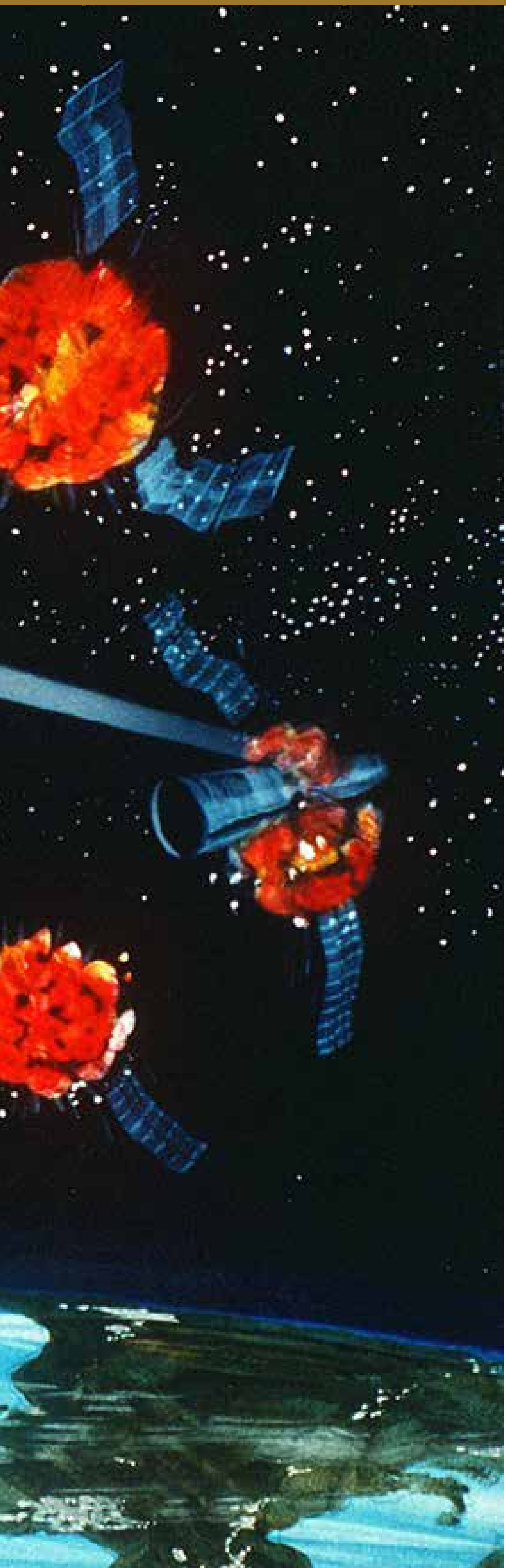
The tentacles of change reached far beyond the SP-100 program. The EBR-II, one of the nation's only fast-reactor test facilities, was shut down in 1994. The ZPPR facility was shut down in 1990[38] and the Hanford FFTF was shut down in 1992 (the last fuel was removed from the reactor years later, in 2008). Other facilities, such as the Plutonium Recycle and Test Reactor Complex, would eventually succumb to the massive cleanup effort conducted under the DOE Environmental Management Program. For some, such shutdowns and dismantlement may have signified progress relative to the nation's Cold War cleanup legacy. For others, the shutdowns meant the loss of a livelihood. Regardless, the nation lost a piece of its nuclear heritage and a significant amount of its nuclear infrastructure.

As the vision for global defensive systems capable of protecting against the threat of a Cold War Soviet attack expanded, energy-intensive space-based weapons system concepts such as electromagnetic rail guns, free electron lasers, and neutral particle and charged-particle beam systems began to emerge.



6

The Multimegawatt Program
Taking Space Reactors to the Next Level



As development of a 100-kilowatt electric space reactor power system progressed under the SP-100 program, space-based weapon and sensor designs continued to evolve under SDI. As the vision for global defensive systems capable of protecting against the threat of a Cold War Soviet attack expanded, energy-intensive space-based weapons system concepts—such as electromagnetic rail guns, free electron lasers, and neutral particle and charged-particle beam systems—began to emerge. And with the emergence came a need for advanced power systems capable of feeding the energy-hungry weapons.

From Kilowatts to Megawatts

SDI space-based weapons concepts were categorized into three operational modes (housekeeping, alert, and burst) with general power groupings. A housekeeping mode, applicable to operational baseloads such as communication and surveillance systems, required power levels of several kilowatts to tens of kilowatts over an operating life of 10 or more years. An alert mode, applicable to placement of a system in a state of readiness in the event of a hostile threat, required power levels of 100 kilowatts to 10 megawatts. A burst mode applied to weapon systems during battle scenarios and required power levels from tens to hundreds of megawatts for a period of hundreds of seconds. These high-power space-based concepts soon gave rise to the need for advanced multi-megawatt (MMW) power systems.[1]

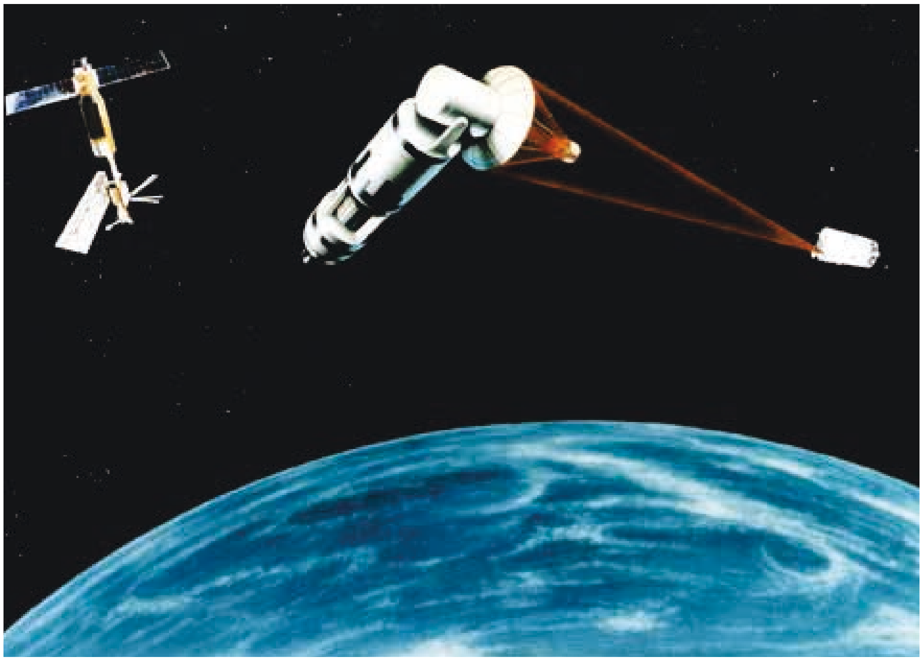
Development of MMW power systems fell under the auspices of an SDIO MMW space power program, through which overall programmatic direction and guidance for power development efforts were given. The program had three principal elements: (1) military-mission analyses and requirements definition, (2) non-nuclear concepts and technology, and (3) nuclear concepts and technology. While responsibility for the first two elements was assigned to the Air Force, the nuclear concepts element was addressed in a joint initiative between SDIO and DOE.

An artist's concept of a ground/space-based hybrid laser weapon, 1984. (Image: U.S. Air Force)

The MMW Space Reactor Program

The joint SDIO-DOE initiative, or MMW Space Reactor Program, began in 1985 as part of a DoD/DOE Interagency Agreement under which DOE supported SDI efforts. The objective of the new MMW program was to establish the technical feasibility of at least one space reactor system concept that could meet applicable SDIO performance requirements. The goal was to demonstrate technical feasibility by 1991. Based on the outcome of the feasibility work, SDIO would subsequently decide whether to proceed with engineering development and ground system testing of the reactor power system concept.[2]

The program was planned to consist of four phases, with technical feasibility work comprising the first two phases. During Phase I, several reactor power system concepts would be selected for concept evaluation, analysis and tradeoff studies, and identification of issues that might adversely affect system feasibility. Phase II was planned for detailed analysis of the two or three power-system concepts that showed the most promise for meeting SDI application requirements. Phase II was also to include preparation of preliminary safety assessments, component selection, and resolution of feasibility issues. If desired, Phase III would consist of ground-engineering system development for a single reactor concept during the mid-to-late 1990s. Flight demonstration work was planned for the last phase, Phase IV, and expected to commence in the late 1990s, with completion in the early 21st century.[3]



Strategic Defense Initiative space-based weapon concept. (Image: U.S. Air Force)

To support development of the reactor power system concepts during the first two phases, DOE initiated a technology development program through which the expertise and resources of its national laboratories could be accessed to address reactor technology issues. Information learned during the technology development process would also support decisions regarding concept feasibility. Pacific Northwest Laboratory had the lead for reactor-fuel development while materials work was completed at ORNL. SNL led development efforts associated with instrumentation and controls. LANL led heat pipe and thermal management development efforts. Finally, the Idaho National Engineering Laboratory (later the INL) was responsible for system and technical integration among the various laboratories, while coordination of nuclear safety was the responsibility of LANL.[2, 4]

Although the new space reactor program was a joint DOE-SDIO initiative, implementation was the responsibility of DOE. The DOE management structure included DOE Headquarters and their Idaho Operations Office (DOE-ID). Overall program responsibility resided with the Assistant Secretary for Nuclear Energy. Responsibility for program direction was assigned to the Division of Defense Energy Projects under the Office of Defense Energy Projects and Special Applications (in the Nuclear Energy organization). Day-to-day program execution and project management was delegated to a project integration office established at DOE-ID, and included responsibility for managing day-to-day project activities and oversight of the Idaho National Engineering Laboratory.

Through the efforts of several national laboratories and private companies, development of a broad spectrum of preliminary reactor system concepts began in 1986. As reactor power system concept development progressed, the young DOE program soon found itself face-to-face with two decades-old problems—a lack of funding and mission requirements that presented themselves as a moving target. As SDIO mission planning evolved, uncertainties soon arose as to when the space reactor power system would be needed. In response to the possibility of a timeframe earlier than originally planned, DOE modified its overall program strategy and developed three broad preliminary power categories to cover a range of SDI applications. The categories were used as a framework for subsequent reactor power system concept development. Category I concepts consisted of short-duration burst-type systems producing tens of megawatts with effluents permitted (open system). Category II systems were similar to Category I but with no effluents (closed system), a minimum life of one year, and capable of meeting burst-power requirements continuously or recharging within a single orbit. Category III concepts were intended to provide hundreds of megawatts of burst power and could be open or closed systems.[3, 5]

Through the efforts of several national laboratories and private companies, development of a broad spectrum of preliminary reactor system concepts began in 1986.

MMW Reactor Power Categories

DOE developed MMW power system categories to address the following SDI space applications:[6]

	Category I	Category II	Category III
Power Requirements (MWe)	10s	10s	100s
Operating Time (seconds)	100s	100s one-year total life	100s
Effluents Allowed	Yes	No	Yes

Preliminary reactor power system concepts included open- and closed-cycle systems and thermionic systems concepts. Of particular interest by SDIO were gas-cooled open-cycle reactor-system concepts because of potential mass advantages over reactor systems that utilized a closed-cycle design.[7] Work on the preliminary power-system concepts began in 1986 and was followed by a multi-agency team evaluation consisting of representatives from several DOE laboratories, the Lewis Research Center, and the Air Force Weapons Laboratory in 1987.[8]

After evaluation of the initial reactor-system concepts, further concept-development work was cut short due to funding shortfalls. Development efforts restarted in 1988 when six contractor teams, representing six different reactor concepts, were awarded contracts to refine their respective power system concepts. In addition to the conceptual development work, the contractor efforts included identification of technical issues that could affect the feasibility of the proposed power system. With Phase I formally underway, initial concept designs were completed by early 1989.[9] Of the six concepts selected for Phase I studies, three were for Category I systems, two for Category II, and one for Category III.[6, 10]

The funding shortfall and its impact on the program were highlighted during an audit of DOE space nuclear reactor research and development activities by the General Accounting Office (GAO) in 1987. The audit stemmed from a Congressional request in May 1986 and included review of the MMW and SP-100 space reactor programs. The review considered program status and the management and coordination among the sponsoring organizations of the space reactor programs. In their final report, GAO noted that both programs faced several challenges and observed that:

"The Multimegawatt program, which is still in its infancy, faces perhaps even greater challenges than the SP-100 program…Higher reactor operating temperatures and major technological advances in space power systems are needed. However, the program's funding levels have been reduced. As a result, DOE has adjusted the time frames and scope of work originally planned. Program managers state that it will still be possible for DOE to meet its goal of determining the technical feasibility of providing MMW nuclear power for SDI by the early 1990s. However, program officials stated that high risk, but promising, space reactor concepts may not be practical to pursue at currently forecast budget levels and time constraints."[5]

Open-Cycle vs. Closed-Cycle Systems

Open-cycle reactor power systems are designed such that the working fluid is used only once and then exhausted to space. Unique features of an open-cycle system include operation at a higher temperature relative to a closed-cycle system and the need for a working fluid storage system in lieu of a heat rejection system. While these features generally translate to advantages in weight and materials, an open system introduces the potential for an adverse reaction of the hot exhaust gas with the spacecraft weapons and sensors.[1]

Closed-cycle reactor power systems are designed such that the working fluid is contained in the system rather than being exhausted directly to space. Features of closed-cycle systems include operation at a lower temperature (relative to open-cycle systems) and use of a heat rejection system, both of which generally translate to advantages in system efficiency.[1]

As noted in the GAO report, funding problems for the MMW program started in 1986, when the program received only $15.8 million of the $17.2 million (combined funding from DOE and SDIO) requested. In fiscal year 1987, the situation worsened, as the program received only $14.6 million of the $40 million requested. With the 1987 funding level at only 37 percent of request, and the future looking no better, it was no surprise that schedule delays ensued. Reactor power system concept definition, originally planned to proceed until August 1987, was delayed with a planned resumption date of April 1988. By 1988, budget limitations were expected to push design concept selection beyond 1991, and final development of a MMW reactor beyond the year 2000. In addition to funding shortfalls, SDIO began to decrease funding for development of nuclear space power technology in favor of non-nuclear technologies. The program, barely in its infancy, was already feeling the effect of broad Federal fiscal belt-tightening that had resulted from ballooning Federal budget deficits. Nevertheless, DOE continued to move forward with system studies.[5]

MMW Space Reactor System Category I Concepts[6]

GE proposed a derivative of the 710 reactor designed for the PLUTO nuclear ramjet program conducted in the 1960s. The fast-spectrum, ceramic-metal fuel, gas-cooled reactor concept included twin counter-rotating open Brayton cycle turbines/generators integrated with super-conducting generators. Testing of fuel elements for the 710 program had produced data on this fuel type.

Boeing developed a hydrogen-cooled open Brayton cycle system using a new reactor design with a fuel-pin core designed by Britain's Rolls Royce. The core used a two-pass flow configuration in which the hydrogen would enter the reactor, flow through an outer ring of fuel pins to an upper plenum, reverse direction, and then flow down through the center array of fuel pins. The system was designed to be scalable, with the objective of meeting the Category III requirements with modifications.[11]

A Westinghouse team designed a NERVA-derivative hydrogen-cooled reactor using an open Brayton cycle with counter-rotating turbines and generators. The design had substantial operational data from the NERVA program.

MMW Space Reactor System Category II Concepts

General Atomics proposed a closed-cycle system consisting of a liquid-metal-cooled in-core thermionic reactor coupled to alkaline fuel cells that could be used to supply burst power.

Rockwell proposed a lithium-cooled, ceramic-metal-fuel fast-reactor system to drive a Rankine-cycle power conversion system. The closed-cycle reactor system would be used to recharge sodium-sulfur batteries after a power burst.

MMW Space Reactor System Category III Concept

A Grumman-led team proposed a hydrogen-cooled particle bed reactor using an open Brayton cycle system with a ten-step turbine and alternator.

While GAO reviewed DOE space reactor research and development activities, a National Research Council review team examined advanced power systems for space missions in a broader context. Stemming from a DoD request made when SDIO was in its infancy in 1984, the Research Council review was initially intended to address space power systems related to SDI applications but was broadened to include military space power requirements, other than those of SDIO, and potential NASA space power requirements. MMW space reactor systems offered several desirable features, including low weight, compactness, long life, potential for continuous use, benign or no effluents, high reliability, and inherent radiation hardness and survivability. As such, potential civil applications included nuclear electric propulsion and nuclear thermal propulsion to reduce interplanetary transport times, nuclear-surface-power systems for manned bases on the moon or on Mars, and nuclear power systems for large-scale industrial processing schemes in space.

Based on a review of advanced power system concepts and information in 1987, the final report provided several recommendations for consideration by those involved in planning space missions requiring MMW power levels. Relative to MMW power systems, the committee recognized that power requirements for SDI burst-mode applications could significantly exceed the capacity of available and planned power systems and recommended that "both the nuclear and non-nuclear SDI MMW programs should be pursued." The report provided a caveat relative to the nuclear option, however, noting that "a nuclear reactor power system may prove to be the only viable option for powering the SDI burst mode (if effluents from chemical power sources prove to be intolerable)…."[1] A similar caveat was provided relative to alert-mode power levels.

In light of the funding shortfalls in 1987, the external GAO review, and the National Research Council effort, the MMW program still made progress on the technology front. Emphasis was placed on those areas that were particularly relevant to the concept-feasibility evaluation, including reactor fuels, materials, energy storage, thermal management, and instrumentation and control. Relative to reactor technology, progress included the issuance of contracts for fabrication of depleted and enriched uranium-carbide zirconium-carbide-coated fuel particles and fuel elements for a particle bed reactor concept, and development and demonstration of ceramic-metal-fuel fabrication processes using surrogate and uranium-nitride fuel particles. Tests were conducted to evaluate the compatibility of uranium nitride fuels with tungsten-rhenium and molybdenum-rhenium alloys, and on the fabrication, welding, and materials properties of high-temperature refractory alloys.[2] Progress continued in 1988, with advances in lightweight heat pipe and refractory reactor materials, and in fabrication and testing of particle bed reactor materials and components, including in-core reactor testing of particle bed fuel element assemblies for MMW reactor types.[12]

In early 1989, the project got its first taste of success with the submittal of six reactor-system concept packages at the conclusion of Phase I. The concept packages provided a description of the reactor power system concept, provided a preliminary approach to safety, and detailed an approach for follow-on development work that was planned for Phase II. Of the six concepts evaluated, three were planned for follow-on design development: (1) the Westinghouse NERVA-derivative concept, (2) the Grumman particle-bed open-cycle concept, and (3) the Rockwell ceramic-metal-fuel closed Rankine cycle concept.[8]

As the reactor-concept development efforts progressed, the evolution of the SDIO architecture away from high-power space-based platforms finally caught up with the space reactor program. SDIO system designs eventually changed, resulting in decreased power requirements. With lower power requirements, non-nuclear power system alternatives became more competitive. The need for an MMW space reactor program soon disappeared and, with it, the SDIO funding. Although NASA had identified possible uses for MMW space reactor technologies, they had no funding for development. DOE wasn't prepared to fund reactor development without a sponsor. Consequently, the MMW program, barely in its fourth year of existence, was terminated in 1990 before Phase II began.[8] The total funding provided for the program by SDI and DOE from fiscal year 1986 through fiscal year 1989 was $37.1 million.

Although the MMW program died after its first phase, some elements of the program continued. With the advent of the SEI in 1989, several MMW concepts and technologies were later identified as leading candidates for NASA space nuclear propulsion and power applications. Thermionic technology also continued to draw the interest of DoD.[g]

Designing Reactors for Space

Space reactor power system design offers many technical challenges resulting from constraints imposed by criteria such as weight, microgravity, and high temperatures. In the case of SDI applications, the following designs also benefited from the unique aspects of space-based weapons.[11]

Weight:
With launch costs on the order of thousands of dollars per kilogram, the need to minimize weight was reflected in the use of high operating temperatures to increase system efficiency; the use of high-strength, high-temperature metals and composites; and the development of improved heat rejection and power conversion and power conditioning systems.

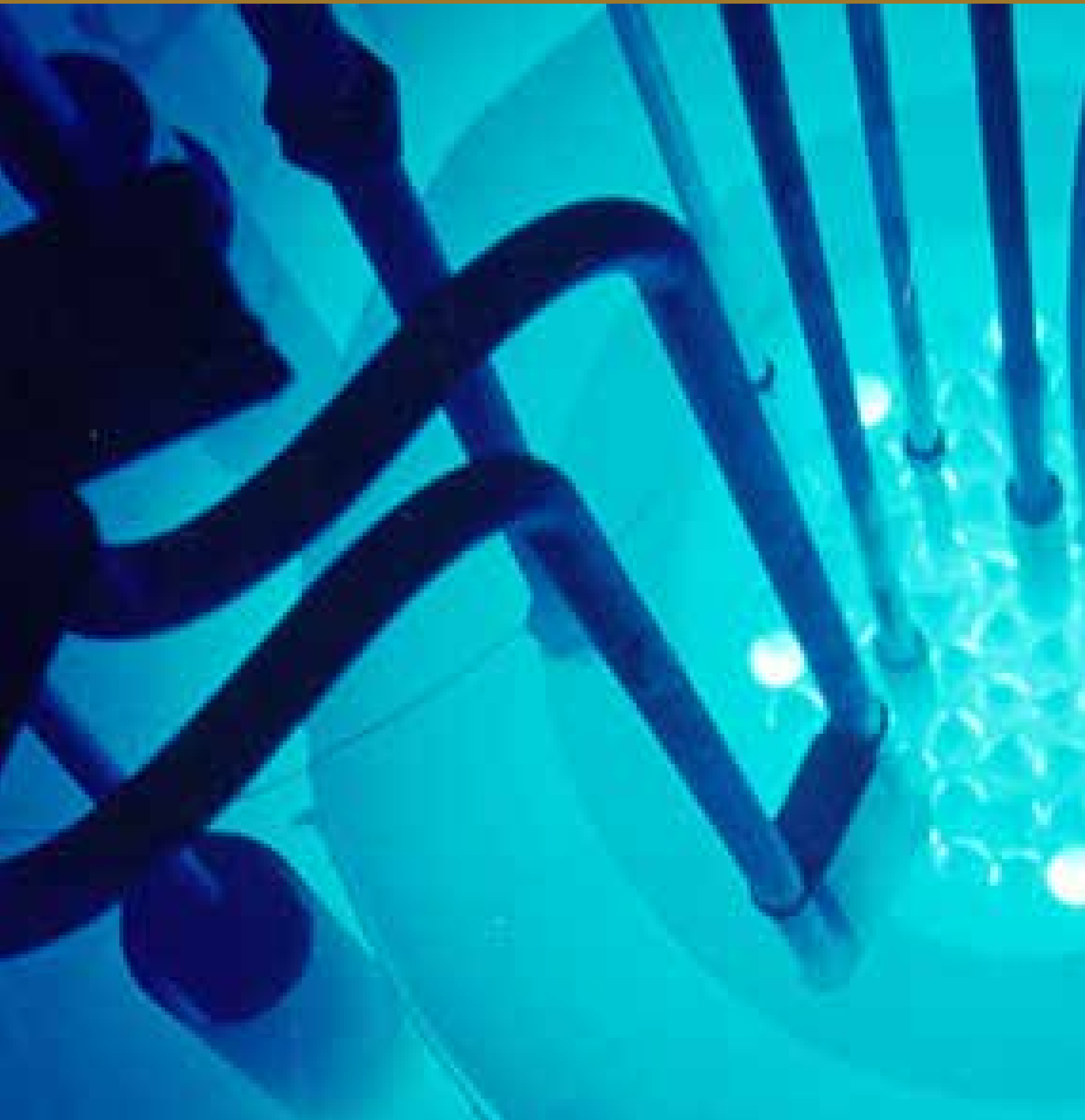
Microgravity:
The effects of microgravity on systems that rely on two-phase (gas and liquid) flow, such as the closed-Rankine-cycle system, require special design considerations. For example, vapor condensation is controlled by shear forces since no falling film condensation occurs. Also, the absence of gravity introduces pumping startup issues that must be considered.

Temperature:
The temperatures associated with high-power space reactors such as those envisioned under the MMW program generally require the use of materials and nuclear fuels capable of operating near their melting points. Development of such materials may require a proportionately larger investment of time and funding.

Benefit:
Many SDI system concepts used liquid hydrogen to cool the weapon. Once exhausted from the weapon, the hydrogen could be used as a coolant in open-cycle reactor concepts, such as the open Brayton cycle system.

g. Thermionic technology is discussed in Chapter 7.

With the announcement of SDI by President Ronald Reagan in March 1983, interest in space nuclear power systems for space-based satellites and weapons was rekindled.



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Thermionics Revived

A Second Chance

Development of thermionic space reactor power systems in the United States had its origins in the mid-1950s. Between 1963 and 1973, thermionic reactor programs under the direction of AEC emphasized development of in-core conversion concepts, in which the nuclear fuel and thermionic power conversion system are integrated in a thermionic fuel element. Thermionic reactor concepts developed under the early AEC programs resulted in designs for a broad range of space applications and power levels, including 5-kWe systems for unmanned satellites, 40-kWe systems for a manned space laboratory, and a 120-kWe system for nuclear electric propulsion. However, none of the concepts were ever developed to the point of flight readiness. Following termination of AEC space nuclear reactor power system development in 1973, thermionic reactor power system research shifted to development of out-of-core thermionic converter concepts, in which the power conversion function was located external to the reactor. Within a decade, the focus would return to in-core reactor concepts.[1]

With the announcement of SDI by President Ronald Reagan in March 1983, interest in space nuclear power systems for space-based satellites and weapons was rekindled. Although a fast-reactor thermoelectric power conversion system was selected for development under the SP-100 program, thermionic reactor technology was still considered a viable alternative. To capitalize on that viability and provide a backup technology for the SP-100 program, in-core thermionic technology development was revived by DOE under a TFE Verification Program (TFEVP) in the mid-1980s. To capitalize on foreign thermionic research and development, DoD parted ways with the domestic DOE development program in favor of technology that began to be available as the Cold War drew to a close.

