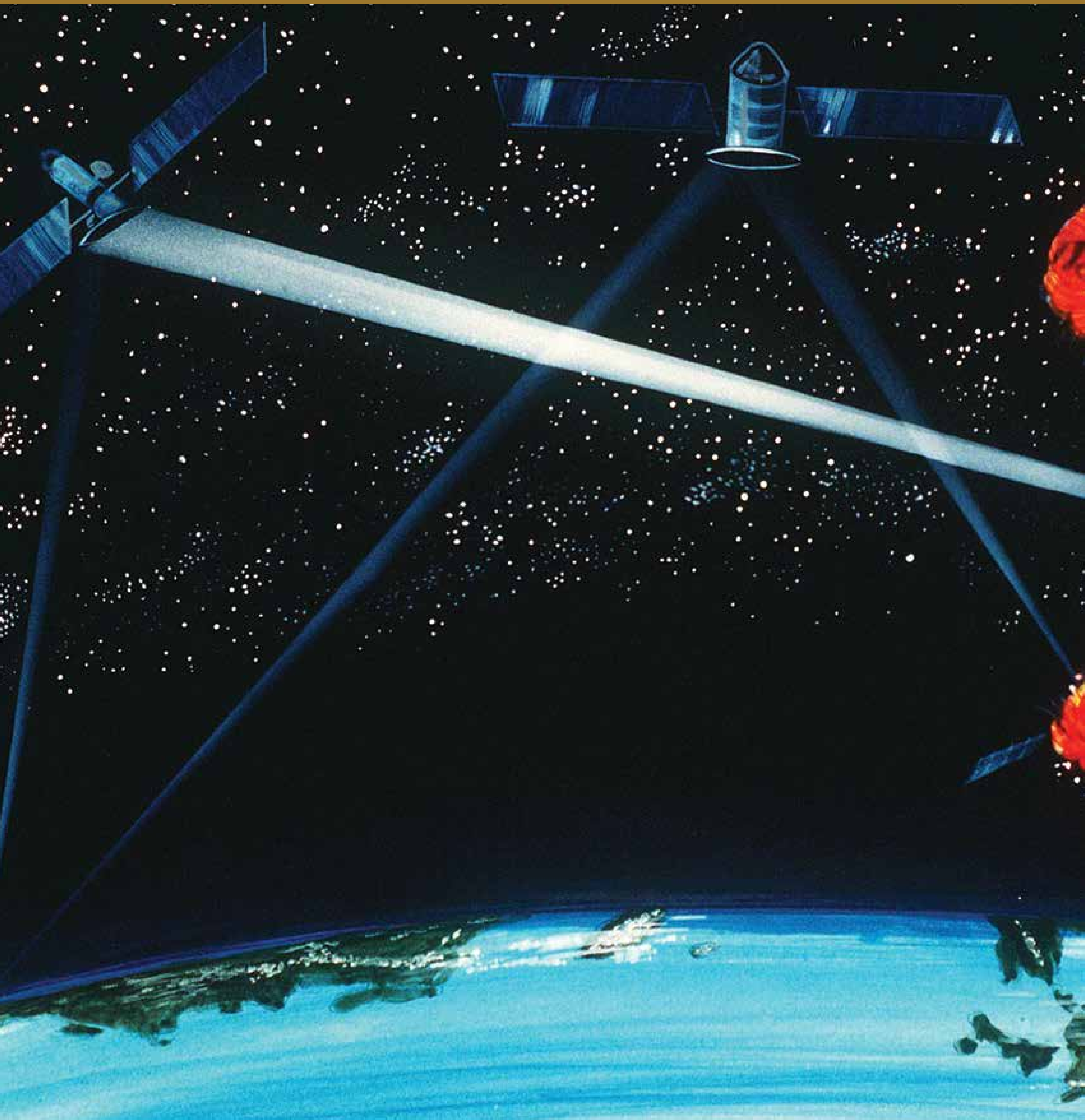
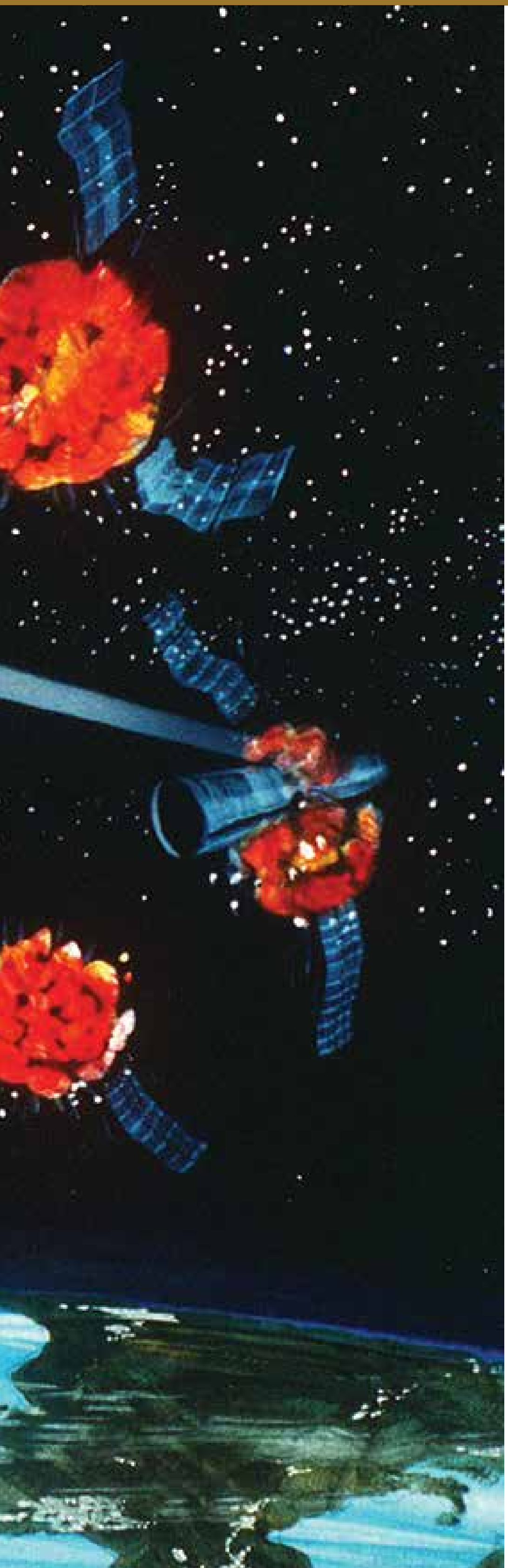
As the vision for global defensive systems capable of protecting against the threat of a Cold War Soviet attack expanded, energy-intensive space-based weapons system concepts such as electromagnetic rail guns, free electron lasers, and neutral particle and charged-particle beam systems began to emerge.