Thermionic Power Systems (In-Core)

In-core thermionic space reactor power systems utilize TFE converters to produce electricity. At the heart of the thermionic reactor power system is the nuclear reactor itself. In the United States, thermionic reactor designs were centered on a multicell TFE. Other reactor designs, such as some developed in Russia, utilized single-cell TFE technology. Each approach had pros and cons regarding the testability, weight, and conversion efficiency.

Materials testing under the TFEVP was conducted in a General Atomics TRIGA reactor (pictured), EBR-II at INL, and Hanford's FFTF. (Image: General Atomics)

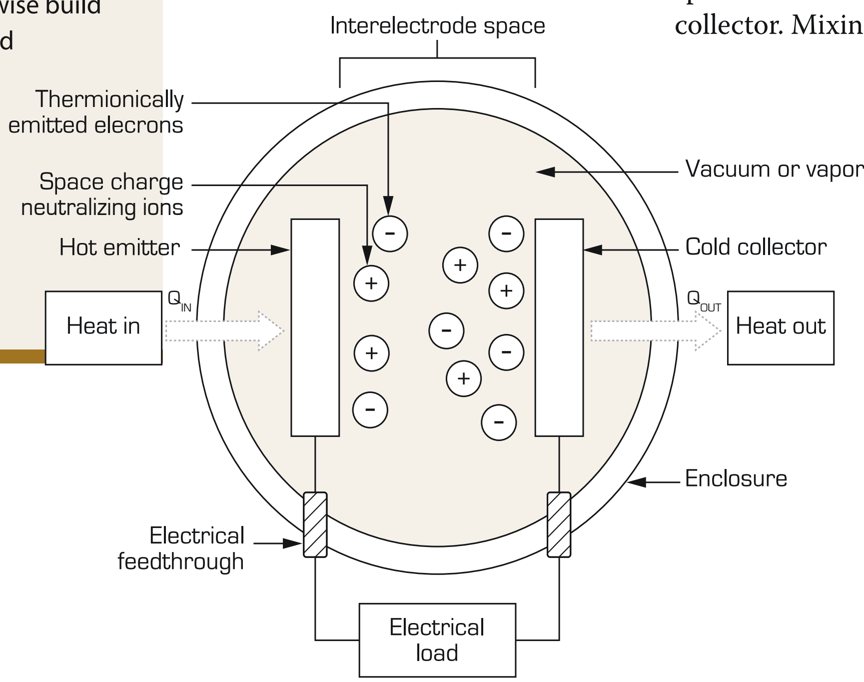
Thermionic Power Conversion

Thermionic emission is the heat-induced flow of electrons from a hotter surface (emitter) to a cooler surface (collector), typically across a small gas-filled gap.

A thermionic converter is a static power-conversion device in which electrons are boiled from the hot emitter surface across a small gap, typically less than 0.5 millimeter, to the cooler collector surface. The electrons absorbed by the collector produce an electrical current as they return to the emitter through an external circuit. The space between the emitter and collector is filled with an ionized gas (typically cesium) that serves to neutralize the space charge that would otherwise build up around the emitter and slow the passage of electrons. Thermionic converters have efficiencies of approximately 5 to 10 percent.[1]

A typical multicell TFE contained six individual TFE converters stacked inside a fuel element, much like batteries are stacked in a flashlight. With a nominal output of 0.4 We for each converter, an individual multicell TFE could produce 2.6 We with its individual converters connected in series. The reactor core was consequently sized to produce a desired power output. For example, a thermionic reactor power system consisting of 176 multicell TFEs generating approximately 1.3 MWt could generate 110 kWe.[1]

When domestic space reactor power system programs were terminated in 1973, design of a multicell TFE had advanced to a point where the element had an operating life of approximately 20,000 hours, consistent with the performance goals at the time. Two major issues prevented longer operating life. The first was deformation of the emitter. Emitter deformation was caused primarily by dimensional swelling of the fuel pellets. Swelling of the fuel pellet caused bulging of the emitter, which resulted in contact with the surface of the collector. The resulting emitter-collector contact created short circuits inside the fuel cell, thereby reducing the output voltage to zero. The second issue involved radiation induced structural damage of the insulator seals. The damage consisted of small cracks through which fission gases could pass into the inter-electrode space between the emitter and collector. Mixing of fission-product



gases with the cesium gas reduced the effectiveness of the space charge provided by the cesium.[2]

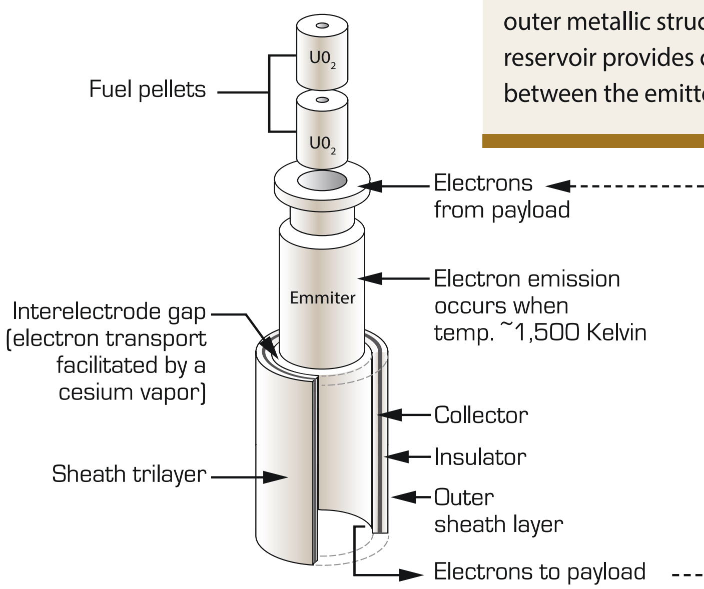
TFE Verification Program

Efforts to address TFE lifetime issues were restarted in 1984 under a thermionic technology program conducted as part of the broader SP-100 program. The work was led by General Atomics with support from Rasor Associates, Space Power, Inc., and the Thermo Electron Corporation. Through an iterative process that included design, fabrication, in-core irradiation testing, and analysis, the renewed thermionic program continued the advancement of multicell thermionic fuel element technology. For example, the fuel emitter deformation issue was addressed by increasing its thickness, doubling the gap between the emitter and collector, and lowering the operating temperature of the emitter. The insulator issue was addressed through selection of alternative materials.[2] By the end of 1985, nine fueled emitters and several insulator test articles had been designed and fabricated and were being irradiated in a Training, Research, and Isotopes General Atomic (TRIGA) reactor. Irradiation testing of the fueled emitter and insulator specimens continued into 1986 under a separate thermionic irradiation program, which eventually became part of a broader TFEVP initiated by DOE in 1986.[3]

The TFEVP was established by DOE to demonstrate the readiness of a multicell TFE suitable for use in a thermionic reactor with an electrical power output of 0.5 to 5.0 MWe and a full power life of seven years. Led by General Atomics, with support from Space Power, Rasor, and the ThermoTrex Corporation, the program included a broad set of non-nuclear tests, component tests, and integrated TFE testing. Westinghouse Hanford provided overall coordination of fast-reactor testing, while program-level technical oversight was provided by LANL.

Thermionic Converter (in-core)

An in-core thermionic converter is made up of several individual components, including the nuclear fuel, an emitter, a collector, an insulator sheath, and a cesium reservoir. The emitter includes the nuclear fuel and various components that hold the fuel in place during launch. A fission product trap provides for the collection of solid and condensable fission products to prevent their exit from the fuel cell. Heat shields serve to protect the upper and lower parts of the emitter from the high temperature of the fuel. A tri-layer sheath consists of an inner collector, a middle insulator that provides electrical isolation of the collector from the fuel element structure and coolant, and an outer metallic structural layer. A cesium reservoir provides cesium gas to the gap between the emitter and collector.



Thermionic fuel element schematic. (Adapted from "Summary of Space Nuclear Reactor Power Systems (1983-1992)," David Buden, pg. 64 in *A Critical Review of Space Nuclear Power and Propulsion*, 1984-1993, Ed. Mohamed S. El-Genk, American Institute of Physics, 1994)

Building on the TFE technology and database developed by AEC and NASA in the 1960s and early 1970s, and the more recent SP-100 thermionic development work, a baseline multicell TFE was designed for a 2-MWe conceptual reactor. Consistent with the SP-100 program goals, the baseline fuel element was designed for a seven-year operating lifetime and provided the starting point for design of the various fuel element components. Components that required specific design for the power and lifetime goals included the uranium oxide fuel, emitter and collector, insulator, fission-product trap, and various alignment and support items.[4]

In addition to the design effort, fabrication and production processes were established for each component. For example, equipment and processes for chemical vapor deposition of tungsten on emitters were developed, as were procedures and equipment for the fabrication of uranium oxide fuel pellets. Electron-beam welding equipment and a facility for plasma-spraying sheath insulators were established. Once the fabrication processes were developed and operators trained on each process, component production commenced, which was followed by a rigorous testing program.[4]

Component-level testing served to verify and validate the design and demonstrate acceptability of the fabrication and production processes. Such testing included non-nuclear development and screening tests, as well as nuclear testing conducted in FFTF at the Hanford site and EBR-II at ANL-W. The FFTF and EBR-II reactors provided a fast-reactor environment in which the components were bombarded with neutrons and tested under reactor thermal conditions.

Once the fabrication processes were developed and operators trained on each process, component production commenced, which was followed by a rigorous testing program.

Once the design of every component was verified and validated, the components were assembled into an integrated fuel element that was then tested in a TRIGA reactor. Testing in the TRIGA reactor provided an environment in which the TFEs were subjected to multiyear radiation and thermal conditions. Using several partial-length elements, a series of tests were conducted to determine parameters, such as fuel element performance relative to emitter swelling, durability of insulator materials, and adequacy of fission gas venting channels. The results allowed estimates to be made of expected fuel-element performance over the desired seven-year lifetime. A total of six TFEs were tested in the General Atomics reactor during the TFEVP: three single-cell fuel elements, two three-cell fuel elements, and one six-cell fuel element. Irradiation of the fuel elements was performed between September 1988 and October 1993. The in-core testing time for the first four elements ranged from 14,000 hours to 20,000 hours. Problems with test instrumentation or the TRIGA test vehicle limited the duration testing of the first four elements. The last two elements were in the process of being irradiated when the verification program was terminated in fiscal year 1994; the two elements had been in the irradiation environment for a period of 4,300 hours and 8,000 hours when testing was terminated.[4]

Nuclear testing revealed two issues. During one of the early tests, a tungsten component inside the emitter appeared to affect emitter lifetime, which was successfully corrected in a subsequent test. The other issue discovered during testing was related to the size of the fission-gas port for channeling fission gases out of the emitter. No other lifetime or materials issues affecting fuel element performance were identified during the reactor testing.

TFE testing in the TRIGA reactor ended in October 1993, finally giving way to other thermionic program efforts. By the end of the TFEVP, a multicell TFE lifetime of 18 months had been demonstrated and multicell TFE technology had also been advanced in several areas, including TFE fabrication processes and fuel-emitter and sheath-insulator longevity. Nonetheless, issues related to the desired seven-year life still remained and pointed to additional testing and analysis related to fueled-emitter degradation mechanisms, TFE performance prediction, and sheath-insulator lifetime.[4]

Thermionic Space Nuclear Power System Program

As the TFEVP was progressing, DoD began to re-evaluate the power needs for its future missions, largely in response to changing conditions as the Cold War drew to a close. Following a series of reviews and design studies, a new set of performance goals was established that was lower than those being worked in the SP-100 program. In response to the reduced DoD requirements, DOE, SDIO, and the Air Force initiated the thermionic space nuclear power system design and technology demonstration program in 1991. Under a Memorandum of Agreement signed in June 1991, the agencies sought to build on Air Force thermionics work and capitalize on the availability of Russian thermionic technology. The new thermionic program encompassed the multicell TFE testing that was being performed under the TFEVP, which had been running on a parallel track with the SP-100 program. The goal of the program was to design and demonstrate a 40-KWe thermionic power plant with a design-life goal of 10 years.[5]

In a dual-path down-select process that began in 1992, contracts were awarded by DOE to two different teams to develop a thermionic space nuclear power system scalable over five to 40 kWe. One concept, developed by a Rocketdyne Corporation consortium called S-Prime Thermionic Nuclear Power System, was based on multicell thermionic fuel element technology. The other concept, developed by a Space Power, Inc. consortium called the Space Power Advanced Core-length Element Reactor Thermionic System, was based on single-cell thermionic fuel element technology. Initial calculations indicated that both systems had a specific power of 18 We/kilogram for a 40-kWe system, and growth capabilities above 100 kWe.[6] The original plan was to complete preliminary designs and demonstrate key technologies and components by the end of 1995. However, funding cuts led to program termination in 1995.

Russian Technology Finds Its Way to America[h]

While DOE was working to improve its multicell thermionic fuel element under TFEVP, SDIO began exploring the use of Russian

h. The process by which Russian TOPAZ-II reactors were acquisitioned by SDIO was centered on a desire to minimize development costs of a space reactor power system by building upon the developmental efforts of the former Soviet Union. It provides lessons in procurement, contracting, and partnership development with foreign entities. It also provides lessons related to the requirements set forth in the Atomic Energy Act that govern the transfer of nuclear-related technology to and from the United States. The interested reader is encouraged to consult Booz-Allen & Hamilton[8] and Dabrowsk.[9]

thermionic reactor technology to meet its mission needs. Space nuclear reactor power systems had long been used in the former Soviet Union. Radar ocean reconnaissance satellites, known in the United States as RORSATs, were powered by a fast reactor coupled with a silicon-germanium thermoelectric power conversion system. The reactor power system produced power levels ranging from several hundred watts to a few thousand watts.[6]

In the late 1980s, a new thermionic reactor power system was tested in a series of two space tests. The new thermionic system, based on a multicell thermionic fuel element design, came to be referred to as TOPAZ-I in the United States. The tests were successfully completed when the TOPAZ-I system provided in-orbit power to two Cosmos satellites in 1987. In a separate (but parallel) effort, another thermionic reactor power system based on a single-cell thermionic fuel element design had also been developed in the former Soviet Union. The TOPAZ-II system, as the unit came to be called in the United States, was never launched by the Soviets, but had undergone a significant development effort and was considered flight-ready under the former Soviet system.[6, 7, 8]

As the political and economic environment in the former Soviet Union changed in the late 1980s, the Russian space nuclear research community faced an uncertain future. During this time, officials of the Russian space program offered to sell to DoD two complete, unfueled, electrically-heated TOPAZ-II reactor systems and associated test equipment.

The arrangement was viewed by DoD as a means of acquiring a turn-key system, including the two reactors, a vacuum test stand and associated pumps, a fuel-element test rig, and control hardware at a cost significantly less than would be required if a comparable development program were undertaken in the United States. After a lengthy process of negotiations, licensing, authorizations, and approvals that involved multiple Federal and foreign agencies, private companies, and consortiums, two unfueled TOPAZ-II reactors and associated testing equipment were purchased and transferred to the United States in May 1992 under the auspices of the SDIO and the Air Force Phillips Laboratory in New Mexico. The equipment transfer and subsequent Thermionic System Evaluation Test (TSET) program effort represented a prominent example of international cooperation between the United States and Russia, in what was once a tightly controlled and classified technology, following the collapse of the former Soviet Union.[9, 10]

Testing the Russian Technology

Under the TSET program, non-nuclear testing of the two unfueled TOPAZ-II reactors and single-cell thermionic fuel elements began in November 1992 at the University of New Mexico Engineering Research Institute in Albuquerque, New Mexico. The TOPAZ-II reactor system was designed to be ground tested using tungsten electric heaters in lieu of fueled elements, thereby allowing the entire reactor system to be tested at elevated temperatures in the absence of nuclear fuel. The TOPAZ-II test program included a series of electrical, mechanical, and thermal tests and operations that provided verification of baseline design and system performance, and provided the opportunity to train American operators on the Russian systems. Of particular importance was the need to demonstrate the viability of the TOPAZ-II technology against DoD space flight requirements. Reflecting upon the TOPAZ-II acquisition, Richard Verga, the SDIO manager for power technology, described the thinking as "not just [to] reverse engineer, but to see if it was possible to make a U.S. variant of the TOPAZ [II] technology that would embody our expectations of power [weight], particularly safety."[11]

The TOPAZ-II reactor system was designed to produce approximately 6 kWe (including the 1 kWe needed to operate the sodium-potassium pump) from a reactor thermal output of approximately 115 kilowatts. The cylindrical reactor core was relatively small, with a diameter of approximately 10 inches (25 cm) and a length of 15 inches (38 cm). The reactor core consisted of 37 single-cell TFEs, each of which contained a stack of annular-shaped highly enriched uranium oxide fuel pellets. Reactor cooling was provided by a liquid-metal consisting of sodium and potassium.[6]

During the approximately three-year TSET program, an American-Russian research team completed facility and reactor system acceptance testing, training of U.S. operators on the Russian reactors, and testing necessary to characterize performance of the reactor systems. A total of 11 thermal-vacuum tests were completed on the two reactor systems. Testing of one of the reactor systems showed susceptibility to output-power oscillations. The other

Russian Thermionic Technology

The former Soviet Union began researching thermionic space reactor technology in the 1960s. By 1967, two thermionic reactor concepts were being independently developed in secret programs by two different teams of Soviet technical institutes. Development occurred in a largely competitive environment between two technical institutes, akin to the competition one might see between the Lockheed-Martin and Boeing corporations in the current U.S. aerospace industry. While the United States focused on development of RTG technology, space nuclear power development in the former Soviet Union included a substantial investment in the two thermionic reactor technologies.

The Central Design Bureau of Machine Building, in conjunction with the Kurchatov Institute of Atomic Energy and Krasnaya Zvezda (Red Star) State Enterprise, led the development of one thermionic concept that utilized a multicell TFE. The multicell TFE consisted of a stack of short thermionic cells that acted as a single fuel element, similar to the way batteries are stacked in a flashlight. The multicell TFE concept was developed under a program called TOPAZ, a Russian acronym meaning "thermionic experiment with conversion in active zone."[9] In 1987, the TOPAZ system was launched aboard two Russian satellites, Cosmos 1818 and Cosmos 1867, marking the first successful use of thermionic nuclear reactor power systems in space. Cosmos 1818 operated for 142 days and Cosmos 1867 operated for 342 days.[6, 7, 8]

Design life was a major difference between Russian and U.S. designs. The TOPAZ design life was only one year, limited in part by the on-board cesium supply. Unlike the sealed U.S. designs, the cesium in the interelectrode gap flowed through the gap during operation. Both units produced approximately five kWe after accounting for the approximately one kWe of electrical power needed to operate the pump for the sodium-potassium liquid metal cooling loop.[5] For safety reasons, reactor operation began only after a nuclear-safe orbit of approximately 800 kilometers above Earth was attained.[12]

The second thermionic concept, developed by the Kurchatov Institute of Atomic Energy and Scientific Industrial Association Luch, used a single cell TFE that had been developed under a program called ENISEY (pronounced Yenisee). Although the reactor system was never launched, it had been subjected to a significant ground-testing effort, both unfueled and fueled, by its developers. One advantage it held over its multicell counterpart was a design that allowed the use of electrical heaters, in lieu of nuclear fuel, during testing. In an effort to distinguish the two reactor systems in the United States, the single-cell reactor system, ENISEY, became known as TOPAZ-II, and the multicell system, TOPAZ became known as TOPAZ-I.[9]

The End of the Soviet Union

As the Soviet Union weakened economically in the late 1980s, Mikhail Gorbachev pulled the Soviet Union back from its international commitments and stopped participating in the Cold War arms race with the United States. The perceived loss of prestige led to resistance within the Soviet government that culminated in a failed coup d'état by a core group of Soviet hardliners in August 1991. When the hardliners announced on state television that Gorbachev, whom they had sequestered, was ill and would not be able to govern, massive protests immediately ensued across the country, and the military refused to obey orders to crush the protests. After three days, the coup organizers surrendered, realizing that they would be unable to govern without the support of the military. The magnitude of the protests made it clear that the Soviet Union was no longer governable under the old system, and the country began preparing to dissolve itself.

On December 25, 1991, Mikhail Gorbachev resigned his post as the Executive President of the Soviet Union, having already resigned as General Secretary after the coup. On January 1, 1992, the Soviet Union officially ceased to exist, and 13 independent countries were formed. The decades-old long post-World War II rivalry between the United States and the Soviet Union was over, leaving the United States as the world's only remaining superpower.

unit, which included testing at nominal operating conditions for up to 1,000 hours, resulted in the observation of small leaks in the interelectrode gap and intermittent short circuiting of one of the thermionic fuel elements. Other tests were performed that assessed the electrical output of the thermionic fuel element converters, verified thermophysical properties of the reactor and fuel elements, and operated the systems under mechanical and shock loads.[9, 13, 14]

Based on the results of the tests, a follow-on demonstration project was planned in which a TOPAZ-II reactor would be used as a power source for satellite-based electric propulsion technologies in space. The Nuclear Electric Propulsion Space Test Program (NEPSTP) became part of the Ballistic Missile Defense Organization (BMDO) following an organizational name change of SDIO in May 1993. In late 1993, the TOPAZ-II program was also renamed the TOPAZ International Program, in a move to better reflect the international makeup of the TSET team, which included British and French researchers in addition to the Americans and Russians.[9, 15]

TOPAZ-II: Preparing for Flight

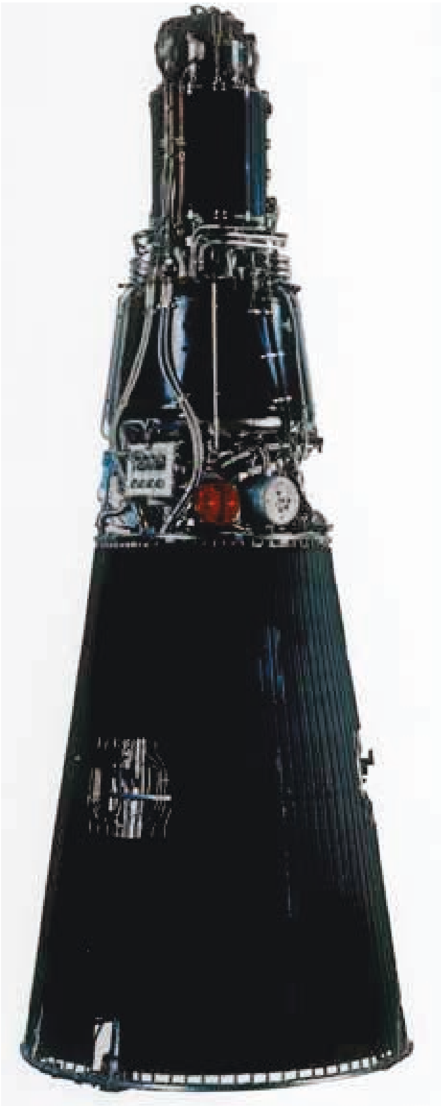
Under BMDO management, NEPSTP had four goals: (1) demonstrate the feasibility of launching a reactor power system; (2) demonstrate the ability to adjust orbits using nuclear electric propulsion; (3) evaluate the in orbit performance of the TOPAZ-II reactor and selected electric thrusters; and (4) measure, analyze, and model the nuclear electric propulsion environment. The intended mission called for initial launch into a circular orbit of 3,260 miles (5,250 kilometers). Once in orbit, reactor startup would be prompted by a ground command. With successful reactor operation, each of several on-board ion propulsion thrusters would then be tested for a 1,000-hour period. The thrusters would slowly raise the orbital altitude of the satellite to 25,000 miles (40,000 kilometers) over a period of approximately 27 months.[15, 16]

The NEPSTP would include all aspects of a launch program, including mission and spacecraft design, safety, integration and qualification, launch approval, and launch operations. One key benefit of performing such a mission would be possibly characterizing the electromagnetic and plasma environments generated by a reactor and electric propulsion in orbit, which could be used for future reactor-based electronic system designs. Another benefit would be the identification of requirements associated with reactor launch, such as safety and approvals. The interest in the second benefit had its basis in the fact that the only reactor ever launched by the United States had been the SNAP-10A unit in 1965, and almost 30 years had passed since that first launch. As project managers soon discovered, the path leading to success, particularly when success hinges on foreign technology, presented many challenges.[15]

As project managers soon discovered, the path leading to success, particularly when success hinges on foreign technology, presented many challenges.