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.

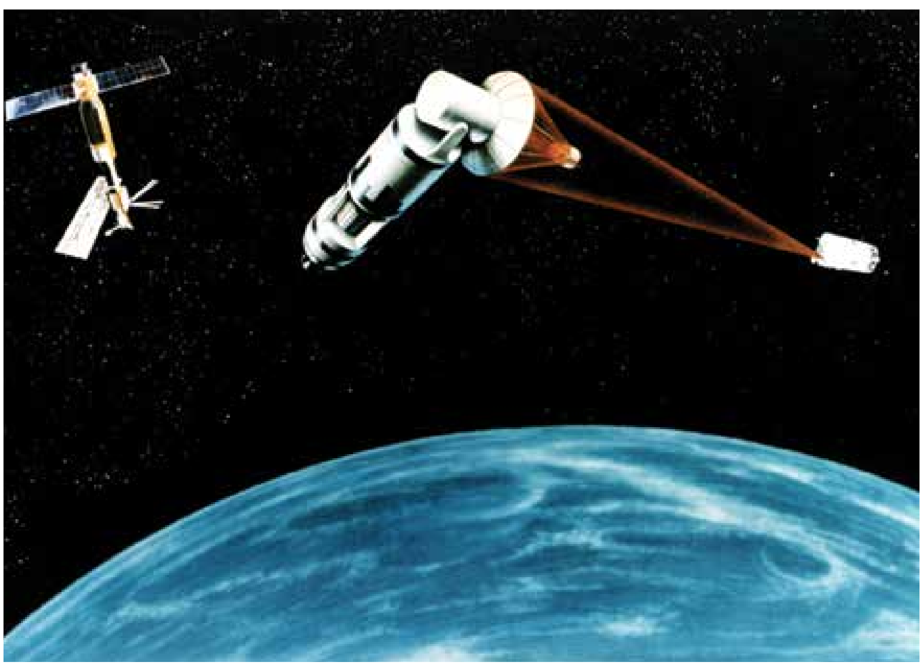
An artist's concept of a ground/space-based hybrid laser weapon, 1984. (Image: U.S. Air Force)