The first major challenge presented itself in the form of technology integration. For example, the TOPAZ-II reactor had been designed for integration with a Soviet proton rocket; design changes were needed to support integration with a U.S. launch vehicle. Design changes also manifested themselves in the approach to thermal management for spacecraft electronics. In the TOPAZ-II system, electronics were enclosed in a pressurized vessel, and convective heat transfer was used to remove excess heat generated by the electronics. Although thermal management was simplified with this approach, it added mass and volume to the spacecraft. The TOPAZ-II electronics were subsequently replaced with a smaller unit based on U.S. thermal management philosophy that relies on conduction and radiative heat transfer processes, thereby minimizing mass and volume. Other design changes centered on the approach to ensure the liquid-metal coolant didn't freeze prior to reactor startup in space. Rather than using high-current ground-based electrical heaters to heat the coolant prior to launch, as the Russians did, NEPSTP designers incorporated an approach that used a combination of ground-based temperature control airflow with a reduced time period before reactor startup.[15]

Safety considerations gave rise to yet additional design changes. A preliminary nuclear safety assessment, performed to demonstrate compliance with guidelines for a U.S.-based launch, identified the need for several safety features to ensure nuclear safety of the reactor system during the planned mission. The needed

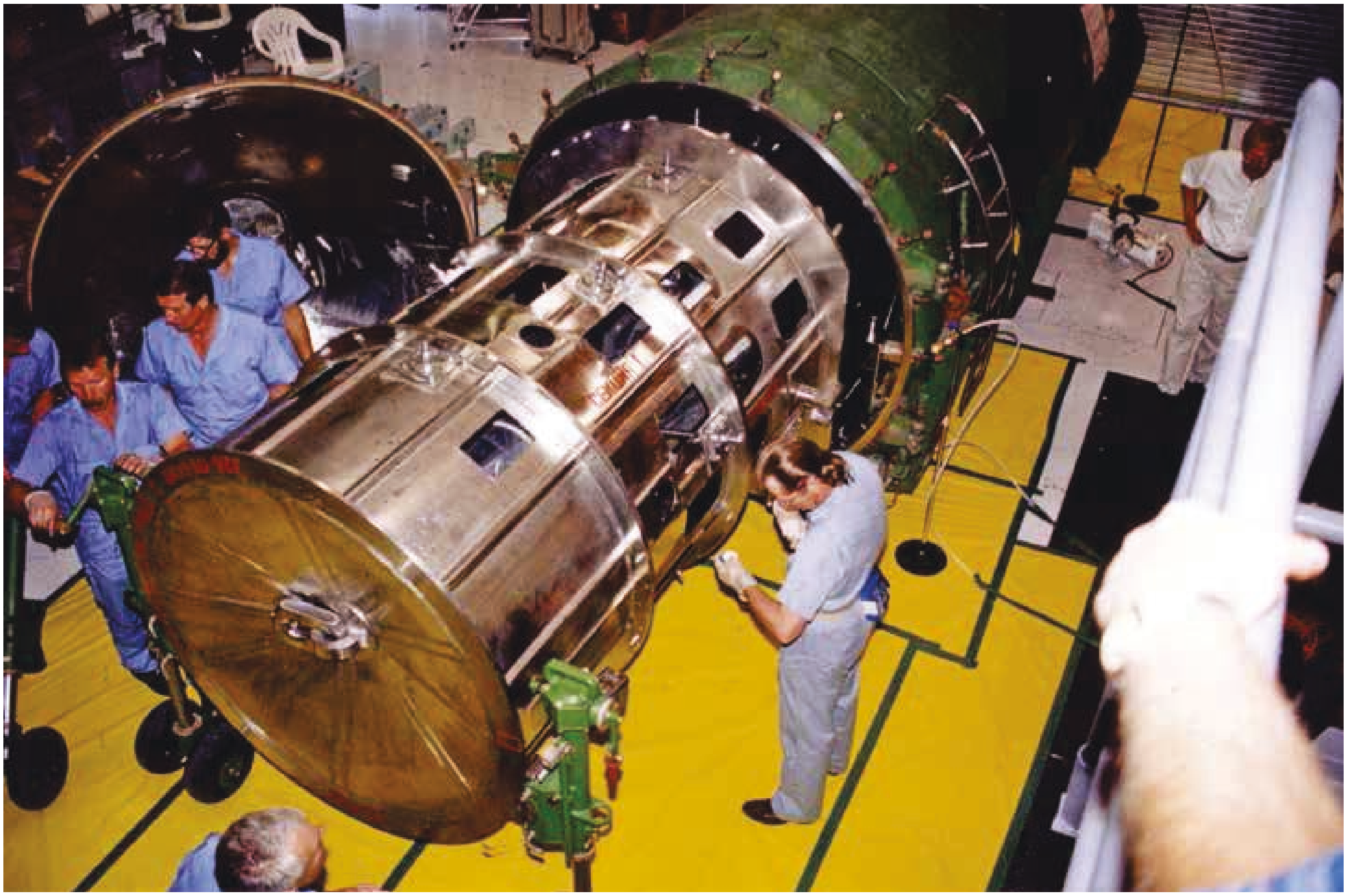


TOPAZ-II reactor system. (Photo: Scott Wold)

Safety considerations gave rise to yet additional design changes.

safety features included a thermal shield to prevent breakup of the reactor system during a postulated re-entry event; engineered controls to ensure the reactor remained subcritical during flooding events, such as would occur if the reactor landed in the ocean or other body of water; and a control system to ensure automatic reactor shutdown. The safety concerns gave rise to additional design changes and development of a safety requirements document that was modeled on an earlier interagency (DoD, NASA, and DOE) study conducted for the SEI.[16, 17]

While non-nuclear ground testing provided significant value, the overall demonstration effort couldn't be completed without testing in a fueled configuration. Each TOPAZ-II reactor was designed to be fueled with approximately 59 pounds (27 kilograms) of high-enriched



Unloading TOPAZ-II from its shipping container. (Photo: Scott Wold) uranium. After considering its options, BMDO elected to purchase Russian fuel that had been specifically fabricated for the TOPAZ-II reactor. In addition to the fuel, four additional unfueled TOPAZ-II reactor units were also made available to BMDO. The four additional units included two units built to Russian flight standards (the first two units acquired by SDIO were not flight-qualified). With two flight-qualified units, BMDO would have one unit dedicated for flight use and another serving as a backup flight unit. Following receipt of DOE authorization for the purchase (import and utilization for non-fueled ground testing only), the four unfueled units were delivered to the United States in March 1994.[16]

As BMDO and the Air Force moved forward with design changes and non-nuclear testing of the TOPAZ-II systems, DOE initiated an independent safety assessment of the TOPAZ-II space nuclear power system. The pre-authorization assessment was performed in anticipation of a DoD request to conduct operations involving nuclear material, including the purchase of nuclear fuel for the TOPAZ-II reactors, ground testing involving nuclear fuel, and the launch of the fueled TOPAZ-II system, as modified to meet applicable U.S. requirements; such authorization was (and still is) required under Section 91b of the Atomic Energy Act. The review team concluded that the information available at the time of the assessment was insufficient to confirm the safety of the proposed flight program and that it would be "extremely difficult to conclusively demonstrate that inadvertent criticality can be prevented for all credible accident conditions during the launch or for end-of-mission re-entry phases." Alan Newhouse, Director of the DOE Office of Space and Defense Power Systems at the time, later described one of the key problems with the Russian reactor:

"The Russians… [had] an interesting design. It had good features to it. It just had flaws… it had what was called a positive temperature coefficient, which meant if it were immersed in water, for example, it would go prompt critical and dissolve itself with a big boom. We… wouldn't allow our space reactors to be launched with that characteristic. You want the thing to be self regulating. All the Navy reactors are."[18]

The review team concluded that low-power (critical) nuclear experiments could be safely performed under DOE oversight, and recommended that an additional, independent safety review be conducted after all analyses, experiments, and safety report preparations had been completed.[16]

TOPAZ Sputters Out

In 1993, funding for the TOPAZ-II International Program was reduced as the result of cost-cutting pressures and changing defense-spending priorities. To keep the program alive, SDIO expanded its goals to include defense conversion—aiding the Russians in converting portions of their defense industry to civilian operations—in addition to the original technology transfer goal. The remaining four TOPAZ-II reactors in the Russian inventory were brought to the United States in March 1994. Two were intended for ground testing to support spacecraft integration; the other two were planned for use during proposed flight tests.

In October 1995, the TOPAZ-II International Program was transferred from BMDO to the Defense Nuclear Agency (DNA). In anticipation of the transfer, DNA formed a working group and invited DOE to help guide the future of its thermionic development program. Having begun under BMDO and its predecessor agency as a demonstration program for TOPAZ-II capabilities, followed by a flight demonstration, funding cuts severely reduced the program. As a result, DNA planned to re-orient the program for improved consistency with the broader space nuclear reactor technology needs of the country.

Shortly before its transfer to DNA, the TOPAZ-II International Program came under the scrutiny of several investigations amidst allegations of mismanagement and contracting improprieties. Questions arose surrounding the acquisition, contracting, and funding practices of the program. Concerns had also surfaced within DOE and the Air Force Phillips Laboratory regarding lack of accessibility to all the TOPAZ-II technology due to proprietary and trade-secret assertions by Russia. The GAO questioned whether the original program goal of technology transfer was truly accomplished.[19]

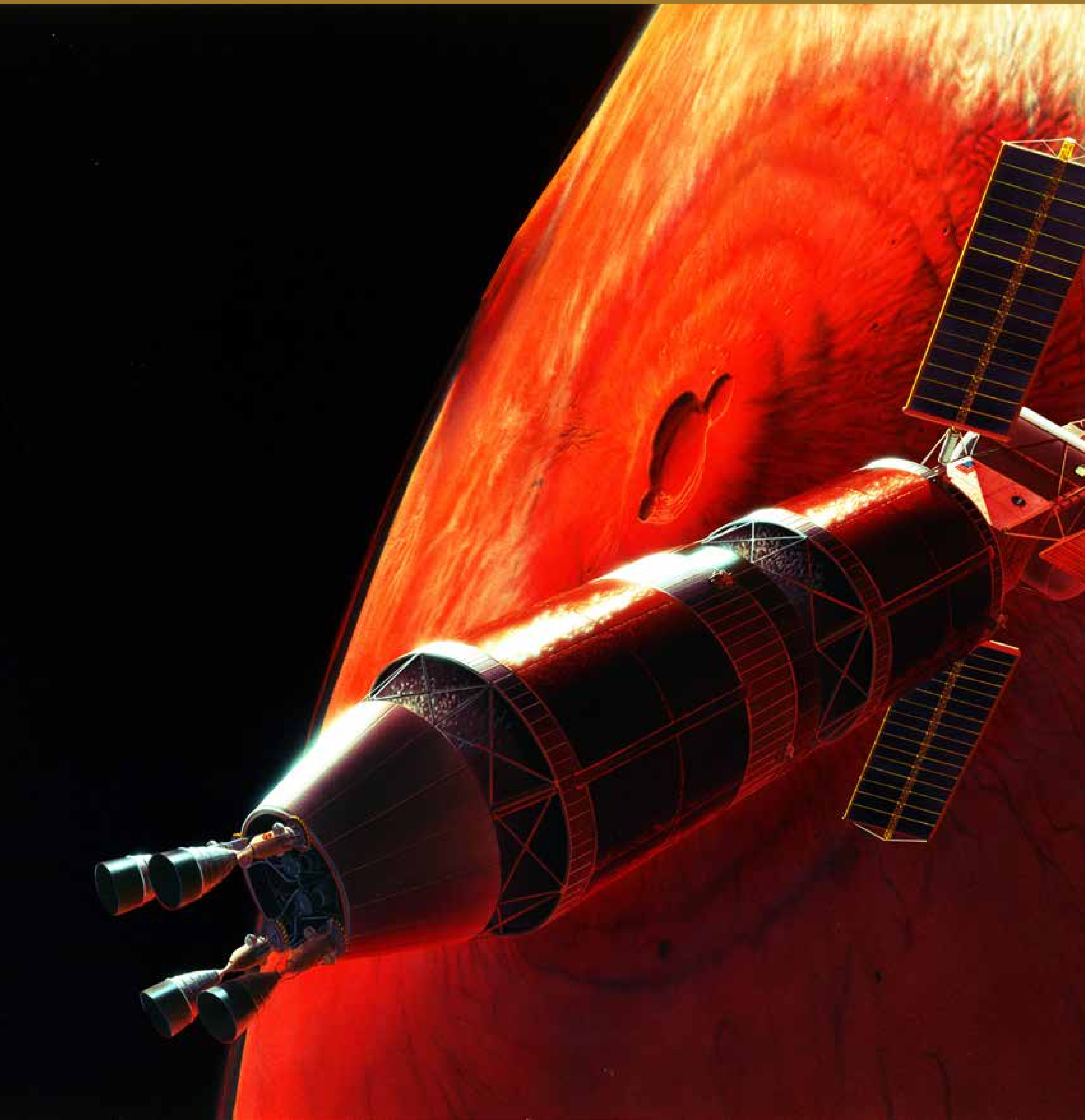
In 1996, the beleaguered TOPAZ-II International Program was officially terminated. The termination came in part due to findings from the GAO audit but also from the lack of a defined DoD or NASA mission and changing priorities within the defense agency. Following its termination, the six TOPAZ-II reactors originally purchased for testing and flight demonstration were returned to Russia by 1997, consistent with the plans conceived early in the TOPAZ-II negotiations.

In 1996, the beleaguered TOPAZ-II international program finally met its demise when it was officially terminated.

Thermionic Space Power Program Reflections

From its new beginnings under the SP-100 program, through the DOE TFEVP and thermionic space nuclear power system programs, and then the DoD acquisition and testing of the TOPAZ-II reactor systems, thermionic space reactor technology had found the favor of a contingent within the broader space nuclear power system community. Although the nearly decade-and-a-half effort had clearly served to advance the technology base of space nuclear thermionic power conversion, it also revealed divisions that had plagued the U.S. space nuclear power community in the past, such as which space reactor technology held the most promise. Although the much hoped for gains of utilizing foreign technology were never fully realized, the effort did provide lessons related to the pursuit of such exchanges.

The two initiatives resulted in two separate nuclear propulsion programs... providing possibly the broadest support for space nuclear thermal propulsion systems since the days of NERVA.



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Nuclear Propulsion
Space Reactors Heat Up

With the termination of the NERVA nuclear rocket program in 1973, U.S. space nuclear propulsion efforts lay dormant for more than a decade. The little amount of space nuclear reactor research that did exist was focused largely on development of reactor power systems rather than propulsion systems. By the late 1980s, that began to change, first under the auspices of SDI, and then under the umbrella of SEI. The two initiatives resulted in two separate nuclear propulsion programs, one built around military missions, and the other built on space exploration. For a brief moment, the two initiatives overlapped, providing possibly the broadest support for space nuclear thermal propulsion systems since the days of NERVA.

Timberwind and the Particle Bed Reactor

While SDIO held a large stake in the development of the SP-100 space reactor power system, its attention soon turned to yet another space nuclear power system for possible military applications. With support from the DOE Office of Defense Programs and the national laboratories under its purview, SDIO initiated a program in 1987 to explore the feasibility of developing a new nuclear-powered rocket. Rather than building on Rover/NERVA reactor technology, SDIO selected for its new propulsion system a particle bed reactor (PBR), a concept that had its origins in the 1960s.[1]

The concept of a particle bed space reactor was first investigated in the 1960s at Brookhaven National Laboratory in Upton, New York. During the 1970s and 1980s, Dr. James Powell of Brookhaven developed the particle bed concept further by designing a gas-cooled reactor that employed a fuel element consisting of small spherical fuel particles packed between two concentric porous cylinders called frits. The PBR was envisioned to consist of 19 fuel elements assembled to form the reactor core. Each fuel element could contain millions of tiny uranium fuel particles (approximately 0.01 inch [0.5 millimeter] diameter). Hydrogen gas would enter the top of the reactor core and pass through the outer cylinder walls of the fuel elements into the fuel particle bed where the heat from fission would be transferred to the hydrogen. The heated hydrogen gas would then be expelled through the inner cylinder wall of the fuel element and exit the reactor core into a nozzle chamber, from which the exhausted gas would provide thrust for

Artist's concept of a nuclear thermal propulsion transfer vehicle and the ascent stage of a two-stage Mars lander. (Image: NASA, Pat Rawlings, SAIC)

Nuclear Thermal Propulsion

Nuclear thermal propulsion systems produce thrust by heating a propellant (usually hydrogen) passing through a nuclear reactor and expanding the hot gases through a nozzle. Upon exiting the throat of the nozzle, the hot gas expands against its flared sides, thereby generating thrust, which propels the nozzle/rocket forward. The very-high-temperature capability provided by a reactor and the use of a low-molecular-weight propellant offer the potential for a high specific impulse (a measure of the efficiency of a space propulsion system defined as the ratio of engine thrust to propellant flow rate) and high levels of thrust for a relatively low propellant and system mass. Such systems also have the capability to produce very high velocities. With these benefits, SDIO hoped to develop an interceptor system that would more than double the performance of conventional rocket engines in use at the time (e.g., specific impulse approaching 1,000 seconds and a thrust-to-weight ratio of 25 to 35 for thrust levels of at least 20,000 pounds). Other applications that have been considered for nuclear thermal propulsion systems include space exploration, such as a manned mission to Mars, and lifting heavy payloads into space.[3]

the spacecraft. In theory, the small fuel particle size provided a very high surface-area-to-volume ratio, thereby enabling efficient heat removal, high power density, and compactness, which resulted in a relatively small, lightweight reactor system.[2]

In the early 1980s, Powell and Brookhaven began collaborating with an industry team led by Grumman Aerospace Corporation to develop the PBR concept for various space applications. As a compact, lightweight, high-density power system, the particle bed technology soon caught the attention of SDIO as a potential power system for a kinetic energy weapon called the electromagnetic rail gun. Interest in kinetic energy weapon applications gave way to the concept of using a PBR-powered nuclear rocket as a rapid intercept vehicle to destroy ballistic missiles in the early stages of their boost phase.[3] It was the boost-phase interceptor application that led to a highly classified program in 1987, codenamed Timberwind, under which the feasibility of the PBR nuclear thermal propulsion system concept was first evaluated. Until the time that the program was declassified several years later, development of the new nuclear propulsion system was invisible to the public and the broader space nuclear community.[1]

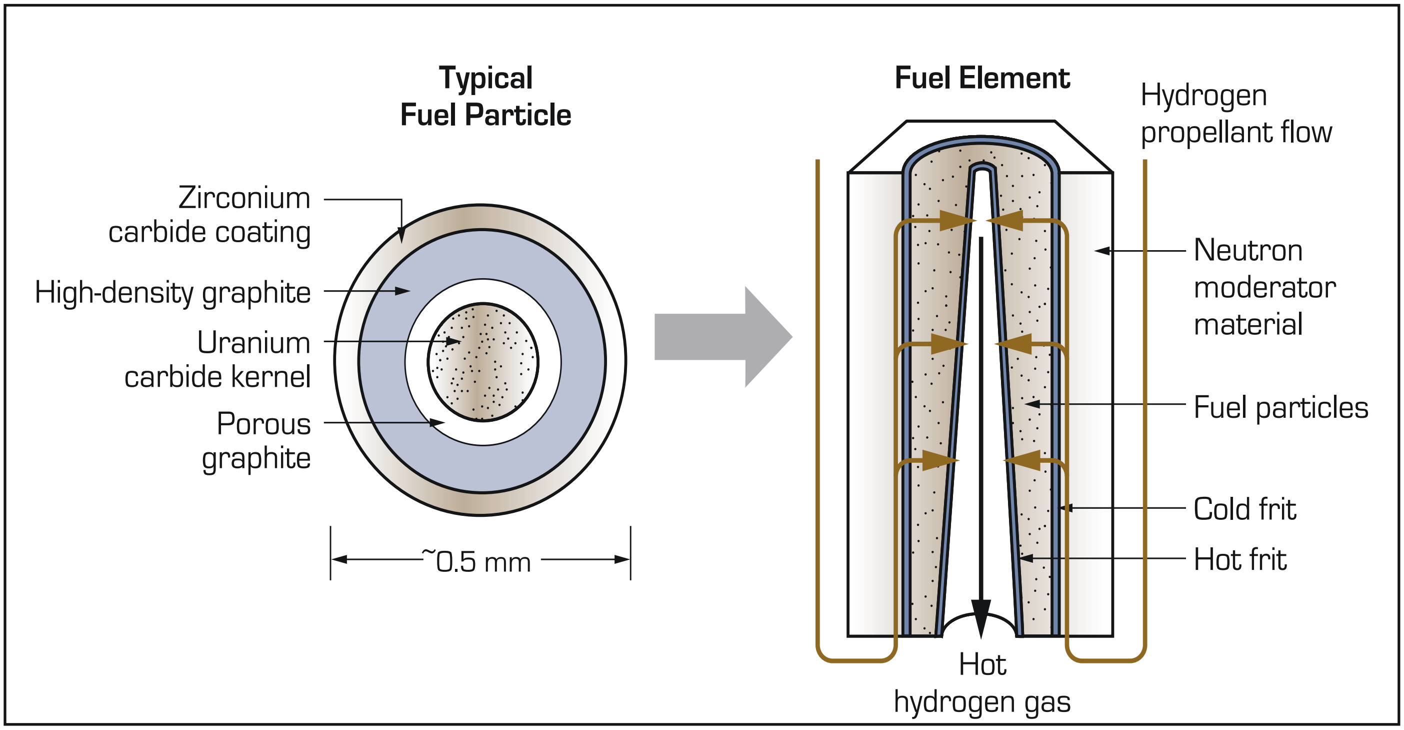
PBR Feasibility

With the initiation of Timberwind in mid-1987, SDIO began a two-year effort to evaluate the feasibility of the PBR technology. With support from the Office of Defense Programs at DOE, an industry team led by Grumman, and two DOE national laboratories (Sandia and Brookhaven), the two years were filled with design, analysis, fabrication, and testing activities. The major emphasis was placed on development and testing of the reactor systems, including the fuel particle, fuel element, and reactor.[3]

Fuel designers sought to develop a fuel particle that could withstand an extremely high temperature of approximately 3,500 Kelvin to achieve a desired hydrogen gas exhaust temperature of approximately 3,000 Kelvin. As a point of reference, the maximum fuel temperature actually demonstrated during the Rover/NERVA projects was approximately 2,600 Kelvin. A baseline fuel particle design, derived from a commercial-scale high-temperature gas-cooled reactor program, was developed that consisted of a uranium carbide fuel kernel surrounded by a porous graphite buffer layer. Surrounding the porous graphite layer was a dense graphite layer, which was then surrounded by an outer layer of zirconium carbide. Although the baseline fuel particle had an inherent temperature limitation of approximately 2,800 Kelvin (well below the 3,500 Kelvin planned for flight-qualified fuel), its development and use served to develop an experience base and support the development of other components.[3]

Along with the design of the baseline fuel particle, a production capability was needed to produce the very small (0,01 inch [0.5-millimeter] diameter) fuel particles. Fortunately, fuel developers got help from ORNL, from which they received the technology and equipment to manufacture the coated micro-particle fuel. The production process included the use of a fluidized-bed chemical vapor deposition process by which the graphite layers were applied. With the aid of LANL and General Atomics, the Babcock and Wilcox fuel designers also developed a chemical vapor deposition process for coating the small fuel particle with the zirconium carbide.[3]

Testing of fuel particles and fuel elements included non-nuclear and nuclear aspects. For example, non-nuclear fuel particle heating tests were performed using furnaces at Babcock and Wilcox facilities. Nuclear testing was performed using the Annular Core Research Reactor, a TRIGA-type test reactor at SNL.[4] Such testing, and the inspection that followed, provided data on temperature limits, coatings, particle strength, and other parameters that served to verify the fuel design, identify potential failure modes, and evaluate effects of manufacturing process variability. The importance of such testing was soon evident. During testing of the early fuel element design, performed under the Pulse Irradiation of a Particle



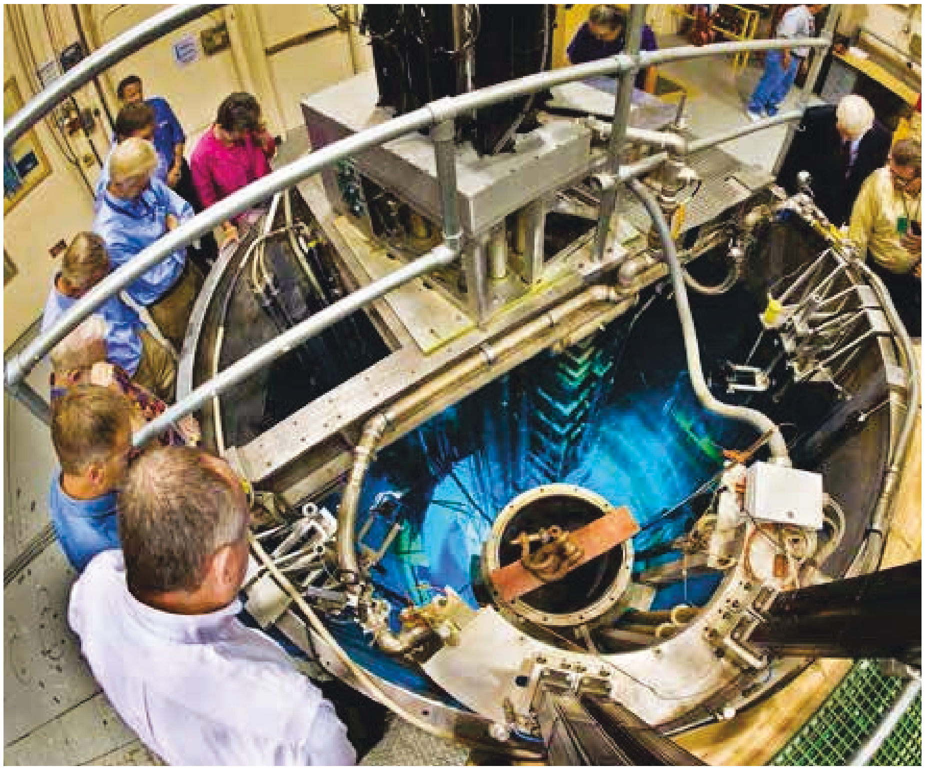
Typical PBR fuel particle and fuel element. (Adapted from Final EIS for the Space Nuclear Thermal and Propulsion Program, May 1993)

Bed Fuel Element project, fuel particle breakdown was observed when carbon contamination of the test loop was discovered. During a later series of tests, it was discovered that the baseline design fuel particles failed at a temperature of approximately 2,500 Kelvin rather than the theoretical limit of 2,700 to 2,800 Kelvin. As a consequence of the failure, fuel designers began developing two advanced fuel particles: an infiltrated kernel particle and a mixed-carbide particle.[3]

As development of the fuel particle and fuel element progressed, such efforts would have to eventually address the possibility of hydrogen flow instabilities in the core, a phenomenon largely unique to the PBR. Because the fuel element consisted of randomly packed spherical fuel particles, the pathways through which the hydrogen coolant could pass would naturally vary. Reduced hydrogen flow in one of the pathways would reduce the amount of heat being carried away from the fuel, and the resulting temperature increase could further reduce the density of the hydrogen and the amount of heat carried away by the hydrogen flow. This cycle could continue until the fuel particle failed, producing particles that could block additional flow pathways, causing progressive failure of the system.[5, 6]

In addition to the heating-induced particle failure, attention was also given to other mechanisms by which fuel particles might be damaged, such as corrosion, friction from fuel particle movement or vibration during launch, or from the propulsion system turbomachinery. Although early evaluations by Brookhaven National Laboratory suggested that most of these particulate sources would be insignificant and not create a problem of flow instability, the long-term testing and experience needed to address plugging or local flow blockage was not performed due to program termination.[3, 7]

In support of the reactor design, a 19-element critical experiment reactor was also designed, built, and tested at zero power at SNL. Following approval of the critical experiment reactor by DOE, a series of critical experiments began in late 1989 that served to verify the nuclear-specific design of the reactor



Annular core research reactor at SNL. (Photo: SNL Flickr) and benchmark reactor design codes. Because the heterogeneity of the PBR was expected to produce nonuniform neutron flux and power distributions, designers needed to be able to calculate the internal neutron physics behavior to match coolant flow and obtain a uniform hydrogen exit temperature. Analytical methods predicted performance within 0.5 percent of actual behavior, providing confidence in the design.[3]

After two years of design, analysis, fabrication, and testing, the feasibility of the PBR technology had been established to an extent sufficient to support a follow-on development and testing phase. Existing test facilities had been put to use and new test facilities were in the initial throes of planning and design. The project team had worked together for over two years and many of the bumps and hurdles that come from bringing a diverse team together had been ironed out and cleared. With the feasibility of the PBR technology showing promise, a new contract was initiated in 1989 to begin the next phase of development, testing, and validation of the PBR propulsion system in preparation for an eventual ground test of a flight demonstration engine.

Timberwind Expansion Faces Headwinds

Although the Annular Core Research Reactor provided excellent data on fuel particle and fuel element designs, operational and power limitations of the research reactor limited its usefulness in terms of the testing needed to fully qualify the fuel and other nuclear components for flight use. In reality, there were no domestic test reactors capable of producing the high temperatures (3,500 Kelvin fuel particle), power densities (40 megawatts per liter), and operational environment (flowing hydrogen) needed to qualify the PBR and its components. To address this issue, a new test reactor was planned. The PBR Integral Performance Element Tester (PIPET) was conceived as part of a larger new test complex at which the systems and infrastructure needed for testing and qualifying an integrated nuclear thermal propulsion engine could be located.[3]

As originally conceived by SDIO, PIPET was going to be a small, low-cost, single-use facility for testing PBR fuel elements and engines. Over time, the concept evolved into a large-scale ground-test facility for reactors and all nuclear components, with a separate facility for testing integrated nuclear thermal propulsion engines. The planned location for the new nuclear propulsion test complex was the Saddle Mountain Test Site at the Nevada Test Site, which would include several testing facilities, analogous to the old Rover/NERVA facilities. The PIPET facility was to include testing systems for the fuel assemblies, including a bunker for control consoles; an assembly facility for non-nuclear testing of reactor cores; the PIPET reactor test cell; a coolant supply system to supply cryogenic hydrogen (the primary coolant) and helium (to be used to purge the system); a remote inspection and maintenance system to allow reactor evaluation in a high-radiation environment; and an effluent treatment system to remove potential radioactive contaminants from the hydrogen exhaust gas so it could be flared while keeping atmospheric emissions within limits.[3]

The plan accommodated expansion to a full-scale facility, including a building with cells for testing ground-test and qualification-test articles, coolant- and effluent-system upgrades, a disassembly facility for post-irradiation evaluation, and a non-nuclear engine integration test facility in which comprehensive cold flow tests (without a reactor) could be performed to characterize, integrate, and qualify the engine feed system, propellant management system, and engine components. The PIPET reactor would be sited in a reinforced concrete cell, partially below ground. The reactor core would be confined in two carbon-carbon pressure vessels and a metallic pressure vessel.[3]

Two other major facilities were planned for testing of non-nuclear components. The first was the San Tan Hydrogen Test Facility located in a valley on the Gila River Indian Reservation approximately 20 miles (32 kilometers) outside of Tempe, Arizona. The facility was being built to enable tests with both cryogenic and high-temperature (3,000 Kelvin) hydrogen. The site had been in operation for over 30 years to test aerospace systems and components produced by Allied Signal. The facility would enable design, development, verification, and qualification of components and materials exposed to hydrogen, such as the engine turbopump, feed valves, nozzles (subscale), and the hot frit.[3] The second non-nuclear facility was located at the Grumman complex in Bethpage, New York. The Grumman System Integration and Test Laboratory was used to develop integrated engine systems and was integral in the development, verification, and validation of operational software. The laboratory developed the flow control system for nuclear element tests at SNL and included special-purpose computer resources to support thermal/fluid, neutronic, and other reactor system modeling.[3]

As SDIO worked to address Congressional concerns, the headwind of agency and mission change was soon felt when the former Soviet Union was in the throes of significant political and economic reform...

As the vision for an expanded testing capability unfolded, progress on Timberwind soon stalled in the face of several headwinds, including congressional actions, global events that resulted in agency and mission changes, and public awareness of the planned nuclear rocket program. In fiscal year 1990, Congress limited funding for the nuclear rocket program pending broader DoD endorsement, including that of the Defense Science Board, a committee of civilian experts that advises DoD on a various scientific and technical matters. Technical progress slowed while the program satisfied the Congressional language. By October 1990, the required endorsements had been received. As part of its endorsement, however, the Defense Science Board had recommended a multi-agency development for the PBR-based nuclear thermal propulsion system, suggesting that the nation would be better served by a broad development effort.[1,3]

As SDIO worked to address Congressional concerns, the headwind of agency and mission change was soon felt when the former Soviet Union was in the throes of significant political and economic reform that brought the Cold War to an end in 1991. Priorities in defense systems were soon redefined, and the SDIO plans for its nuclear-powered interceptor missile gave way to the use of the PBR technology to lift heavy payloads into Earth's orbit. As an upper-stage launch vehicle, the new mission focus lent itself well to the Air Force need to launch heavy satellites and other communication systems into space. With the PBR-based interceptor off the table, there was no reason for SDIO to continue funding it. In fiscal year 1991, after an investment of $131 million, SDIO abandoned the nuclear project it had started four years earlier. The project was subsequently transferred to the

Air Force, with management of the nuclear rocket activities assigned to the Air Force Phillips Laboratory in Albuquerque, New Mexico.[8]

In early 1991, as SDIO was preparing to hand the PBR technology program off to the Air Force, the existence of, and information on, the still-classified program was leaked to the public. Several public revelations followed, including an April 1991 *New York Times* article that revealed the general outlines of the program. The article also cited Steven Aftergood of the Federation of American Scientists as saying that an analysis prepared by SNL showed that the probability of crashing into New Zealand in the event of the failure of a prototype nuclear rocket during a projected suborbital flight test over the ocean near Antarctica would be one in 2,325.[9] Other articles followed, including an article in *Scientific American* magazine in which representatives from the working groups of the Federation of American Scientists (including Aftergood) and the Committee of Soviet Scientists for Global Security put forth an argument for banning the use of nuclear power in Earth's orbit; the Timberwind program was used to bolster their case.[10] Questions regarding the level of classification and concerns regarding the adequacy of technical review and Congressional oversight of the classified program soon followed.[11] Classification of the program was lifted in early 1993, at which time only the nuclear technology portions of the program under the cognizance of DOE remained classified.[3]

Timberwind Rebranded—Space Nuclear Thermal Propulsion

Following transfer of the Timberwind program to the Air Force, it was rebranded as the Space Nuclear Thermal Propulsion (SNTP) Program and restructured as a technology development effort. The new program was introduced to the public by Senator Pete Domenici and representatives from Phillips Laboratory during the Ninth Space Nuclear Power Symposium in January 1992. It was announced that the Air Force had been supporting a nuclear rocket technology development program using an advanced PBR concept. Although the main applications for the nuclear thermal rocket were upper-stage launch vehicles and orbital transfer vehicles, no specific mission was identified.[12]

In the absence a specific mission, the Air Force established a broad set of performance goals for its new thermal propulsion program in order to remain flexible to potential user needs and technology developments. The final baseline design represented a system capable of 40,000 pounds of thrust (1,000 MWt) with a specific impulse of 930 seconds and a thrust-to-weight ratio of 20:1, a capability somewhat reduced from earlier goals established for the boost-phase interceptor missile. Compared to chemical propulsion systems, such as those used with the Titan- and Atlas-class launch vehicles, the design represented an improvement of approximately two to four times for payload lift capability. With the shift in mission focus to an upper-stage launch vehicle or orbital transfer vehicle, the concern with use of the nuclear thermal rocket in Earth's atmosphere was addressed by planning for reactor startup only when it was 497 miles (800 kilometers) above the earth. The decision significantly improved the risk picture of the nuclear propulsion project.[3]

Nuclear Propulsion and the Space Exploration Initiative

As DoD worked through its agency and mission changes, NASA soon entered the national nuclear propulsion venue in a much larger role with the announcement of a new SEI in July 1989. Marking the 20th anniversary of the Apollo 11 moon landing, President George H. W. Bush set forth a vision for the future of U.S. space exploration that included a permanent return to the moon and a human mission to Mars. To bring focus to the new initiative, Bush put forth several challenges, including a goal to place humans on Mars by 2019, a lofty goal that would mark the 50th anniversary of man's first landing on the moon.[13] In *America at the Threshold* (a foundational report that set forth a sort of technology roadmap for achieving the goals of the new space initiative), nuclear thermal propulsion was identified as "the only prudent propulsion system for Mars transit," in part since it would result in a significant reduction in travel time to and from the red planet, thereby minimizing the adverse effects of long-term space travel on astronauts.[14]

In a separate but parallel effort, NASA, DOE, and DoD also began looking at propulsion technologies to support the new space initiative. Under the leadership of Gary Bennett (NASA), Earl Wahlquist (DOE), and Roger Lenard (DoD, Air Force Phillips Laboratory), an extensive evaluation process began in 1990 to identify and evaluate both thermal and electric nuclear propulsion technologies. Early planning evolved into a broad-based effort in which six interagency teams, including several nuclear-industry participants, delved into the details of nuclear propulsion technologies, mission analysis, nuclear safety policy, fuels and materials technology, and the facilities that would be needed to test and qualify new nuclear propulsion systems.[15,16]

As nuclear thermal propulsion and nuclear electric propulsion concept development and evaluation evolved, the agencies eventually banded together to implement a national, broad-based nuclear propulsion program to support SEI and other civilian and military missions that might arise. Overall program direction came from the headquarters of NASA and DOE. A nuclear propulsion project office, established at the NASA Lewis Research Center (now the GRC), was responsible for nuclear propulsion technology development, while responsibility for nuclear systems resided at DOE-Idaho. By October 1991, the agencies had formed the foundation for a new civilian nuclear propulsion program; however, funding in fiscal year 1992 was only approximately $3.5 million.

Nuclear Thermal Propulsion Doubles Down

By 1992, the nation was supporting two separate nuclear propulsion programs, with funding and oversight provided by different congressional committees. The NASA-led SEI effort focused on nuclear thermal propulsion and nuclear electric propulsion concept and technology feasibility evaluations for its moon and Mars missions but had yet to transition into technology development or other hard efforts.

Meanwhile, SNTP continued on technology development for the PBR. Efforts included development of a laboratory-scale process to produce the advanced infiltrated kernel fuel particle, including its graphite microspheres. Several critical experiments (using the baseline fuel particle) had been performed to support determination of reactor physics parameters.[3] A nuclear element test (the first of four planned) designed to validate the PBR fuel element concept, obtain engineering data, and benchmark codes was performed using the Annular Core Research Reactor; failure of the fuel element at a temperature of 1,700 Kelvin, however, showed ongoing issues with the fuel element design (particularly the frits).[3,17,18] In addition, the reality of the potential cost to complete the planned ground engineering development effort also began to show, with Phase II cost projections ranging from $500 million to over $1.2 billion for a comprehensive development and testing program.[3] heavily redacted classified EIS had been previously issued for the earlier DoD efforts), providing an opportunity for full public scrutiny of the agency's nuclear propulsion plans. In its EIS, the Air Force noted it was considering whether the SNTP should be continued and, if so, at what location—the proposed Saddle Mountain Test Site at the Nevada Test Site or at an alternative, contained test facility at the Idaho National Engineering Laboratory in southeast Idaho.[2] In the process of identifying and evaluating the alternative testing

On the other side of the nuclear propulsion house, SNTP continued a forward march on technology development for the PBR.

With two separate programs and two hefty price tags on the table, improved cooperation was inevitable. For example, the agencies eventually began to explore the possibility of using common nuclear thermal propulsion testing facilities, such as PIPET, to meet the needs of both programs.[19,20] In June 1992, responsibility for SNTP support within DOE was also transferred from the Office of Defense Programs to DOE-NE. With support from DOE-NE, the Air Force issued an unclassified SNTP EIS for public review (a locations, competition had been created between the two proposed sites, as each site hoped for the promise of new facilities and new jobs in light of the DOE emphasis to consolidate and cleanup its weapons complex.

Notwithstanding efforts to search for common ground, the two nuclear thermal propulsion programs were the topic of a Congressional hearing held in October 1992, at which representatives from DoD, NASA, and DOE were in attendance.

Traveling to Mars

When planning for a mission to Mars and back, two space nuclear propulsion systems are available for consideration—nuclear thermal propulsion and nuclear electric propulsion. In selecting a specific system for a given task, planners consider the use (e.g., lifting heavy objects into space versus spacecraft propulsion through space), payload weight, and mission timing relative to launch windows.

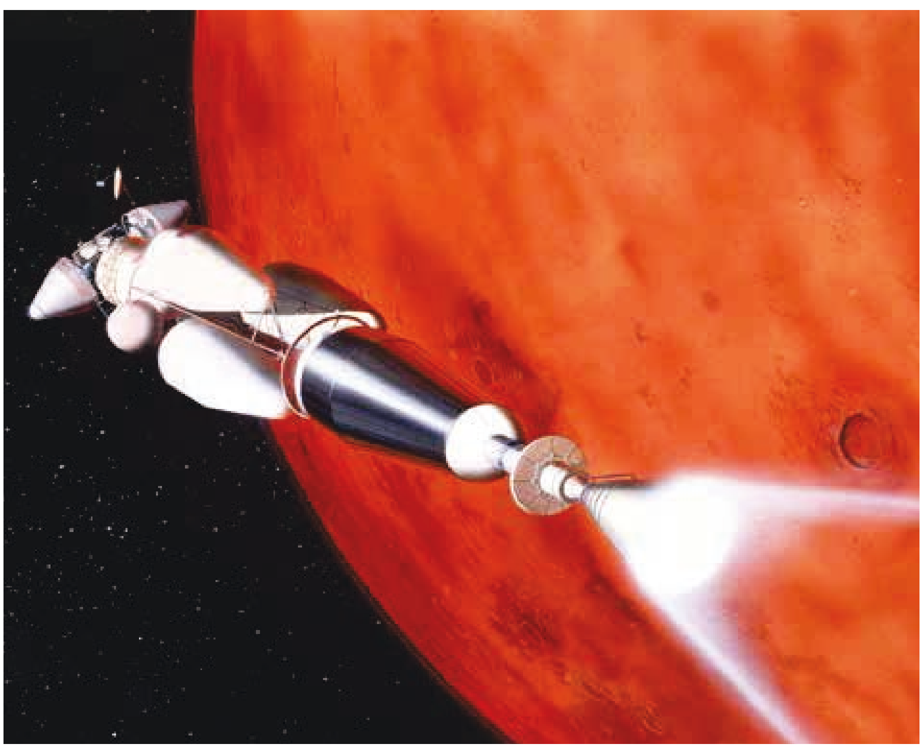
Nuclear electric propulsion systems use a nuclear reactor to generate electricity that provides power to an electric thruster system. Unlike nuclear thermal propulsion systems, nuclear reactors used in electric propulsion systems are designed to operate at lower temperatures over a period of several years. Nuclear electric propulsion systems typically generate very low vehicle thrust and acceleration levels, but much higher specific impulse (force per unit mass of rocket propellant), which makes the most efficient use of propellant over a long period of time.

Conversely, nuclear thermal propulsion systems offer high vehicle thrust and acceleration levels, which translate to relatively brief reactor operational times (hours) and generally lower specific impulse. For the planned SEI Mars mission, nuclear thermal propulsion solid-core concepts were proposed as the baseline technology for propulsion from Earth's orbit to Mars' orbit and back.[14]

Of interest to Chairman Harold Wolpe and his oversight committee was the prospect of another expensive space nuclear endeavor (the other being SP-100) and the need and expected benefits thereof. Topics included nuclear thermal propulsion technologies, anticipated development costs, and agency roles and cooperation. At the conclusion of the hearing, Wolpe expressed ongoing concern despite agency efforts to alleviate them, and noted his hope that Congress would look hard at the propulsion program before proceeding further.[1]

Requiem for Nuclear Propulsion

By 1993, a new presidential administration was in place under Bill Clinton. Although NASA continued SEI planning even as the Bush Administration came to an end, it appeared unlikely that the incoming Clinton Administration would pursue the same space exploration goals. As NASA historian Thor Hogan noted, the broad political and Congressional support needed to provide any hope for SEI survival was lacking, largely the result of a hefty price tag (upwards of $400 to $500 billion over a 30-year period), and "a deeply flawed policy process that failed to develop (or even consider) policy options that may have been politically acceptable given the existing political environment."[13]



Artist's concept of possible exploration programs. A nuclear thermal rocket fires upon arrival in the vicinity of Mars to insert the transfer vehicle into orbit. Nuclear propulsion can shorten interplanetary trip times and can reduce the mass launched from Earth. (Photo: NASA, Pat Rawlings/SAIC)

Upon his inauguration, Clinton and his administration embarked on a new direction for the country, one that included a major emphasis on Federal deficit reduction. Clinton noted in his first State of the Union address on February 17, 1993:

"It puts in place one of the biggest deficit reductions and one of the biggest changes of Federal priorities...in the history of this country…My recommendation makes more than 150 difficult reductions to cut Federal spending... We are eliminating programs that are no longer needed, such as nuclear power research and development. We are slashing subsidies and canceling wasteful projects...We're going to have to have no sacred cows except the fundamental abiding interest of the American people."[21]

Funding for the small NASA nuclear propulsion effort (approximately $3.5 million per year) didn't materialize in fiscal year 1993; the broader SEI program was canceled in 1996.

As for the SNTP, despite the fact that an unclassified EIS was eventually released for public review, the Air Force requested no new funding for fiscal year 1994. It also withheld further funding in fiscal year 1993 pending transfer of the technology program to another agency, presumably one that would be interested in carrying the technology forward. When a transfer failed to materialize, the SNTP program was finally terminated in January 1994.[1, 2] In seven short years, the two nuclear thermal propulsion programs had come to an end.

> The broad political and Congressional support needed to provide any hope for SEI survival was lacking, largely the result of the hefty price tag...

When planning to utilize a nuclear electric propulsion system, in missions that will gather increasingly more data and transmit them in ever-decreasing times, one factor emerges as a recurring hurdle—power.

9

The Prometheus Project
Space Reactor Resurrection

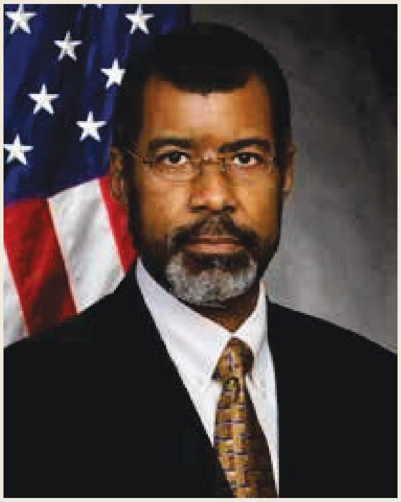
Following the resurgence in space nuclear reactor development between 1983 and 1993, U.S. investment in space reactor research and development largely waned. Although some small study and technology efforts continued, the focus was on solar, chemical, and radioisotope systems to meet the power and propulsion demands of space and planetary exploration missions. However, when planning to utilize a nuclear electric propulsion system, in missions that will gather increasingly more data and transmit them in ever-decreasing times, one factor emerges as a recurring hurdle—power. If that hurdle could be cleared, exploration of the solar system would take on a whole new dimension.

As a new millennium began to unfold, a change in presidential administration brought renewed interest to nuclear technology. On January 20, 2001, George W. Bush was sworn in as the 43rd President of the United States. Early in his first term, Bush announced a new national energy policy. The policy included strong support for nuclear power as a key component in the nation's energy portfolio.[1]

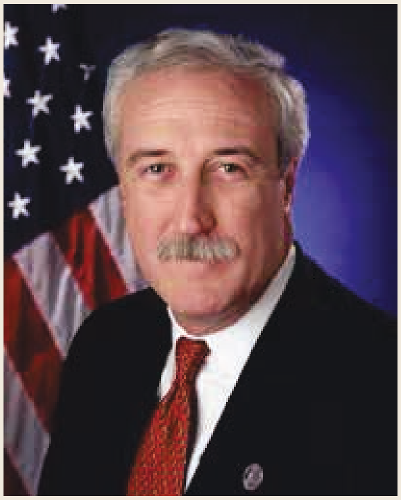
A Project Takes Flight

During the early part of the Bush presidency, the men and women of NASA were working with foreign partners to develop and operate the International Space Station and were continuing efforts to establish a robotic presence on Mars. Along with continued exploration of the solar system, NASA also worked to maintain a long-term program of remote earth sensing. Those efforts would soon be placed under the direction of Sean O'Keefe, the new NASA Administrator. With a background in public administration and financial management, O'Keefe wasn't a renowned space guy. He was, however, a keen and determined administrator who had a distinguished career in government and academia prior to his appointment at NASA. O'Keefe was tapped for the NASA position upon the departure of Daniel Goldin. In addition to his skill in public administration, O'Keefe brought to NASA an awareness of the capabilities of nuclear propulsion. He began his appointment as the 10th Administrator of NASA on December 21, 2001.[2]

Small ion rocket being tested inside a vacuum test facility in 1959. Such systems were first used operationally in the Soviet Union and later employed by American commercial spacecraft and NASA space probes. (Photo: NASA)



William D. Magwood IV
Director of the Office of Nuclear Energy, Science and Technology at DOE.



Sean O'Keefe
10th NASA Administrator.

Early in 2002, NASA put forth a reformulated planetary exploration program. A key element of the new program included an investment in the development of nuclear-electric propulsion technologies. Perhaps such an investment would address limitations to space exploration imposed by solar and chemical power. In the eyes of some, the technology supporting planetary exploration was stuck in the past. Dr. Edward Weiler, then head of space science at NASA, offered this perspective in a *New York Times* article describing the paradigm shift: "We are trying to continue the exploration of the solar system in covered wagons…Now it's time to switch to the steam engine and build railroads to explore the solar system like railroads contributed to the exploration and expansion of this country."[3] The tracks for this cosmic railroad would be laid by the Nuclear Systems Initiative (NSI). The initiative was to be a five-year, $1 billion investment that would resurrect space nuclear reactor research and development, and continue development of a new generation of RPSs, a technology that had been successfully used in NASA missions for decades. Finally, the power hurdle could be cleared.

As with all things nuclear, NASA would need the continued support of DOE. The DOE Office of Nuclear Energy, Science and Technology (later returned to its previous name, DOE-NE) had worked with NASA to provide RPSs and was supporting NASA in new space reactor technology efforts. During Senate hearings on the 2003 budget for DOE, William D. Magwood IV, Director of the DOE Office of Nuclear Energy, Science and Technology, acknowledged the new NASA initiative and noted that DOE would continue to participate in the nuclear electric propulsion development effort; however, the extent of that participation by his office had not yet been defined.[4]

The extent of DOE-NE involvement in the nuclear fission reactor work was still evolving because O'Keefe had been collaborating with a separate arm of DOE, the Office of Naval Reactors (DOE-NR) within the National Nuclear Security Administration, to garner technical support for the space reactor development effort. In response to questions regarding DOE-NR involvement, Admiral Frank L. "Skip" Bowman, DOE-NR Deputy Administrator, acknowledged that preliminary discussions had taken place between high-level officials within DOE and NASA. He also noted the purpose of the discussions had been to identify issues that would need to be addressed to allow DOE-NR involvement in the space nuclear power effort. Bowman also offered a caveat, reminding the Senate Committee that any decision regarding such involvement would reside with the president or Congress since DOE-NR was responsible for naval nuclear propulsion, and not civilian space reactors.[4] While involvement of DOE-NR was not yet firmly established, O'Keefe had set the stage for a new player to come to the space nuclear reactor table.

As the vision for use of nuclear electric propulsion evolved, it was soon connected to a specific mission. The mission would employ a nuclear-reactor-powered spacecraft that would tour Jupiter and three of its moons. In late 2002, the Jupiter Icy Moons Orbiter (JIMO) mission was born. As envisioned, JIMO would be part of a broader project called Prometheus, into which the RPS and space reactor goals of the NSI had been incorporated. Beginning with $20 million in 2003, and a request for $93 million in 2004, the Prometheus/JIMO project began in March 2003.[5, 6]

Deep-space Inroads

Project Prometheus had two overall objectives: (1) develop a space vehicle that combined a nuclear reactor with electric propulsion for robotic exploration of the outer solar system; and (2) execute a scientific exploration mission to Jupiter and three of its icy moons—Callisto, Ganymede, and Europa.[5]

The space vehicle was conceptually straightforward. A nuclear reactor would generate heat from the fission of uranium. The heat from the reactor would be transferred to a power conversion system and converted to useable electricity. The electricity would power an electric propulsion system and other spacecraft equipment. Any heat that wasn't converted to useable electricity would be transferred, or rejected, to the coldness of space using a heat rejection system.

While conceptually straightforward, the path to achieving a targeted 2015 launch date was extremely challenging. The spacecraft would be designed to operate for 20 years. During those 20 years, the space reactor would provide 10 years of operation at full power and 10 years of operation at a reduced power (assumed to be 30 percent of full power). The reactor output, or power level, would be driven by the power needs of the spacecraft and associated systems. The largest individual power need would come from the ion-thruster propulsion system that would operate at a power level of 180 kWe and a specific impulse in the range of 6,000 to 8,000 seconds. To meet the power demands of the propulsion system and other on-board systems, the reactor-power conversion system would need to generate at least 200 kWe of electric power, which corresponded to a reactor thermal power output level of approximately one megawatt (1,000 kWt).

Dawn of Enlightenment

In Greek mythology, Prometheus, the son of a Titan, brought fire to mankind. As a result of his actions, mankind grew in knowledge and wisdom. The story is often used as a metaphor for enlightenment. During his tenure at NASA, O'Keefe believed that nuclear reactor technology could overcome the challenges posed to future space exploration endeavors. Years later, John Casani, JPL Project Manager, characterized O'Keefe's belief in nuclear with the following: *"…nuclear power in space is going to be the dawn of enlightenment in terms of the next step forward in space exploration, whether it be robotic or human."*[7]

The weight of the spacecraft and all of its systems would be tightly controlled; however, the 37,000 pounds (16,800 kilograms) envisioned for the craft approached the upper limit of launch-vehicle capabilities. Data collection, storage, and transfer rates would be maximized but also constrained, simultaneously, by the capabilities of the Deep Space Network and Planetary Data System, the earth-based data handling and storage systems that support NASA space exploration. Finally, the technologies would have to be extensible to Lunar- and Mars-surface missions, thereby introducing additional technical complexities into the project. Terms such as "aggressive," "unprecedented," and "push the technology envelope" were used when discussing mission goals in the context of the level of technological advancement that would ultimately be needed for mission success.[5, 8]

> From the perspective of NASA, the assignment brought to the project "50-plus years of practical experience in developing safe, rugged, reliable, compact, and long-lived reactor systems designed to operate in unforgiving environments."

To meet the challenges posed by the project, NASA turned to JPL and John Casani to lead the effort. Casani brought decades of experience to the project, having been involved with previous missions, including the Mariner missions to Mars and the Voyager, Galileo, and Cassini missions. The initial project team included members from JPL, NASA, DOE-NE, two DOE laboratories (LANL and ORNL), and the GRC. As the project matured, other partners were brought into the fold. In March 2004, two years after discussions between NASA and DOE began, the space nuclear reactor design and development effort was finally given to DOE-NR. From the perspective of NASA, the assignment brought to the project "50-plus years of practical experience in developing safe, rugged, reliable, compact, and long-lived reactor systems designed to operate in unforgiving environments."[9]

During project execution, DOE-NE would continue to support other NASA space nuclear technology efforts, such as development of RPSs. Later that year, NASA awarded a $400 million contract to Northrup Grumman Space Technology and announced they would be responsible for co-design of the JIMO spacecraft, including integration of all systems with the spacecraft. NASA itself would provide the launch vehicle and associated ground support capabilities. Other components, such as the heat rejection and ion propulsion systems, would be led by NASA field centers.

With all of the organizations, companies, and personnel involved with the project, management and administration of the project would prove every bit as challenging as the technical aspects. With the large number of partner organizations, each with its own culture, systems, and practices, challenges would include geographical separation and communication barriers. Roles and responsibilities would need to be clearly defined, as would organizational interfaces. Reporting, document, and management systems would all require alignment. The list seemed endless, and the experience gained during project execution provided a wealth of lessons from which others could learn.[10]

The Spacecraft Takes Shape

While DOE-NR had significant experience with the design, operation, and maintenance of nuclear electric propulsion systems in the oceans of Earth, the environments of outer space or a Lunar or Martian surface brought a new set of challenges. Where reactors on Earth include provisions for control by human operators, systems in space must be entirely controlled remotely or autonomously. Where an ocean provides an endless supply of water for cooling a reactor core, cooling in space is accomplished using a heat rejection system such as a large radiator. The large radiator would have to be designed to fit inside the rocket fairing (i.e., by folding) and deployed only after the spacecraft reached orbit.[11] To meet these challenges, DOE-NR would solicit the help of the engineers and scientists at their naval nuclear propulsion laboratories, including Bettis Atomic Power Laboratory, Knolls Atomic Power Laboratory, and Bechtel Plant Machinery, Inc. Eventually, engineers from other DOE national laboratories and NASA research centers would also join the DOE-NR team, bringing together decades of reactor and propulsion design, operation, and safety experience.

The DOE-NR team spent several months identifying and evaluating an exhaustive set of nuclear reactor and power conversion technologies. All aspects of a nuclear reactor system were considered, including the reactor core, fuel and materials performance, reactor shielding, primary-coolant transport and materials compatibility, energy conversion and heat rejection operations, and operational concerns. Technologies were considered against the mission established operational, power, and lifetime requirements. They were also evaluated from the perspective of developmental challenges and technical maturity. Hundreds of parametric studies were performed, including trade-off studies and system optimization. Five candidate reactor-plant concepts were eventually developed and evaluated for overall capability, reliability, deliverability, cost, and safety. From the five candidate systems, the DOE-NR team selected a gas-cooled fission reactor coupled with a Brayton cycle power conversion system. As noted in a report that summarized the work performed by the DOE-NR team on the Prometheus project, the gas-reactor/Brayton cycle system "appears capable of fulfilling the mission requirements…simplifies engineering development testing, and offers the fewest hurdles to development."[12] The direct gas/Brayton reactor concept was subsequently approved by DOE-NR.

The reference reactor plant concept employed a single gas reactor, located at the forward end of the spacecraft. An inert gas mixture, consisting of xenon and helium, would be used to transfer heat from the reactor core to the power conversion system. The reactor core would consist of cylindrical highly enriched uranium ceramic fuel elements arranged within an appropriate core structure. The vessel holding the reactor core would be relatively small, only two feet (0.6 meter) in diameter and five feet (1.5 meters) in length. A combination of fixed and moveable reflectors surrounding the reactor vessel would provide the means to maintain reactor reactivity at desired operating temperatures. The reactor system would also include

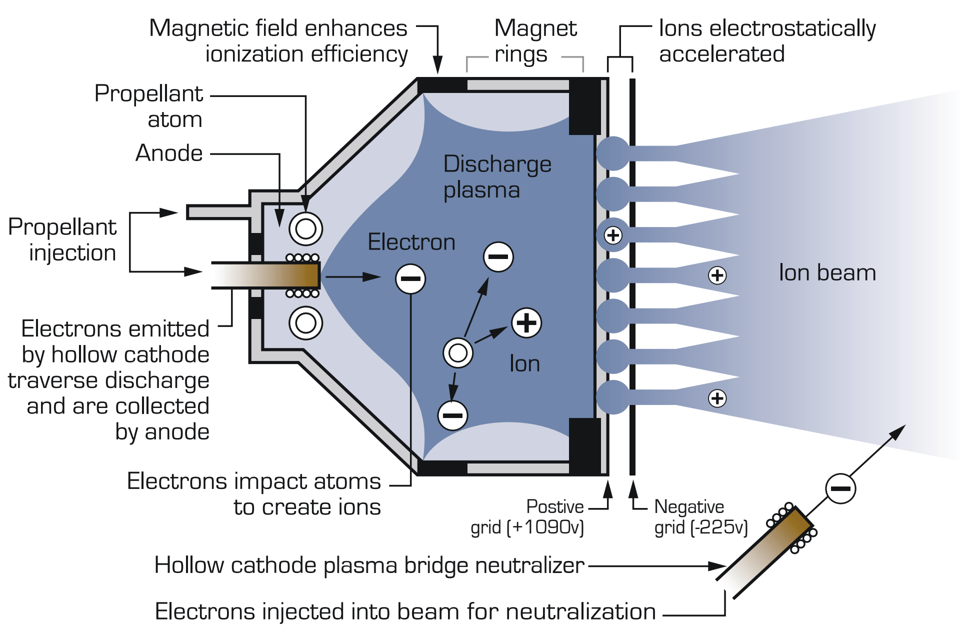
Five candidate reactor plant concepts were eventually developed and evaluated for overall capability, reliability, deliverability, cost, and safety.

Brayton Cycle Power Plant

A Brayton cycle system consists of a turbine, heat exchanger, gas cooler, compressor, and associated piping, valves, and control systems. During reactor operation, a xenon-helium gas mixture would exit the reactor core at a very high temperature and be piped from the reactor vessel to the Brayton cycle turbine. The turbine and an alternator would share a common shaft. As the hot gas passes through the turbine, the turbine-alternator shaft rotates, resulting in the generation of electricity by the alternator. After passing through the turbine, the gas would be routed through a heat exchanger and gas cooler, after which it would be pumped back to the reactor core via the compressor. Excess heat from the gas cooler would be transferred to the heat rejection system via a cooling loop. The electricity generated by the Brayton system alternator would then be conditioned for use in powering an ion thruster propulsion system and other on-board electrical equipment.[12]

at least one safety shutdown rod to preclude inadvertent criticality during operations involving ground transport and launch. A shadow shield, located between the reactor and the remainder of the spacecraft systems, would reduce the adverse effects of neutron and gamma radiation on electronic equipment and other components once the spacecraft achieved orbit and the reactor was placed into operation.

The propulsion system employed an ion thruster technology. In an ion thruster system, thrust is generated by exhausting a high-speed propellant from a thruster chamber. The amount of thrust generated by such a system is a direct function of the mass flow rate of the propellant and the velocity of the propellant as it is exhausted from the system. The primary components of an ion thruster propulsion system include a propellant, a system for generating electrons, a thruster chamber in which the electrons collide with the propellant, resulting in its ionization, and an electrical energy source to create a large voltage potential across which the ionized propellant is accelerated to an extremely high velocity as it exits the thruster chamber. Thus, although an ion thruster has very low thrust, its continuous operation results in a very high specific impulse.



General components of an ion thruster. (Adapted from NASA/TM-2004-213290, Electric Propulsion Technology Development for the Jupiter Icy Moons Orbiter Project)

For the JIMO mission, xenon gas would be the propellant of choice, and electrons would be generated using a microwave source and/or a hollow cathode. Although greatly simplified, thrust is generated by the following process. When the xenon gas and electrons are introduced in the thruster chamber, the gas molecules collide with the electrons, resulting in their ionization. The ions are created at a high voltage relative to the spacecraft. A system of two grids, located at the exhaust side of the thruster, are used to establish a voltage potential (or difference) that is significantly lower than the electrical charge of the ions. The resulting voltage differential creates the force by which the ions are accelerated to an extremely high velocity (e.g., 65,616 to 328,083 feet [20,000 to 100,000 meters] per second) as they exit the thruster, thereby producing the thrust that propels the spacecraft through space.

Changes on the Horizon

As the Prometheus project gained momentum, two events in January 2004 would have far-reaching impacts for NASA and its future missions and plans. On January 14, President Bush announced a new *Vision for Space Exploration*, thereby establishing a new space policy for the nation. In announcing his policy, Bush set the nation's space program on a new course and gave NASA "a new focus and vision for space exploration."[13] The shuttle fleet, grounded since the February 2003 *Columbia* space shuttle disaster,[14] would be returned to service to meet existing obligations connected to construction of the International Space Station by 2010. Following completion of the space station construction, the shuttle fleet would be retired after nearly 30 years of service. NASA would therefore begin development and testing of a new space vehicle to ferry astronauts to and from the space station. Finally, the United States would return to the moon by 2020.

President George W. Bush unveils a new *Vision for Space Exploration* on January 14, 2004. (Photo: NASA)

However, during his State of the Union address later that month, Bush discussed the "war on terror" and the future of the nation as the country continued to move forward. Funding for defense programs would increase while that in other areas of the Federal government would hold steady. The goal was to keep the growth rate of Federal spending to less than one percent and reduce the Federal deficit by 50 percent in five years. In establishing a new financial reality for the nation, agencies like NASA and DOE would begin to feel the constraint of flat-line budgets.[15]

In early 2004, Senators John McCain and Daniel Inouye, who were responsible for oversight of the NASA budget and were concerned with the looming Federal budget constraints, called for an audit of the Prometheus project. The GAO was asked to determine if NASA had established justification for the investment in the Prometheus/JIMO project and how the agency planned to ensure critical technologies would be at an appropriate level of maturity when needed. The NSI, announced in 2002, was targeted as a five-year, $1 billion effort. Prometheus, which began in 2003, expanded upon the initiative and had a five-year budget of $3 billion; however, the budget didn't reflect the cost of out-year activities that would be needed to support the 2015 launch, and a life-cycle cost estimate was not expected until the summer of 2005. To make matters worse, a cost estimate developed by the Congressional Budget Office indicated the project could cost

$10 billion. The final audit report, issued in February 2005, provided a broad discussion of the business case for the project but also made note that "NASA announced in its fiscal year 2006 budget request that it was conducting an analysis of alternatives to identify a new mission with reduced technical, schedule, and operational risk."[11]

> Through design and development, tests and experiments, and successes and failures, the technology base that would be used for JIMO and also serve as a springboard for future space reactor efforts continued to grow.

Growth Curves

As the new policies and realities announced by President Bush began to take root, the engineers and scientists working on the Prometheus project continued their efforts to demonstrate the feasibility of getting a reactor-powered vehicle to Jupiter. Through design and development, tests and experiments, and successes and failures, the technology base that would be used for JIMO and also serve as a springboard for future space reactor efforts continued to grow.

For the nuclear electric propulsion system, development of the gas-reactor/Brayton concept was largely a paper exercise. The project team had gathered, evaluated, analyzed, and documented an extensive database of information in areas such as reactor physics, thermal and mechanical evaluations, reactor core and plant arrangements, material properties, and instrumentation and control development. The biggest challenges were judged to be in the areas of reactor fuel and structural materials. Integrated design and testing of the reactor system would pose another significant challenge. Also, material behavior questions would require irradiation, creep, and compatibility testing to ensure the fuel systems could meet operating lifetime and temperature requirements. Challenges were not limited to the realm of the reactor-propulsion system. Material supplies and manufacturing capabilities would need to be re-established to ensure high quality and repeatable component performance. The final report summarizing DOE-NR efforts on the project noted "…in future projects, the scope and timescale required for an engineering development, manufacturing, and testing effort of this magnitude must be understood from the beginning…."[12]

In the area of power conversion, a team lead by GRC performed a first-ever Brayton ion propulsion test using a 2-kilowatt Brayton test-bed in conjunction with a NASA Solar Technology Application Readiness (NSTAR) engine. The test successfully demonstrated AC-to-DC conversion and fault tolerances for the thruster. Other tests, performed in an inert gas environment and at the project-defined operating temperatures, pressures, and speeds, evaluated conditions related to bearing startup, load capacity, and power loss. Knowledge was gained in the area of materials behavior through long-term tests of the super-alloy materials of which system components would be fabricated.[5] Also, as part of an activity initiated under the JIMO project by the GRC, a dual closed-loop Brayton power conversion system, with a common gas inventory and common heat source, was procured, analytically evaluated, installed, and successfully performance-tested. The test demonstrated that the dual loop configuration could become a viable power conversion system candidate for a direct coupled, gas-cooled nuclear reactor power system.[16, 17]

On the electric propulsion front, teams led by the GRC and JPL pursued advancements in ion thruster technology. Performance testing and 2,000-hour wear tests of two candidate thruster systems, the Nuclear Electric Xenon Ion System (NEXIS) and High Power Electric Propulsion (HiPEP), were successfully completed. Both systems met project-required specifications for specific impulse (6,000 to 9,000 seconds), efficiency (greater than 65 percent), and power levels (20 to 40 kilowatts). These new classes of nuclear electric propulsion thrusters offered substantial performance improvements over the electric propulsion engine used on the Deep Space 1 spacecraft flown in 1999. Improvements included a 10-fold increase in power, a two- to three-fold improvement in specific impulse, a 30 percent improvement in overall thruster efficiency, and improvements in grid voltage and thruster lifetime. Although development efforts for both systems were progressing well, the project team concluded that effort would be better spent focusing on a single-thruster technology because of the similarity of many features of the two-thruster systems. The team subsequently selected a single thruster design, nicknamed Heracles, based on the ion thruster technology used in the HiPEP and NEXIS designs.[5]

Glenn Research Center, Cleveland, Ohio. (Photo: NASA)

Things continued to progress in other areas as well. In the area of heat rejection technology, efforts focused on heat pipe design and testing, development of brazing techniques, and materials- and chemical-compatibility testing. Other teams made headway in the areas of high-power telecommunications, low-thrust trajectory tools, and radiation hardening of electronics, which were necessary to protect against the destructive effects of neutron and gamma radiation generated by the nuclear reactor and the naturally occurring high-radiation environment in the vicinity of Jupiter and its moons. Ground-based systems (i.e., testing facilities, offices, laboratories, and other work spaces) would eventually need to be planned, designed, and developed. The personnel needed to conduct mission operations, the procedures under which those operations would be performed, and the ground-based software needed to conduct mission operations would also need to be put in place to support the Prometheus project and eventual launch of JIMO.[5]

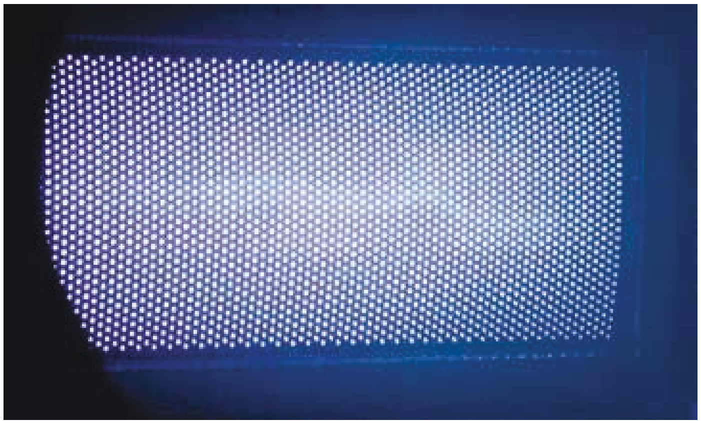
A Vision Fades

As quickly as the Prometheus project became a shining star within the NASA family, that star began to fade. Questions related to project cost and space exploration priorities could not be ignored. The aggressive and unprecedented nature of the nuclear aspects of the project resulted in formidable challenges. And the father of Prometheus (Administrator O'Keefe) eventually removed himself from the game.

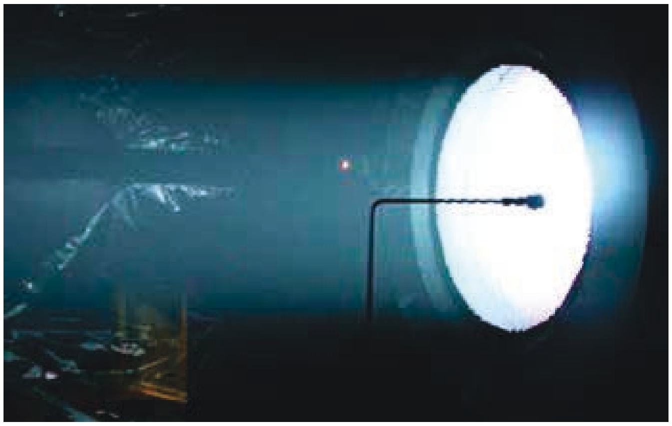
In 2005, after re-evaluating its priorities in light of anticipated budgets, NASA determined that its highest priorities were returning the space shuttles to service, completing the International Space Station, and building the new space vehicle that would replace the shuttle. Those priorities were aligned with the *Vision for Space Exploration* policy presented by President Bush. In the scheme of nuclear initiatives, which were largely postponed, nuclear electric propulsion would be reprioritized behind nuclear surface power and nuclear thermal propulsion.

Reprioritization within NASA came on the heels of the resignation announcement by Sean O'Keefe in December 2004. In a letter to President Bush, O'Keefe cited commitment to family for his pending departure but noted he would remain at his post until a successor was identified. O'Keefe left NASA in April of the following year.

In May 2005, barely three years into the project, NASA pulled the plug on the JIMO project, and the Prometheus project was officially shut down in October. Nearly $465 million had been spent since the project was first announced. However, the hoped-for flight of a space nuclear reactor would have to wait for another day.



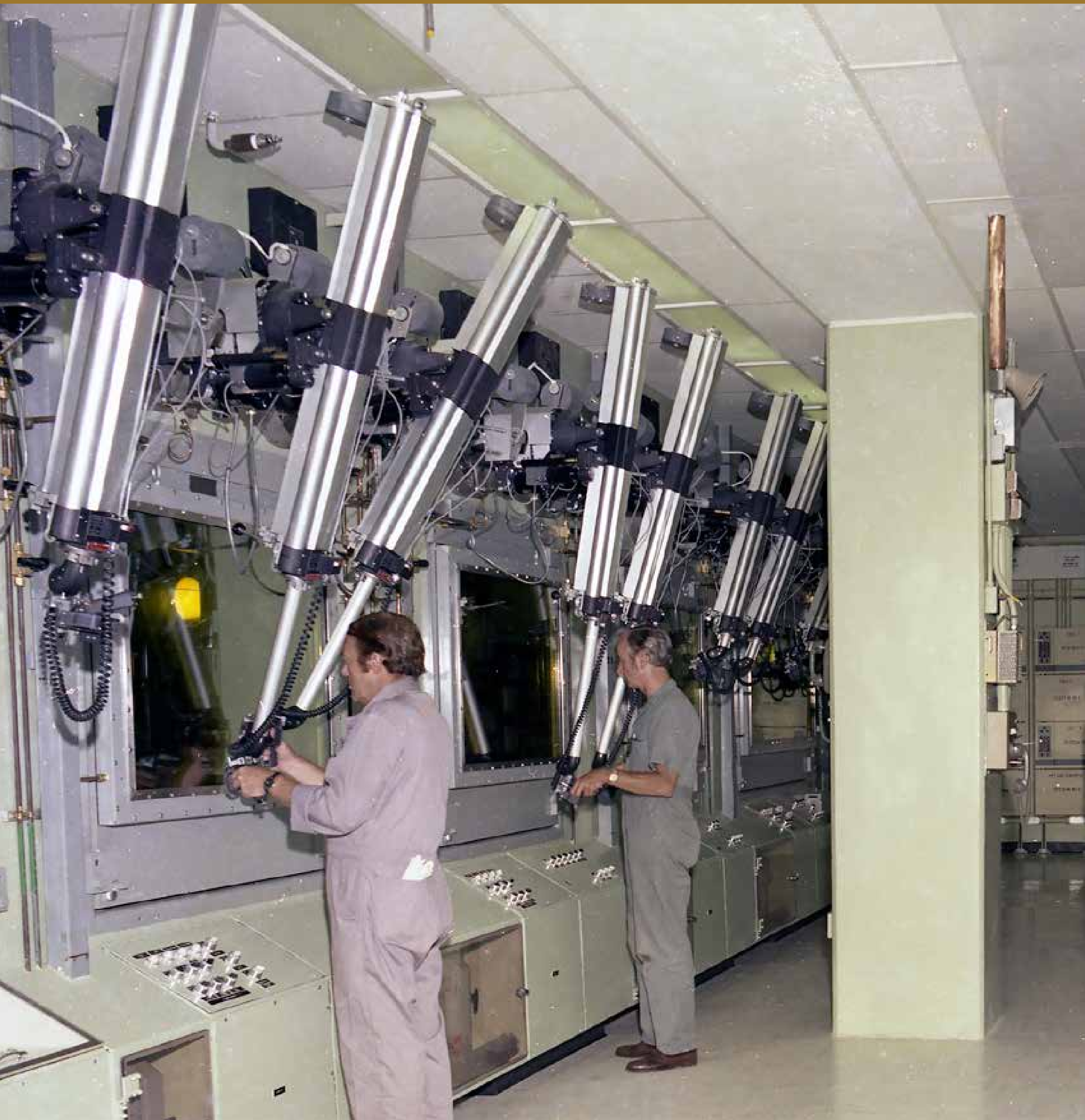
HiPEP thruster beam extraction test. (Photo: NASA GRC)



NEXIS thruster emitting a 4,300V Xenon beam. (Photo: NASA GRC)

Early concept of Jupiter Icy Moons Orbiter spacecraft exploring Jupiter and its moons. The nuclear reactor and Brayton cycle power plant are located at the front of the spacecraft. The large structure in the middle is the heat rejection system. Two ion thrusters, located at the rear of the spacecraft off of the science platform, provide propulsion. (Image: NASA)

To fulfill its responsibility of providing such systems, DOE maintains an infrastructure of facilities, equipment, laboratories, and a cadre of highly skilled workers that provide all facets of RPS development, including design, fabrication, testing, assembly, and delivery.



10

Infrastructure Inroads
Taking RPS Concepts to Flight

When one views images taken by a spacecraft as it journeys through space, or collected by a rover as it traverses a planetary surface such as Mars, the technical accomplishment is awe inspiring. Constantly at work behind the scenes is a power system that allows such feats. For deep-space and planetary missions, an RPS is often the only system capable of providing the reliable, long-lasting power necessary for mission success.

To fulfill its responsibility of providing such systems, DOE maintains an infrastructure of facilities, equipment, laboratories, and a cadre of highly skilled workers that provide all facets of RPS development, including design, fabrication, testing, assembly, and delivery.[1] The infrastructure also includes a group of scientists and engineers who operate and maintain testing and analytical capabilities to support the rigorous safety review processes that must be completed to support the launch of an RPS into space. Although the principal activities have largely remained the same, the locations where those activities have been performed have changed over the years, giving rise to a description of key events and circumstances that formed the modern RPS infrastructure landscape.

Heat Source Production—the Early Days

As RTG technology matured through the 1950s, plutonium-238 eventually became the isotope of choice for use in U.S. RPSs. With increased demand on the horizon, AEC turned to SRS for production of the needed isotope. Operated by DuPont, SRS was home to several production reactors that were used to produce tritium and plutonium in support of the nation's weapons program. With the new plutonium-238 production mission came the challenge of developing the requisite processes and operations needed to support its production.[2]

The Plutonium Fuel Form Facility at the DOE Savannah River Site. (Photo: DOE SRS)

How was plutonium-238 and neptunium-237 produced?

Plutonium-238 does not exist naturally. It is a man-made radioisotope that was produced by the irradiation of small neptunium-237 compacts with neutrons in the SRS K-Reactor. The capture of a neutron by neptunium-237 forms neptunium-238 which, in turn, decays with about a two-day half-life to plutonium-238. After irradiation in the K-Reactor, the neptunium-237 compacts were placed in storage to allow short-lived radioisotopes to decay, and then dissolved using a chemical separations process in the HB-Line to recover the plutonium-238. The resulting plutonium-238 solution was then purified and converted to a solid plutonium oxide before being shipped off-site for fuel form production.

The neptunium-237 was produced by neutron capture of uranium-235 in nuclear reactor fuel during operation of the production reactors. Following irradiation, neptunium-237 was recovered during chemical processing of spent nuclear fuel in the H-Canyon fuel reprocessing facility. The recovered neptunium-237 was subsequently purified, converted into an oxide form, and then fabricated into targets for irradiation.[3]

The first step on the journey to producing plutonium-238 was development of new chemical separations processes to recover neptunium-237 from the highly radioactive liquid by-product left over from ongoing nuclear fuel processing operations at the site. The recovered neptunium-237 was processed to create a small compacted slug, or compact, which was then irradiated in the SRS K-Reactor. Following chemical processing of the irradiated slugs, the recovered plutonium-238 product was transferred to Mound Laboratory where it was processed to produce the encapsulated heat source fuel forms used in RPSs. SRS produced its first plutonium-238 in 1961.[4]

From the early 1960s through the late 1970s, Mound Laboratory was home to RPS heat source fuel form production and encapsulation in addition to its defense-related missions. Initially conducted in the Special Materials Facility, which was built in 1960, the activities were transferred to the Plutonium Processing facility (Building-38), which was constructed in 1967.[5] Operated by the Monsanto Research Corporation, the Mound Laboratory was located in the center of Miamisburg, Ohio, and on the outskirts of the greater metropolitan area of Dayton, home to nearly 2.5 million residents.

By 1971, concern had arisen within AEC over the possibility of an accident during fuel form production operations. Specifically, the concern was centered on the large quantity of plutonium-238 oxide powder present and handled in the facility. Although the operations were performed in gloveboxes, and building and process ventilation systems included high-efficiency particulate air filtration, an AEC evaluation of the operations noted that "…widespread release of radioactivity at Mound appears very unlikely, but an incident can be postulated which could have serious consequences in a densely populated area…". Concern regarding the possibility of such an accident wasn't taken lightly. In March 1971, AEC decided to transfer its fuel form production activities from Mound to SRS, which had the desired benefit of distance between its facilities and the public. AEC subsequently notified the Joint Committee on Atomic Energy of its decision in August of the same year. In 1972, Congress authorized $8 million for the design and construction of a new fuel form processing facility at SRS.[6] Completed in 1977, operations at the new Plutonium Fuel Form (PuFF) facility commenced in 1978.[7]

Although Mound lost the fuel form production mission, it retained responsibility for fuel encapsulation activities. In addition, Mound was also given responsibility for RTG assembly and testing in the late 1970s, work that had previously been conducted at the facilities of the RTG developers – GE and TES. The new RTG assembly and testing mission was performed in Building 50, the facility in which the Mound team built the first-ever flight-qualified GPHS-RTGs that were used on the Galileo and Ulysses missions.

A Decade of Change—the 1980s

By the early 1980s, the RPS infrastructure was spread largely among Mound, SRS, and ORNL. LANL and SNL continued to provide support in the areas of fuel form development and launch-related safety and accident analyses, respectively. As DOE and its infrastructure focused on the upcoming Galileo and Ulysses missions, issues related to facility deterioration and reactor safety at SRS began to emerge that, coupled with the end of the Cold War in 1991, led to a second round of changes in the RPS infrastructure landscape.

To make maximum use of existing facilities, the operations associated with the new PuFF facility at SRS were designed to fit inside an existing facility, Building 235-F. Unlike Mound and LANL, where plutonium-238 operations were performed in gloveboxes, PuFF was designed as a series of nine shielded hot cells in which the fuel form production operations would be performed. Five hot cells provided for the hazardous operations involving plutonium-238 powder, including receiving, processing, hot-pressing, and high-temperature furnace operations. The remaining four hot cells provided for fuel form encapsulation and operations supporting heat source shipments.[8] The decision to use hot cells rather than gloveboxes was related to concerns over worker radiation doses, which were expected to be relatively high due to the quantity (~30 kilograms per year) of plutonium-238 expected to be handled in the facility.

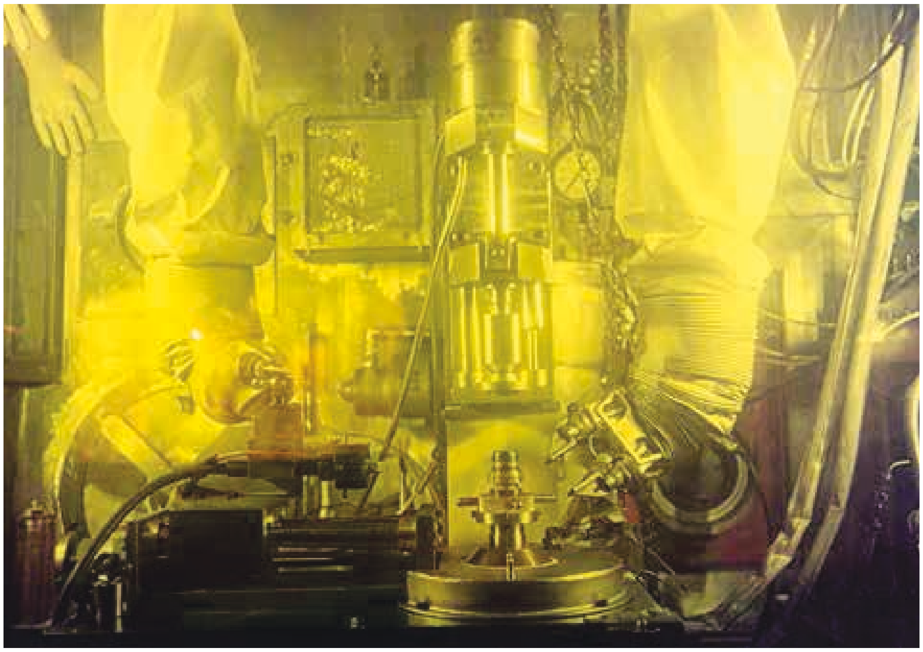
Once operational, the first two years of PuFF operations were centered on production of MHW fuel spheres to be used in the MHW-RTGs originally planned for the Galileo mission. Once the fuel sphere production campaign was completed, operations shifted to the production of GPHS fueled clads, the smaller heat source planned for use in the new GPHS-RTG for the Ulysses and, later, in the Galileo missions. Between June 1980 and December 1983, PuFF operators produced the requisite GPHS fueled clads in support of

Mound Laboratory in Miamisburg, Ohio circa 1990. (Photo: Mound)

RTG assembly chamber for the GPHS at Mound. (Photo: DOE Flickr)

the Galileo and Ulysses missions. Following completion of fueled clad production, the facility was placed in a standby mode pending identification of a new mission for which heat sources would be required.[7]

Unfortunately, the hoped-for mission never materialized. In addition, hot cell and equipment maintenance began to wane. Funding was tight, and an argon gas system used to maintain an inert atmosphere in the hot cells was eventually shut down. In the presence of oxygen (i.e., air), the plutonium-238 contamination in the hot cells began to deteriorate in-cell process equipment. One of the bigger issues involved the hot cell remote manipulators, which were used to perform in-cell operations, decontamination, and maintenance activities. As a result of the corrosive effects of the plutonium-238, the manipulators eventually froze in place, precluding further use.[7]



View of hot cell 6 inside the PuFF facility (looking through water-filled shield window), where iridium shell welding operations were performed to encapsulate GPHS fuel pellets. (Photo: SRS Flickr)

By 1990, estimates to decontaminate and refurbish the hot cells approached $50 million, with a completion window of at least two years. For DOE, this was troubling news, as NASA was then planning two future missions for the mid-1990s (Comet Rendezvous Asteroid Flyby and Cassini) that would require multiple GPHS-RTGs; the plans eventually culminated in the 1997 Cassini mission and its three GPHS-RTGs. In light of the steep price tag and at least two-year refurbishment window tied to PuFF, DOE decided (in 1990) to relocate GPHS fueled clad production activities, including fuel pellet production and encapsulation, to LANL.[9] Although the relocation was initially carried out as a temporary fix pending resolution of the PuFF deterioration issues, the temporary fix eventually became permanent, and PuFF was never returned to service for heat source production.[7]

The selection of LANL for production of the GPHS fueled clads for the Cassini mission was a straightforward solution to a potentially thorny programmatic issue. Research and development related to plutonium materials had been carried out at the Plutonium Handling Facility in Technical Area 55 at LANL for many years. Specific to RPS heat source plutonium, LANL experience included development of the plutonium oxide processing flowsheet for the MHW fuel spheres and the GPHS fuel pellets, which dated back to the early 1970s. In addition, production of the LWRHUs for the Galileo mission between 1981 and 1984 provided the opportunity for LANL scientists to refine their heat source plutonium oxide processing experience.[9] Building on that experience, production of the plutonium-238 heat sources for the Cassini mission eventually began in 1993.[10]

As DOE worked to address the problems at PuFF, another issue arose that required additional attention. By 1989, environmental and safety concerns had resulted in the temporary shutdown of the production reactors at SRS, including the K-Reactor. Without the K-Reactor, the sole plutonium-238 production capability was lost.

With the shutdown of the K-Reactor, DOE began looking at other reactors within its complex for a possible solution to its plutonium-238 production problem. That search took them to the other side of the country and FFTF, located at the Hanford site. FFTF was an attractive option because of its proximity to the Fuels and Materials Examination Facility (FMEF), another Hanford facility then being modified to accommodate a planned transfer of RTG assembly and testing operations from Mound in support of a future DoD mission for a DIPS. With the prospect of becoming a national center for space nuclear power systems, optimism was running high in the state of Washington.[11]

That optimism, however, soon faded. The RTG assembly and testing mission never fully materialized because the DoD plans for high-powered isotope power systems went away when the Cold War ended. The use of FFTF for plutonium-238 production gave way to other priorities within DOE. While hopes for eventual restart of the K-Reactor were initially high, by the early-1990s, those hopes had vanished when the reactor shutdowns became permanent.

While hopes for eventual restart were initially high, by the early-1990s, those hopes had vanished when the reactor shutdowns became permanent.

Although DOE had a sufficient plutonium-238 inventory on hand to meet known existing needs, that inventory was finite and, for the first time in nearly 30 years, DOE faced an unknown future regarding the production of the heat source isotope.[2]

Finally, to consolidate activities associated with the production of iridium hardware, responsibility for production of iridium cladding and frit vents was transferred from Mound to ORNL in the late 1980s. The Metals and Ceramics Division at ORNL had long been home to development of advanced alloys for a wide range of purposes. For 20 years, ORNL had served as home to production of iridium feedstock materials that were subsequently shipped to Mound for fabrication of cladding and frit vents for heat sources such as the MHW fuel sphere assembly and the GPHS fueled clad.[12] Following demonstration of the capability to produce flight-quality iridium hardware, ORNL was given responsibility for future iridium hardware production, beginning with the Cassini mission. ORNL maintained the facilities and equipment needed for production of the carbon-bonded carbon-fiber insulation sleeves used in the GPHS module.[13]

As the 1980s drew to a close, so did the decades-long Cold War between the United States and Russia. With an ensuing de-emphasis on weapons production, DOE began to evaluate how its complex of facilities, equipment, and personnel might be reconfigured to decrease its size and cost. As reconfiguration planning progressed, DOE also began a massive cleanup program to address decades of nuclear material production and the environmental consequences left behind. Both efforts led to facility closures that left no site untouched. At Mound, this led to a decision in the 1990s to shut down all weapons-related activities at the site, thereby leaving RTG assembly and testing operations as its sole nuclear operations activity.

The K-Reactor at DOE's SRS. (Photo: SRS)

RPS Infrastructure and the New Millennium

By the early 1990s, the RPS infrastructure was poised to support production of three GPHS-RTGs for the upcoming NASA Cassini mission. Production of iridium cladding and frit vents was performed at ORNL. LANL produced the pressed oxide fuel pellets using plutonium-238 supplied by SRS, and encapsulated the fuel pellets in the iridium clad-vent sets provided by ORNL. The encapsulated GPHS fueled clads were shipped to Mound for GPHS module assembly and RTG assembly and testing. SRS continued to maintain the plutonium-238 oxide inventory and operate chemical separations processes to purify the oxide for use in heat source fuels.

While efforts to support the Cassini mission were ongoing, a parallel effort was underway to address how best to secure a future supply of plutonium-238 beyond the Cassini horizon. With the shutdown of the SRS K-Reactor, DOE faced a limited number of options: either produce new plutonium-238 using a different nuclear reactor or procure such material from a foreign supplier. With the future of its weapons complex and defense production reactors in a state of flux, DOE ultimately pursued a dual path strategy—supplement the existing inventory with foreign material in the short term while pursuing a domestic plutonium-238 production strategy for the long-term.

On the foreign-supply front, DOE found a most unusual partner, at least at the time, in the former Soviet Union. For decades, the United States and the Soviet Union had been stuck in an arms race, each producing a nuclear arsenal to keep up with the other. Secrecy had been the norm and both countries took extensive measures to protect nuclear-related information and material. With the fall of the former Soviet Union in 1991, however, opportunities for new partnerships between the two Cold War enemies soon arose. From a supply perspective, Russia maintained an inventory of plutonium-238 that had been previously produced. On the demand side, the United States needed plutonium-238 to supplement its dwindling inventory to meet anticipated missions. By the end of 1992, a partnership was consummated when DOE signed a contract with the Russian Federation-Mayak Production Association for the purchase of up to 88 pounds (40 kilograms) of Russian plutonium-238 fuel.[14] The first shipment of Russian plutonium-238 purchased under this agreement made its way to the United States in 1994.

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U.S. plutonium-238 production moved more slowly. For almost 15 years, DOE analyzed production options, evaluated its facilities, and prepared the necessary environmental documentation to support a plutonium-238 production decision. The early 1990s were a time of planning and strategizing as a post-Cold War structure of DOE began to emerge. By 1998, a plan for production of the heat source isotope had been developed, and DOE announced its intent to prepare a plutonium-238 production EIS.[15] That plan was soon abandoned in favor of a broader effort to address the future of DOE's nuclear energy infrastructure, of which plutonium-238 production was but one piece. Development of a nuclear energy infrastructure programmatic EIS ensued. Just months after DOE released a Record of Decision announcing future plans for

Ensuring Safety Before Flight

While heat source production and RTG assembly and testing play a major role in the RPS infrastructure, those activities are supported by the efforts of scientists at SNL, LANL, and JHU-APL, where the safety testing and analysis needed to demonstrate protection of the public and the environment during mission use of RPSs are performed. Safety testing may be performed at numerous facilities, both internal and external to the DOE Complex. Such facilities provide the capability to simulate events such as high-velocity impacts, fires and re-entry, and explosion overpressures, and include a rocket sled at SNL and the Isotope Fuels Impact Tester at LANL.

The information gathered during safety testing is used to support the nuclear risk assessment and safety analysis required by DOE for every mission in which a nuclear power source is planned for launch, as discussed in Chapter 2. Historically, such analyses were performed by a systems integration contractor (e.g., Lockheed-Martin) and reviewed by a DOE-led team that included Tetra Tech NUS, Orbital Sciences, and JPU-APL. In 2005, responsibility for the analyses was transferred to SNL, where such capabilities remain an integral part of the DOE infrastructure needed to support nuclear missions.

that infrastructure,[16] the nation experienced the worst terrorist attacks that had ever occurred on U.S. soil. The September 11, 2001 attacks set in motion a series of far-reaching initiatives as America sought to bolster and strengthen the security of the nation.

For DOE, the new homeland security paradigm translated into a need for improved security and safeguards measures to protect its special nuclear material. That need soon reached Mound, where the RTG assembly and testing facility needed upgrades to meet the new security criteria. As DOE considered

Safety testing for the GPHS-RTG included use of the SNL rocket sled. Simulated GPHS modules were heated and placed in the RTG housing (orange/white item in pictures). The housing was positioned on the rocket sled in the vertical orientation (top and center pictures), then rotated to a horizontal orientation and accelerated to a speed of approximately 57 meters per second (128 miles per hour) for impact against a concrete target. The post-test RTG is shown in the bottom picture; the dented section, shown on the right side of the picture, hit the concrete target first. (Photos: SNL)

For DOE, the new homeland security paradigm translated into a need for improved security and safeguards measures to protect its special nuclear material.

the costs of upgrades against the backdrop of other assets, it appeared that the RTG operations might be more economically performed in an existing secure facility located elsewhere in the DOE Complex. Elsewhere ended up being ANL-W in Idaho.

Established in the early 1960s, ANL-W was home to a variety of nuclear reactor development and testing operations, including fuel development and actinide research. With a host of secure facilities for its own plutonium and uranium fuels, and having been in the DOE-NE family for decades, ANL-W was clearly a logical choice. RTG assembly and testing operations were subsequently relocated from Mound to ANL-W beginning in 2003.[17] Following a year-long effort to transfer equipment, tools, and other material from the Mound location to ANL-W, Mound ceased to be part of the RTG family.[i] In a bittersweet twist of irony, the Golden Anniversary of the invention of the RTG marked the end of Mound's role in RTG-related inventions, development, and operations. Despite that end, the Mound story would continue to live through the efforts of a small group of former employees who established the Mound Museum. Just as RTG assembly and testing operations were moved to ANL-W, in a similar fashion, DOE decided in 2004 to relocate its stockpile of neptunium-237 from SRS to ANL-W.[18]

Along with the new RTG assembly and testing mission, ANL-W also received the equipment and shipping packages used to transport assembled RTGs and related nuclear material over public highways. With the two new missions, ANL-W had been adopted into the DOE RPS family.

Looking Ahead

As the first decade of the new millennium came to an end, the future of plutonium-238 production remained largely unknown. The largest blip on the RPS radar had come in the middle of the decade. Along with the other changes driven by security needs following 9/11, DOE for a time considered a plutonium-238 production approach that was part of a larger initiative to consolidate RPS operations to INL. The concept included use of the INL Advanced Test Reactor and construction of a new production facility for plutonium-238.[19] Ultimately, the plan was tabled when DOE decided to revisit the costs and other criteria associated with their planned approach.

Finally, in 2012, a project was initiated to produce plutonium-238 using existing facilities at ORNL and INL, with an average production goal of 3.3 pounds (1.5 kilograms) per year. With the project underway, the last piece of the RPS infrastructure puzzle had been put in place for continued support of future NASA missions.

i . See Chapter 12 for more information about the transfer of activities from Mound to ANL-W.

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

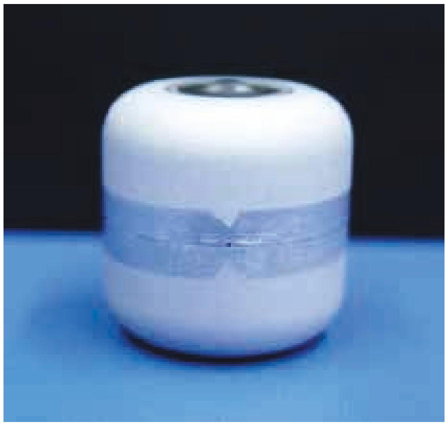
Iridium and Tungsten

"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.

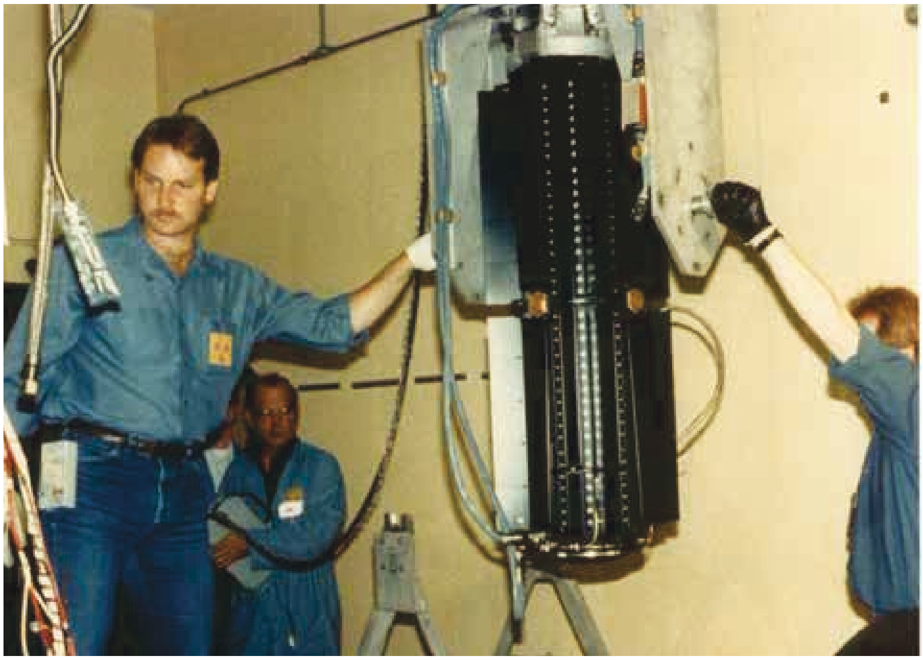
support were also to be provided in areas such as safety assessment preparation, shipment of the assembled RTGs to KSC, and integration of the assembled RTGs into the Cassini spacecraft.

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]

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

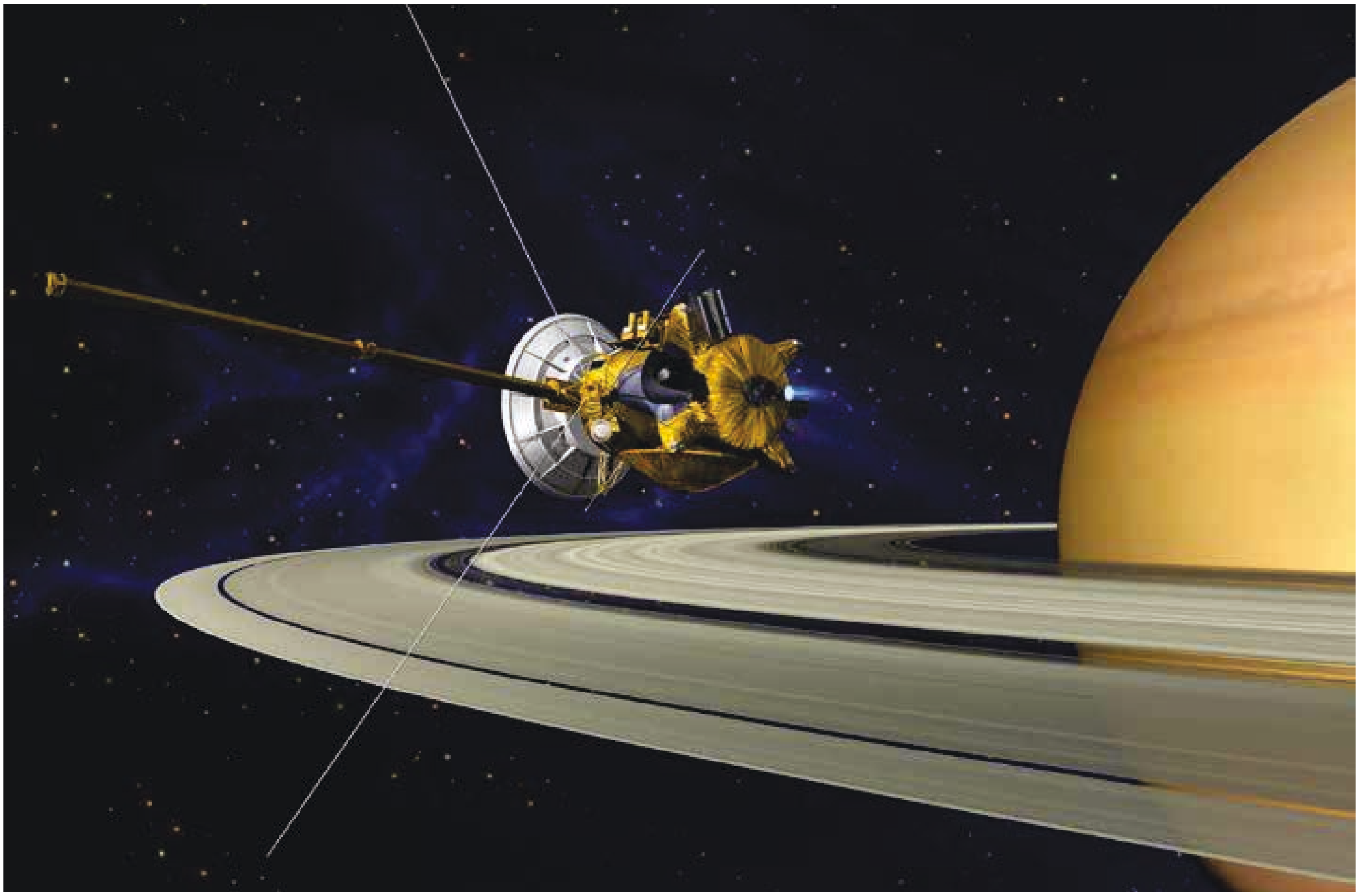
With this and other concerns at the core of the anti-Cassini sentiment, local and national newsprint picked up the debate. Headlines included “Critics Warn of Nuclear Mayhem for NASA Launch”[17] and “Saturn Mission’s Use of Plutonium Provokes Warnings of Danger.”[18] In addition to print and other media, 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]

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]

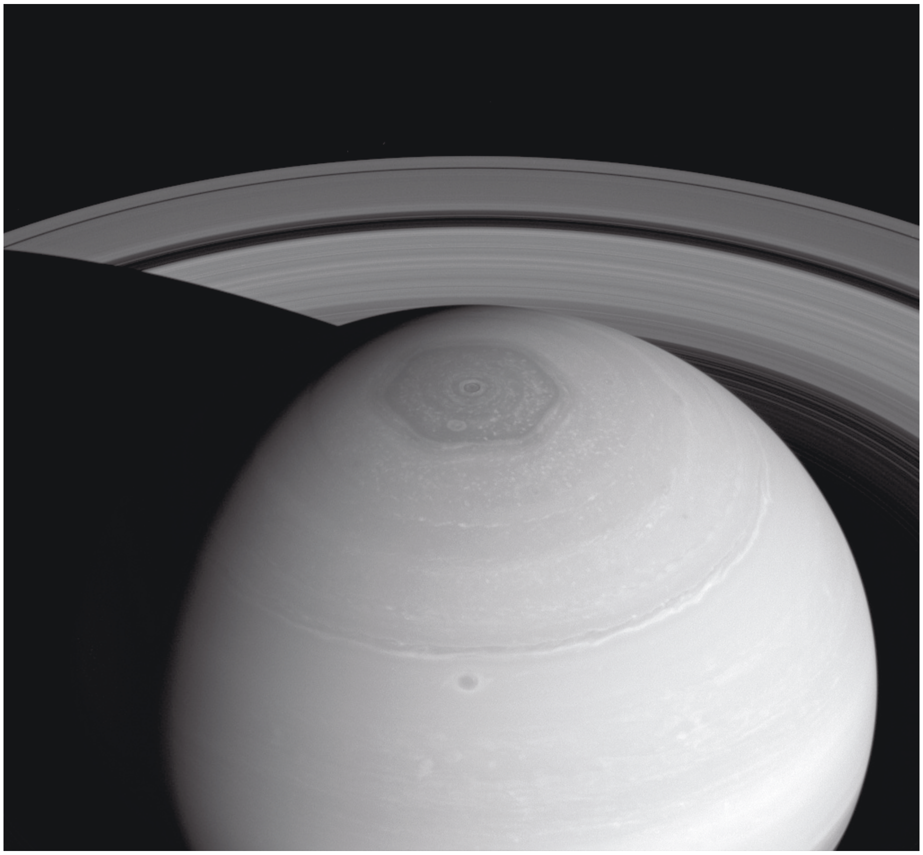
Saturn at Last

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]

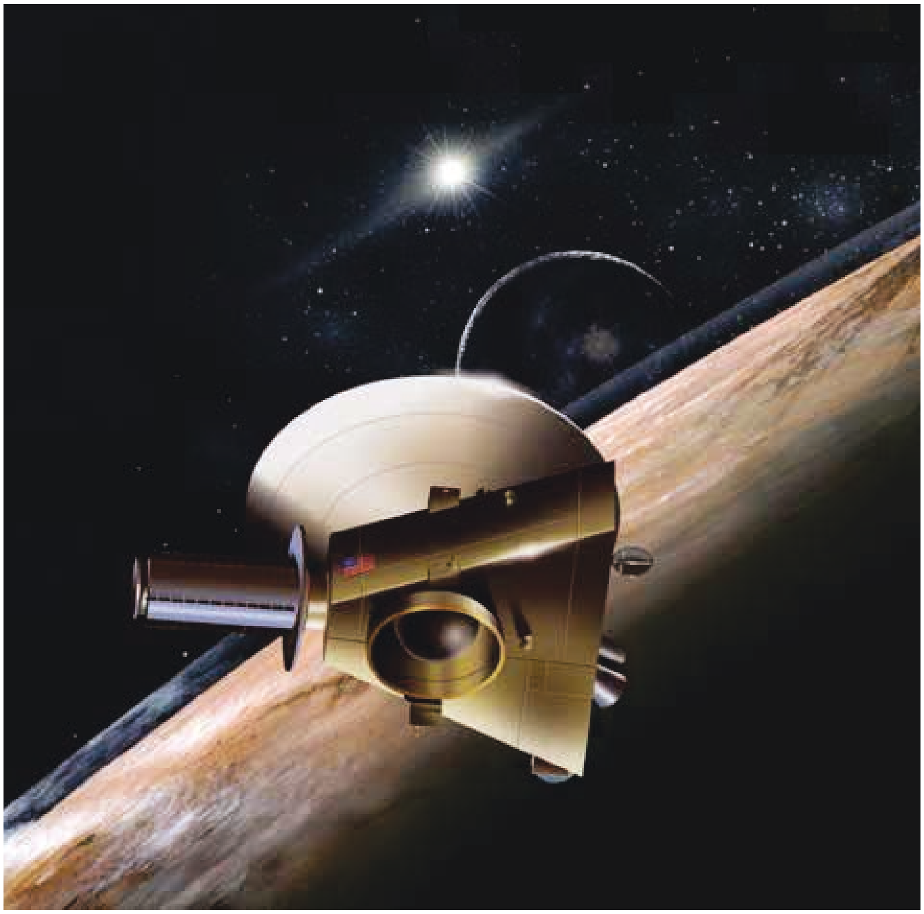
Planning the Trip

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

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.

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

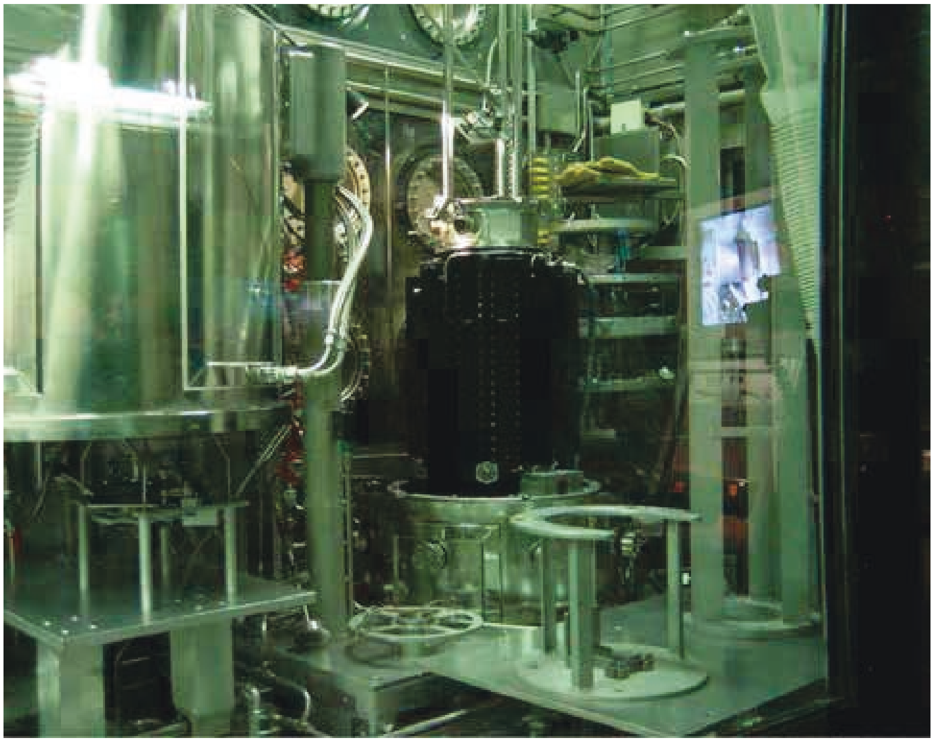
Following assembly, F-8 was subjected to a variety of tests to ensure it would properly operate in space. Mass properties testing determined the RTG center of gravity, which was used by NASA in their planning for control of the spacecraft once in space. Thermal vacuum testing determined the RTG power 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,



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

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]

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

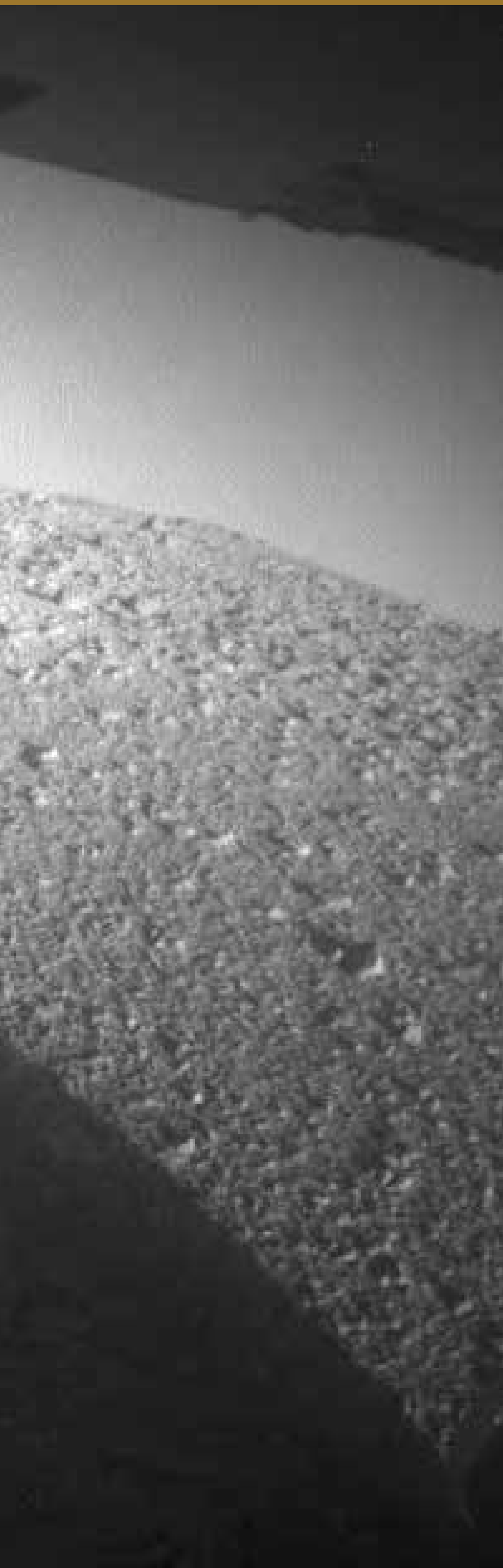
Asteroid 5886 Rutger (formerly 1975 LR) was named after Lyle Rutger in recognition of his role as the DOE Nuclear Launch Approval program manager for the Pluto-New Horizons mission. The name was given by Dr. Alan Stern of the Southwest Research Institute, and principle investigator for the New Horizons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

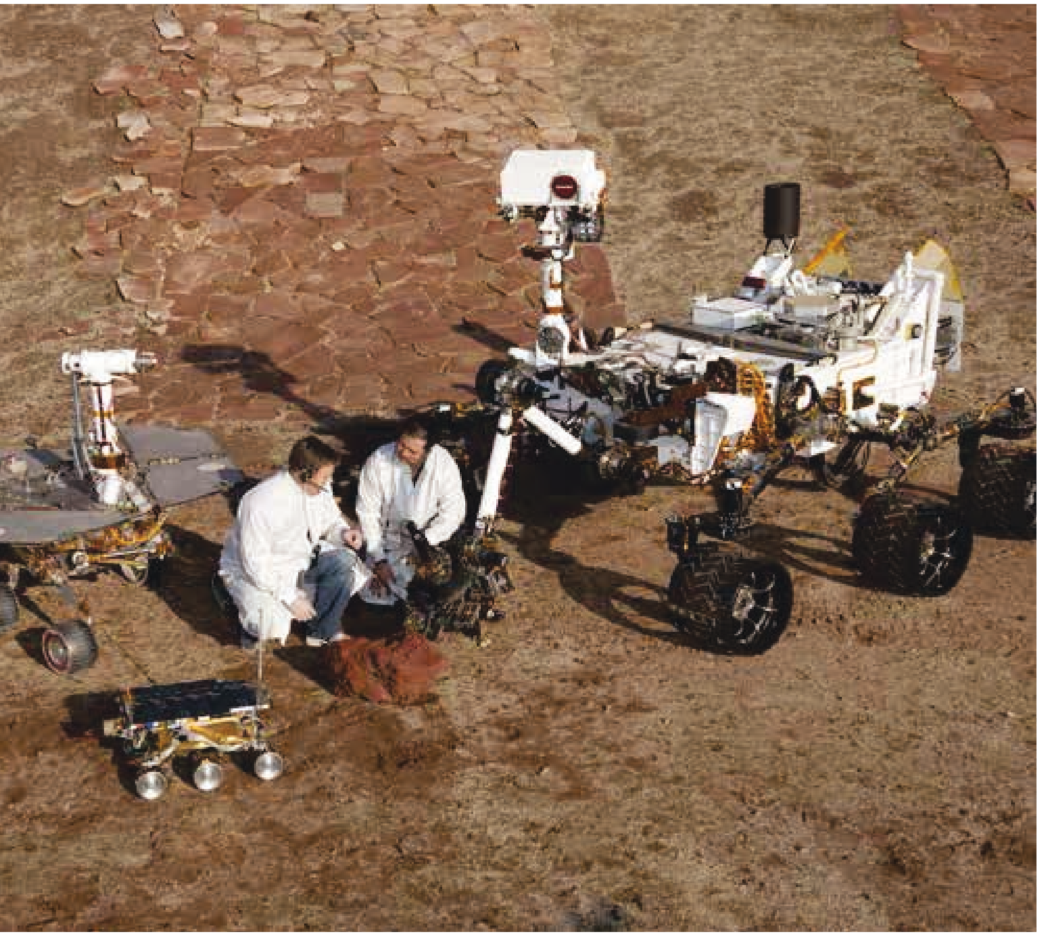
In March 2004, NASA announced its intent to solicit proposals for instrumentation and science investigations to be part of Mars Science Laboratory (MSL), a mission planned for launch in 2009. Later that year, the eight proposals that had been selected to be part of the rover-based mobile laboratory were 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]

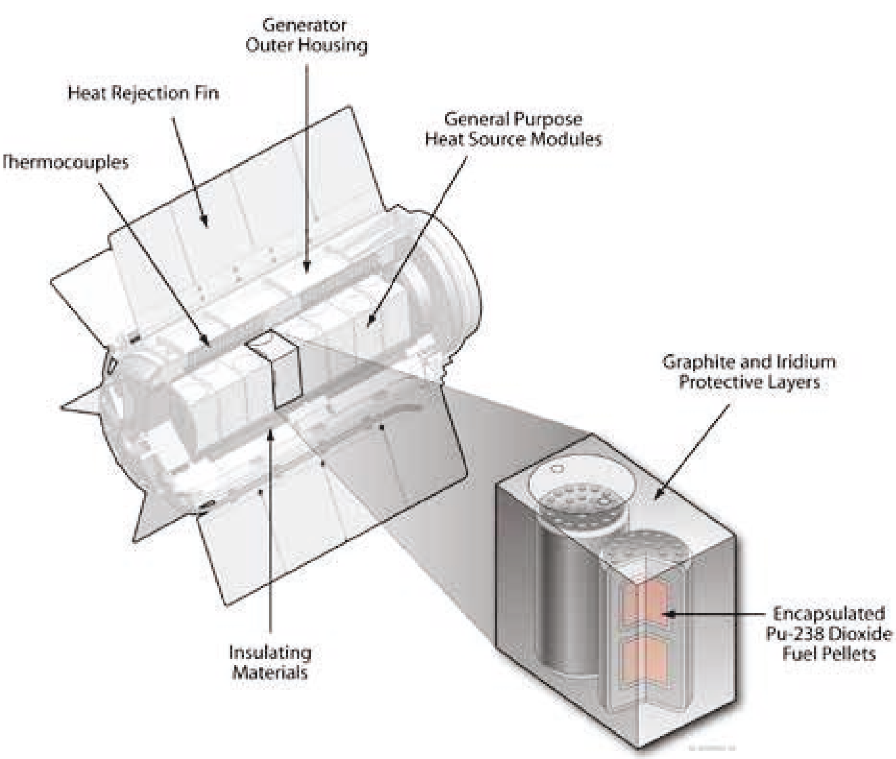
As development of the new RTG progressed, it was only a matter of time before it was connected to a NASA mission. That connection occurred in 2004 when DOE and NASA linked the generator to the upcoming Mars rover mission

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]

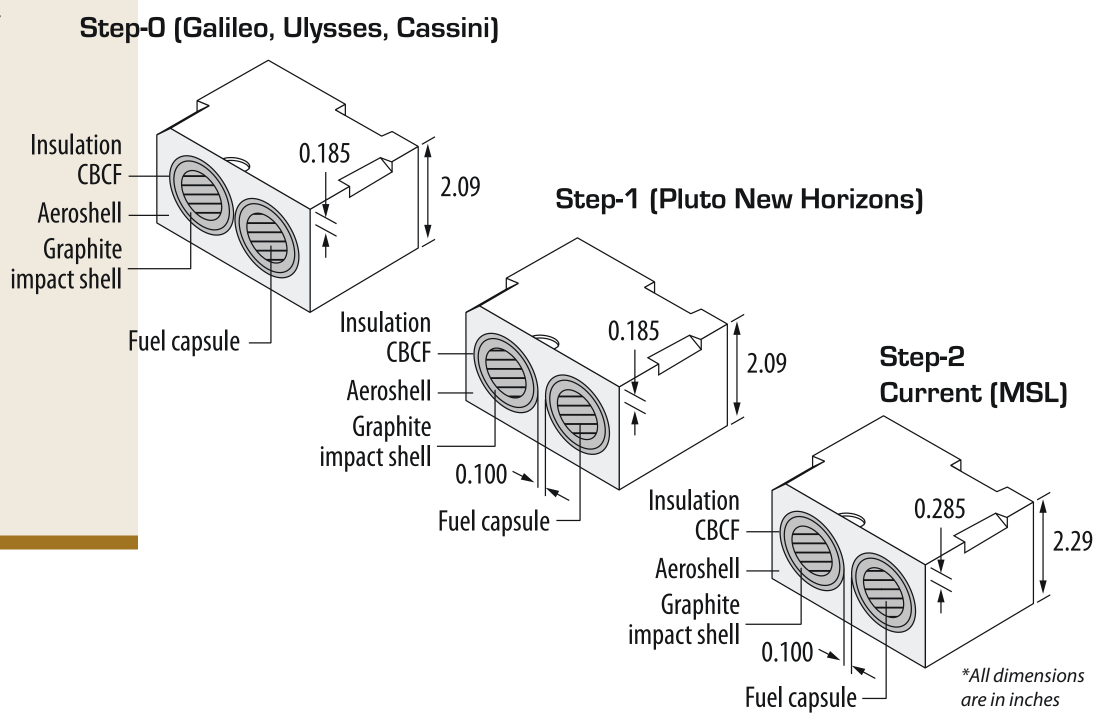
As development of the MMRTG proceeded under the Rocketdyne-Teledyne team, the components needed to fuel the GPHS modules were being prepared by the DOE laboratories. For example, the iridium cups and frit vents that comprised a clad-vent set were fabricated by ORNL. The completed clad vent set hardware was shipped to LANL, where the

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)

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]



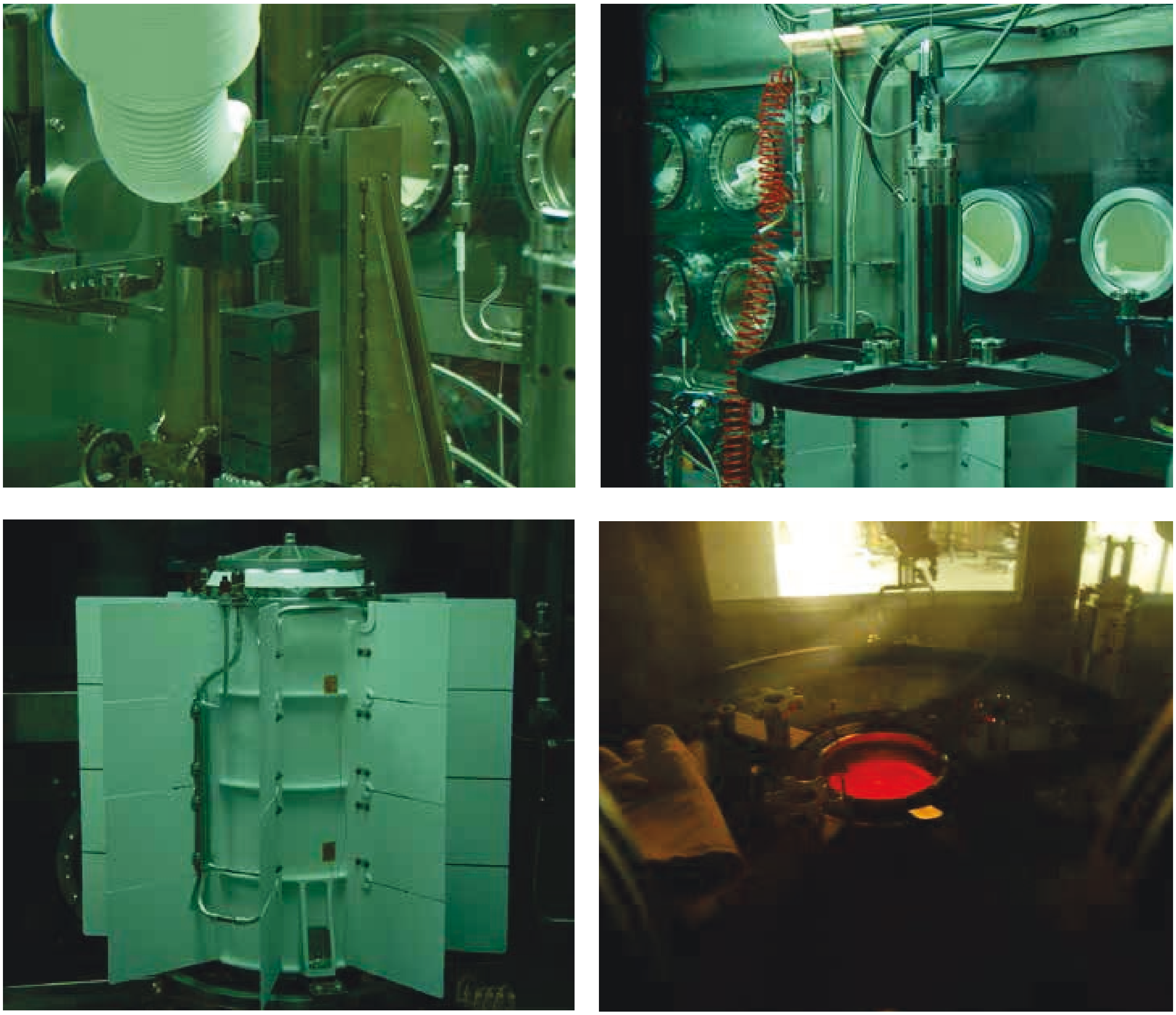
Assembly, Testing, and Bumps

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.

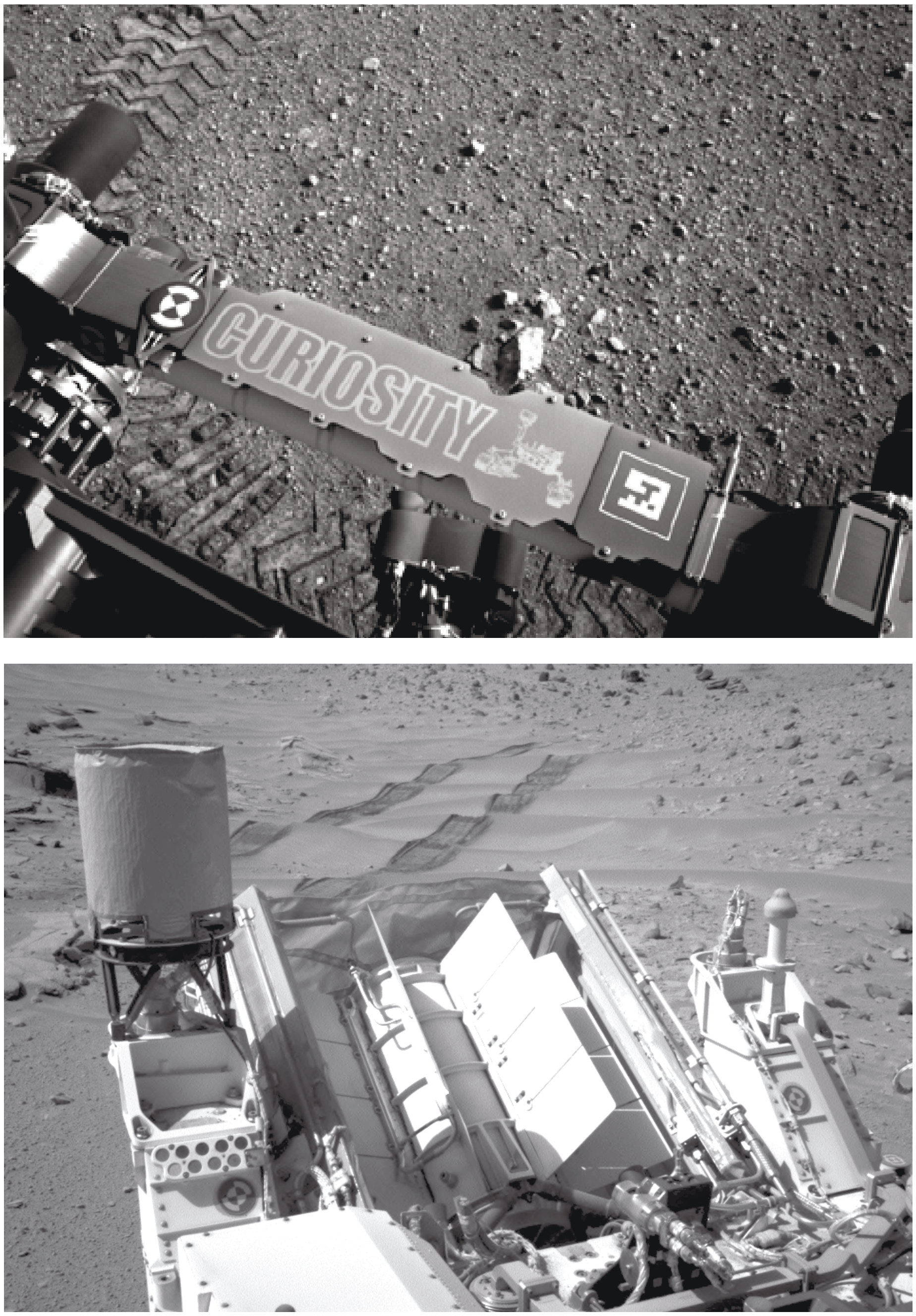
During the second half of 2011, DOE and its contractors continued to maintain a watchful eye over the MMRTG as NASA completed their preparations for MSL launch. In one of the final activities to ensure the MMRTG was ready, it was connected to and fully integrated with the rover Curiosity. In one final 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.



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)

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.

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.

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.

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.

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

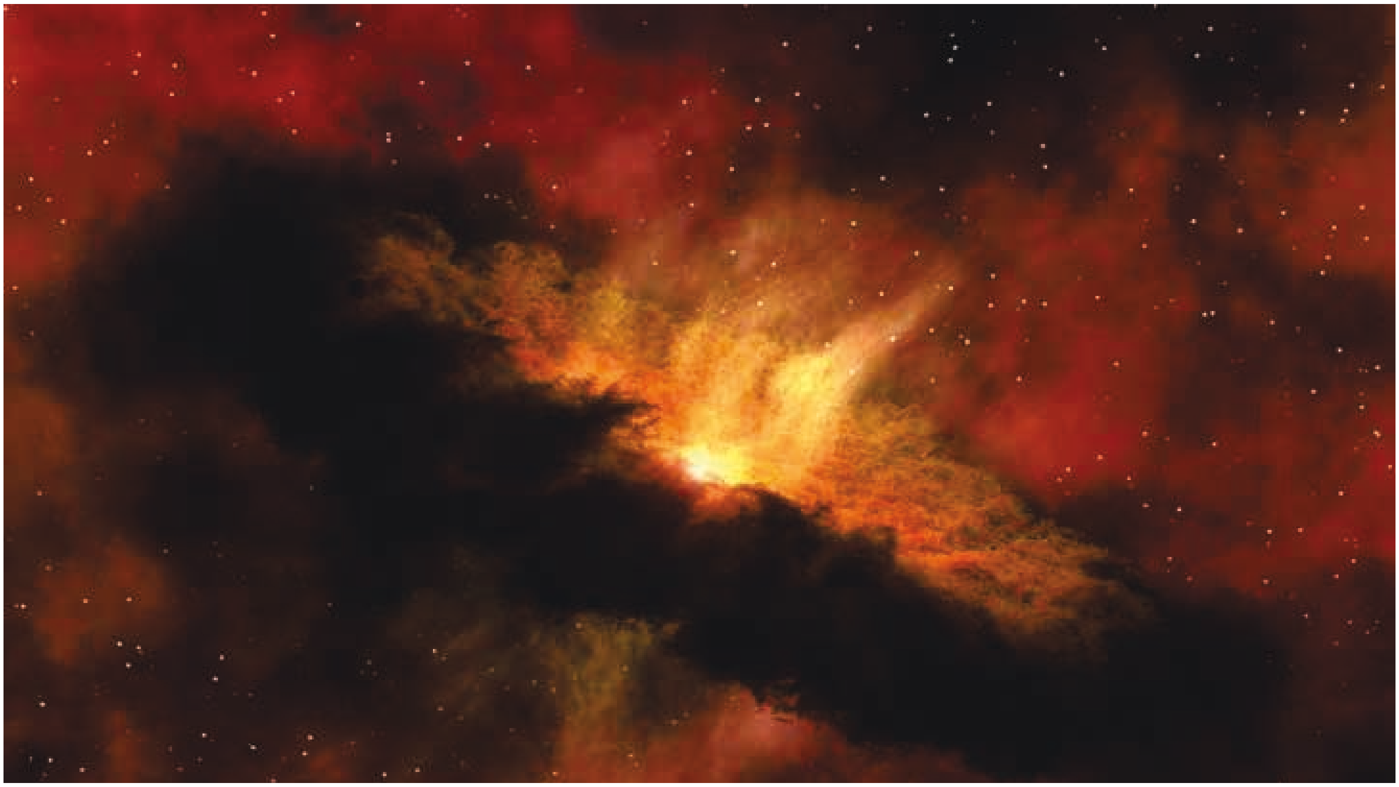
Nuclear safety will remain a significant emphasis for all future space nuclear power system uses. That emphasis will continue to be driven by rigorous launch approval processes and supported by the ongoing enhancement of knowledge pertaining to potential launch accident environments and an ever improving 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)

Appendix A
United States Space Nuclear Power Systems Launched into Space (as of January 2014)

Power Source[a]	Spacecraft	Mission Type	Launch Date	Status[b]	Initial Average RTG Power (We)[b]	Total Initial Spacecraft Power (We)[b]
RTGs						
SNAP-3(1)	TRANSIT-4A	Navigational	29-Jun-61	Succesfully operated for over 15 years. Currently in Earth orbit.	2.7	2.7
SNAP-3(1)	TRANSIT-4B	Navigational	15-Nov-61	Succesfully operated for over 9 years. Currently in Earth orbit.	2.7	2.7
SNAP-9(1)	TRANSIT-5BN-1	Navigational	28-Sep-63	RTG succesfully operated as planned. Non-electrical problems caused satelite to fail after 9 months. Currently in Earth orbit.	25.2	25.2
SNAP-9(1)	TRANSIT-5BN-2	Navigational	5-Dec-63	Sucessfully operated for over 6 years. Currently in Earth orbit.	26.8	26.8
SNAP-9(1)	TRANSIT-5BN-3	Navigational	21-Apr-64	Spacecraft failed to achieve orbit, RTG burned and dispered on re-ntry as designed.	25	25
SNAP-19(2)	NIMBUS-B-1	Meteorologocial	18-May-68	Mission aborted; power source retrieved intact and fuel source reused on later mission.	28	56
SNAP19-(2)	NIMBUS III	Meteorologocial	14-Apr-69	Sucessfully operated for over 2.5 years. Currently in Earth orbit.	28.2	56.4
SNAP-27(1)	APOLLO 12	Lunar/ALSEP	14-Nov-69	Succesfully operated for 8 years and currently on lunar surface.	73.6	73.6
SNAP-27(1)	APOLLO 13	Lunar/ALSEP	11-Apr-70	Mission aborted on way to moon. RTG re-entered Earth's atmosphere and landed in the South Pacific Ocean. No radiation release was detected.	73	73
SNAP-27(1)	APOLLO 14	Lunar/ALSEP	31-Jan-71	Succesfully operated for 6.5 years and currently on lunar surface.	72.5	72.5
SNAP-27(1)	APOLLO 15	Lunar/ALSEP	26-Jul-71	ALSEP sucessfully operated for 6 years and currently on lunar surface.	74.7	74.7
SNAP-19(4)	PIONEER 10	Planetary	2-Mar-72	Sucessfully operated to Jupiter and beyond; spacecraft operations terminated in 2003.	40.7	162.8
SNAP-27(1)	APOLLO 16	Lunar/ALSEP	16-Apr-82	ALSEP successfully operated for 5.5 years and currently on lunar surface.	70.9	70.9
TRANSIT-RTG(1)	TRAID-01-1X	Navigational	2-SEP-72	Currently in Earth orbit.	35.6	35.6
SNAP-27(1)	APOLLO 17	Lunar/ALSEP	7-Dec-72	Sucesssfully operated for 5 years and currently on lunar surface.	75.4	75.4
SNAP-19(4)	PIONEER 11	Planetary	5-Apr-73	Succesfully operated to Jupiter, Saturn, and beyond; spacecraft operations terminated in 1995.	39.9	159.6
SNAP-19(2)	VIKING 1	Planetary	20-Aug-75	Landed and succesfully operated for over 6 years on Mars. Operations ended in 1982.	42.3	84.6
SNAP-19(2)	VIKING 2	Planetary	9-Sep-75	Landed and succesfully operated for over 4 years on Mars. Operations ended in 1982.	43.1	86.2
MHW-RTG(2)	LES 8	Communications	14-Mar-76	Currently in Earth orbit.	153.7	307.4
MHW-RTG(2)	LES 9	Communications	14-Mar-76	Currently in Earth orbit.	154.2	308.4

Power Source[a]	Spacecraft	Mission Type	Launch Date	Status[b]	Initial Average RTG Power (We)[b]	Total Initial Spacecraft Power (We)[b]
MHW-RTG(3)	VOYAGER 2	Planetary	20-Aug-77	Successfully operated to Jupiter, Saturn, Uranus, Neptune and beyond. Extended mission ongoing; currently at heliopause.	159.2	477.6
MHW-RTG(3)	VOYAGER 1	Planetary	5-Sep-77	Successfully operated to Jupiter, Saturn, and beyond. Extended mission ongoing; currently in interstellar space.	156.7	470.1
GPHS-RTG (2)	Galileo	Planetary	18-Oct-89	Successfully explored Venus and then orbited Jupiter. Spacecraft deorbited into Jupiter in 2003.	288.4	576.8
GPHS-RTG (1)	Ulysses	Solar-Polar	6-Oct-90	Successfully explored Jupiter and entered solar polar orbit. Spacecraft operations ended in 2009.	283	283
GPHS-RTG (3)	Cassini	Planetary	15-Oct-97	Successfully explored Venus, Jupiter, and currently orbiting Saturn.	295.7	887
GPHS-RTG (1)	New Horizons	Planetary	19-Jan-06	Explored Jupiter; Pluto fly-by expected July 2015; additional exploration of Kuiper Belt and beyond will follow.	249.6	249.6
MMRTG (1)	Curiosity	Planetary	26-Nov-11	Succssfully landed on August 6, 2012 and currently exploring Martian surface.	113	113
Space Nuclear Reactors						
SNAP-10A (1)	SNAPSHOT	Experimental satellite	3-Apr-65	Reactor operated for 43 days after which it shut down due to non-nuclear electrical problem on the spacecraft. Currently in Earth orbit.	500	500

(a) The number in parenthesis is the number of power sources on the spacecraft.

(b) Personal communication with Ryan Bechtel (DOE), June 18, 2015.

Mission	RHUs (#)	Wt (BOM)
Radioisotope Heater Units		
Apollo 11	2	15 each
Pioneer 10	12	1 each
Pioneer 11	12	1 each
Voyager 1	9	1 each
Voyager 2	9	1 each
Light-Weight Radioisotope Heater Units		
Galileo	120	1 each
Mars Rover Pathfinder	3	1 each
Cassini	117	1 each
Mars Rover Spirit	8	1 each
Mars Rover Opportunity	8	1 each

B

Appendix B
Accidents Involving Spacecraft Carrying U.S. RTGs

Since 1961, the United States has launched 27 spacecraft with RTGs on board. Although three of the missions failed, none of the failures were due to problems with the RTGs.

1. **April 21, 1964: Transit satellite 5BN-3 with one SNAP-9A RTG**

   On April 21, 1964, a Transit satellite, 5BN-3, was launched from Vandenberg Air Force Base in California. When the satellite failed to achieve orbit, the SNAP-9A RTG re-entered the atmosphere in the Southern Hemisphere. Consistent with the burnup-dispersion safety philosophy in use at the time, the SNAP-9A unit and its metal plutonium fuel burned up and was dispersed into the atmosphere. Although there were no unacceptable health risks, with larger quantities of plutonium fuel planned for future RTGs, AEC changed its safety philosophy to one of intact re-entry.

2. **May 18, 1968: Nimbus B weather satellite with two SNAP-19 RTGs**

   On May 18, 1968, a NASA Nimbus B weather satellite with two SNAP-19 RTGs was launched from Vandenberg Air Force Base. Approximately two minutes after liftoff, the rocket went off course, prompting a mission abort command. The abort-induced explosion destroyed the launch vehicle, after which the two RTGs fell into the Santa Barbara Channel just north of San Miguel Island off the coast of California. Five months later, the SNAP-19 units were recovered – intact – from the ocean floor at a depth of approximately 300 feet. The capsules were returned to Mound Laboratory, where the fuel was recovered and reused in a new RTG.

3. **April 17, 1970: Apollo 13 lunar module with re-entry SNAP-27 RTG aboard**

   During the Apollo 13 mission, the lunar module and its SNAP-27 RTG were supposed to be left on the moon. Due to an explosion on the main craft, however, the lunar module was brought back to Earth, along with the command module, to provide life support for the astronauts. Prior to re-entry, the lunar module (with the SNAP-27 RTG onboard) was jettisoned from the command module. During re-entry, the lunar module disintegrated and the RTG fell into the Tonga Trench of the Pacific Ocean. Subsequent monitoring and sampling found no detectable radioactivity, indicating the RTG survived the crash intact.

Appendix C
Space Power Reactor Summary 1955 - 1973

(adapted from "Nuclear Reactors for Space Power," William R. Corliss, 1971)

	Electrical Power Level, kW	Mass, kg (lbs)	Specific mass, kg/kw (lb/kw)	Overall efficiency, %	Core type	Core coolant	Energy conversion scheme (s)	Status
SNAP-2	3	668 (1,470)	223 (490)	5.4	Uranium zirconium hydride	NaK	Rankine-cycle turbogenerator	Discontinued space power plant
SNAP-8	35	4,450 (9,800)	127 (270)	7.8	Uranium zirconium hydride	NaK	Rankine-cycle turbogenerator, mercury working fluid	Component development competed, power plant concept discontinued in 1970
SNAP-10	0.3	–	–	–	Uranium zirconium hydride	None	Thermoelectric	Early design using conductive cooling of reactor; changed to SNAP-10A, convective heat-transfer design
SNAP-10A	0.6	427 (960)	908 (2,000)	1.6	Uranium zirconium hydride	NaK	Thermoelectric	Completed; in orbit April 1965
SNAP-50	100-1,000	At 300 kw, 2,700 (6,000) At 1,000 kw, 9,000 (20,000)	At 300 kw, 9 (20) (unshielded)	15	Fast, uranium nitride	Li	Rankine-cycle turbogenerator, potassium working fluid	Discontinued in 1965. Replaced by Advanced Liquid-Metal-Cooled Reactor
Advanced Hydride Reactors	10-100	–	–	Up to 20%	Uranium zirconium hydride	NaK	Thermoelectric and Brayton	SNAP-8 technology improvements
Advanced Liquid-Metal-Cooled Reactor	100-600 plus	–	–	15-25%	Fast, uranium nitride	Li	Brayton and potassium Rankine	Basic technology program only
In-Core Thermionic Reactor	100-1,000	8,500 (19,000) at 300 kw	28 (62)**	10-20%	Fast with thermal driver	–	Thermionic	Technology program with emphasis on thermionic fuel element

**Two other advanced reactor concepts were investigated in the basic technology programs: a gas-cooled reactor for use with the Brayton cycle and a boiling-potassium reactor for a Rankine-cycle power plant.*

***With shielding for an unmanned mission.*

Appendix D

Timeline (1983 - 2013)

March 1983
President Ronald Reagan proposes Strategic Defense Initiative

October 1983
SP-100 Program Phase I begins

October 1985
SP-100 Program Phase II begins

MMW program begins

January 1986
Challenger accident

April 1986
Chernobyl accident

October 1986
TFE Verification Program begins

Mid-1987
Timberwind begins (SDIO and DOE)

November 1988
George H.W. Bush elected President

October 4, 1989
Bush announces Space Explodration Initiative

October 18, 1989
Galileo launched

1990
GPHS fueled clad production transferred from SRS to LANL

October 6, 1990
Ulysses launched

MMW program terminated

December 1991
Soviet Union collapses

June 1992
Responsibility for space nuclear thermal propulsion transferred from Defense Programs to Office of Nuclear Energy

November 1992
William J. Clinton elected President

December 1993
SP-100 Program terminated

1994
TFE Verification Program ends

SNTP program terminated

December 7, 1995
Galileo Orbiter begins circling Jupiter

July 4, 1997
Rover Sojourner lands on Mars; LWRHUs provide heat for electronics

- Milieu-Defining Events
- Institutional Events
- Technical Events and Developments

January 14, 2004
Bush announces Vision for Space Exploration

January 4, 2004
Rover Spirit lands on Mars; LWRHUs provide heat for electronics

January 25, 2004
Rover Opportunity lands on Mars; LWRHUs provide heat for electronics

June 30, 2009
Ulysses mission ends

September 11, 2001
Terrorist attack on Twin Towers and Pentagon; War on Terror begins

July 1, 2004
Cassini spacecraft enters Saturn orbit

August 5, 2012
Curiosity lands on Mars and begins 2-yr mission

2000 2005 2010

November 2000
George W. Bush elected President

September 21, 2003
Galileo mission ends

November 2008
Barack Obama elected President

October 15, 1997
Cassini-Huygens launched

March 2003
Prometheus project begins

May 2005
Prometheus project terminated

November 26, 2011
MSL-Curiosity launched; first MMRTG launched

2002
RTG assembly and testing operations transferred from Mound to ANL-W (INL)

Bush Nuclear Systems Initiative

January 19, 2006
New Horizons launched; begins 10-yr journey to Pluto

E

Appendix E
Rover/NERVA Reactor Test Summary[1]

Date	Test Article	Maximum Power	Time at Maximum Power*
July 1, 1959	Kiwi-A	70 MW	5 minutes
July 8, 1960	Kiwi-A'	85 MW	6 minutes
October 10, 1960	Kiwi-A3	100 MW	5 minutes
December 7, 1961	Kiwi-B1A	300 MW	30 seconds
September 1, 1962	Kiwi-B1B	900 MW	Several seconds
November 30, 1962	Kiwi-B4A	500 MW	Several seconds
May 13, 1964	Kiwi-B4D	1,000 MW	~40 seconds
August 28,1964	Kiwi-B4E	900 MW	8 minutes
September 10, 1964	Kiwi-B4E	900 MW	2.5 minutes - restart
September 24, 1964	NRX-A2	1,096 MW	40 seconds
October 15,1964	NRX-A2	Restart	Performance mapping
January 21, 1965	Kiwi-TNT	Safety test reactor - deliberately destroyed on power excursion	
April 23, 1965	NRX-A3	1,093 MW	3.5 minutes
May 20, 1965	NRX-A3	1,072 MW	13 minutes
May 28, 1965	NRX-A3	≤500 MW	46 minutes - performance maps
June 25,1965	Phoebus 1A	1,090 MW	10.5 minutes
March 3, 16, 25, 1965	NRX/EST	1,055 MW	1.25 minutes, 14.5 minutes, 13.7 minutes, respectively
June 8, 1966	NRX-A5	1,120 MW	15.5 minutes
June 23, 1966	NRX-A5	1,050 MW	14.5 minutes (restart)
February 10, 1967	Phoebus 1B	588 MW	2.5 minutes
February 23, 1967	Phoebus 1B	>1,250 MW	30 minutes - low power
December 15, 1967	NRX-A6	1,125 MW	62 minutes
June 8, 1968	Phoebus-2A	2,000 MW	~100 seconds
June 26, 1968	Phoebus-2A	4,100 MW	12 minutes
July 18, 1968	Phoebus-2A	1,280 MW – 3,430 MW	30 minutes of total operation
December 3-4, 1968	Pewee	514 MW	40 minutes
June 11, 1969	XE-Prime	1,140 MW	3.5 minutes
Note: XE-Prime had 28 experimental restarts from December 4, 1968 to September 11, 1969.			
June 29 - July 27, 1972	Nuclear furnace	44 MW	109 minutes (6 experiments)
*Note: in several cases the reactor was operated at lower powers for longer times.			

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Acronyms

3M	Minnesota Mining and Manufacturing Company
AEC	Atomic Energy Commission
ANL-W	Argonne National Laboratory-West
ASC	advanced Stirling converter
ASRG	Advanced Stirling Radioisotope Generator
BIPS	Brayton Isotope Power System
BMDO	Ballistic Missile Defense Organization
DARPA	Defense Advanced Research Projects Agency
DIPS	dynamic isotope power system
DNA	Defense Nuclear Agency
DoD	Department of Defense
DOE	Department of Energy
DOE-ID	Department of Energy Idaho Operations Office
DOE-NE	Department of Energy Office of Nuclear Energy
DOE-NR	Department of Energy Office of Naval Reactors
EBR-II	Experimental Breeder Reactor-II
EIS	environmental impact statement
ERDA	Energy Research and Development Administration
ESA	European Space Agency
ETG	electrically-heated thermoelectric generator
FFTF	Fast Flux Test Facility
FMEF	Fuels and Materials Examination Facility
FWPF	fine-weave pierced fabric
GAO	U.S. General Accounting Office
GE	General Electric
GPHS	general purpose heat source
GPS	global positioning system
GRC	Glenn Research Center
HiPEP	High Power Electric Propulsion
INL	Idaho National Laboratory
INSRP	Interagency Nuclear Safety Review Panel
ISA	Italian Space Agency
ISPM	International Solar Polar Mission
IUS	inertial upper stage
JIMO	Jupiter Icy Moons Orbiter
JPL	Jet Propulsion Laboratory

KIPS	Kilowatt Isotope Power System
KSC	Kennedy Space Center
kWe	kilowatts of electric power
LANL	Los Alamos National Laboratory
LASL	Los Alamos Scientific Laboratory (later the Los Alamos National Laboratory)
LRL	Lawrence Radiation Laboratory (later the Lawrence Livermore National Laboratory)
LWRHU	light-weight radioisotope heater unit
MHW	multi-hundred watt
MITG	modular isotopic thermoelectric generator
MMRTG	multi-mission radioisotope thermoelectric generator
MMW	multi-megawatt
MOD	modular
MSL	Mars Science Laboratory
MWe	megawatts of electric power
MWt	megawatts of thermal power
NSA	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NEPSTP	Nuclear Electric Propulsion Space Test Program
NERVA	Nuclear Engine for Rocket Vehicle Application
NEXIS	Nuclear Electric Xenon Ion System
NRC	National Research Council
NRX	nuclear rocket experimental
NSI	Nuclear Systems Initiative
NSTAR	NASA Solar Technology Application Readiness
ORNL	Oak Ridge National Laboratory
PBR	particle bed reactor
PIPET	PBR Integral Performance Element Tester
PRTR	Plutonium Recycle Test Reactor
psi	pounds per square inch
PuFF	Plutonium Fuel Form Facility
RCA	Radio Corporation of America
RFS	reference flight system
RHU	radioisotope heater unit
RPS	radioisotope power system

RTG	radioisotope thermoelectric generator
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SEI	Space Exploration Initiative
SIG	selenide isotope generator
SNAP	Systems for Nuclear Auxiliary Power
SNL	Sandia National Laboratories
SNPO	Space Nuclear Propulsion Office
SNTP	Space Nuclear Thermal Propulsion
SRG	Stirling radioisotope generator
SRS	Savannah River Site
SSPSF	Space and Security Power Systems Facility
STS	space transportation system
TDC	technology demonstration convertor
TES	Teledyne Energy Systems
TFE	thermionic fuel element
TFEVP	TFE Verification Program
TOPAZ	thermionic experiment with conversion in active zone
TRIGA	Training, Research, and Isotopes General Atomic
TSET	Thermionic System Evaluation Test
VEEGA	Venus-Earth-Earth Gravity Assist
We	watts of electric power
ZPPR	Zero Power Physics Reactor

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Chapter 1

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