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]

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



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

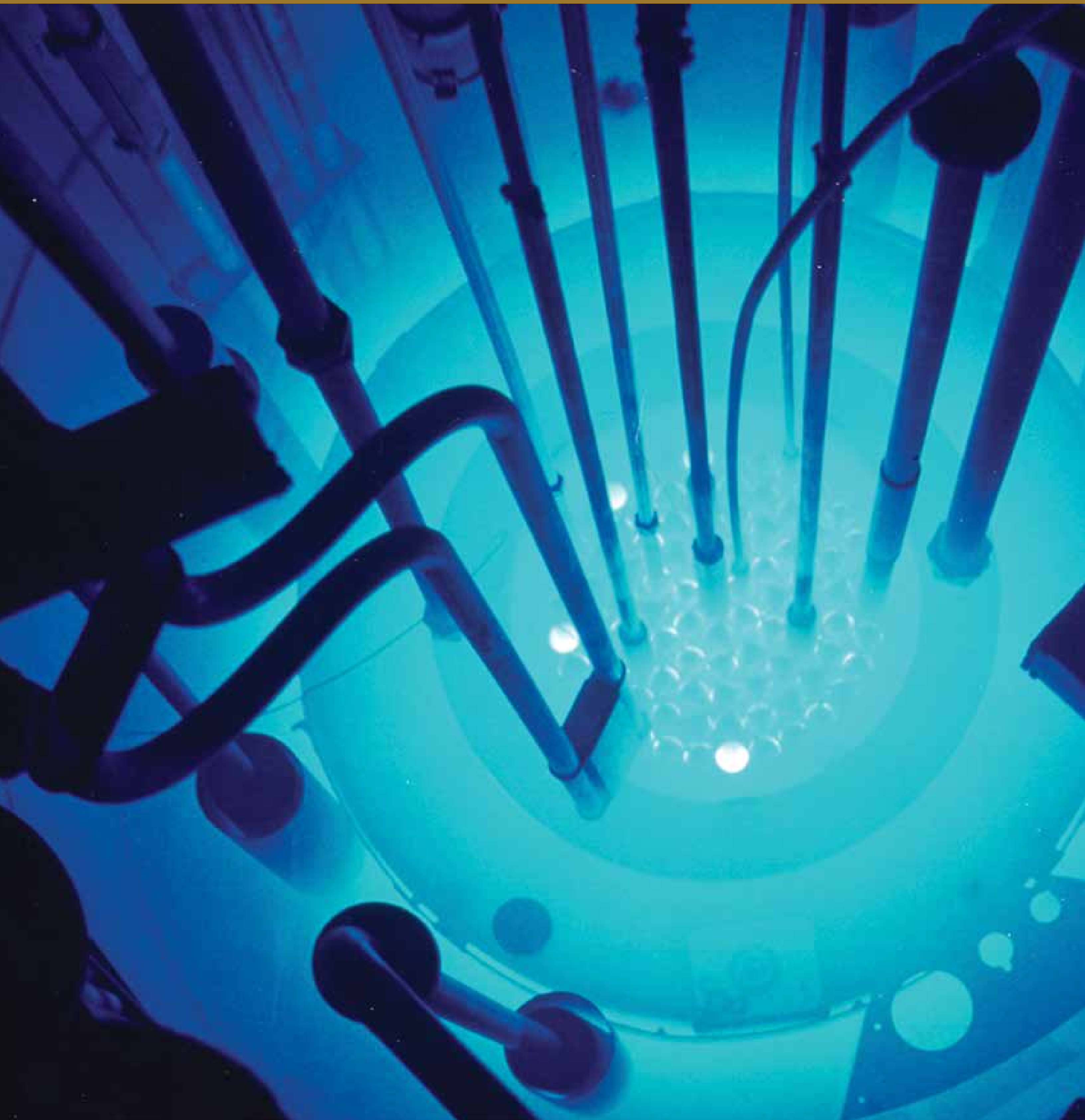
Microgravity:
The effects of microgravity on systems that rely on two-phase (gas and liquid) flow, such as the closed-Rankine-cycle system, require special design considerations. For example, vapor condensation is controlled by shear forces since no falling film condensation occurs. Also, the absence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

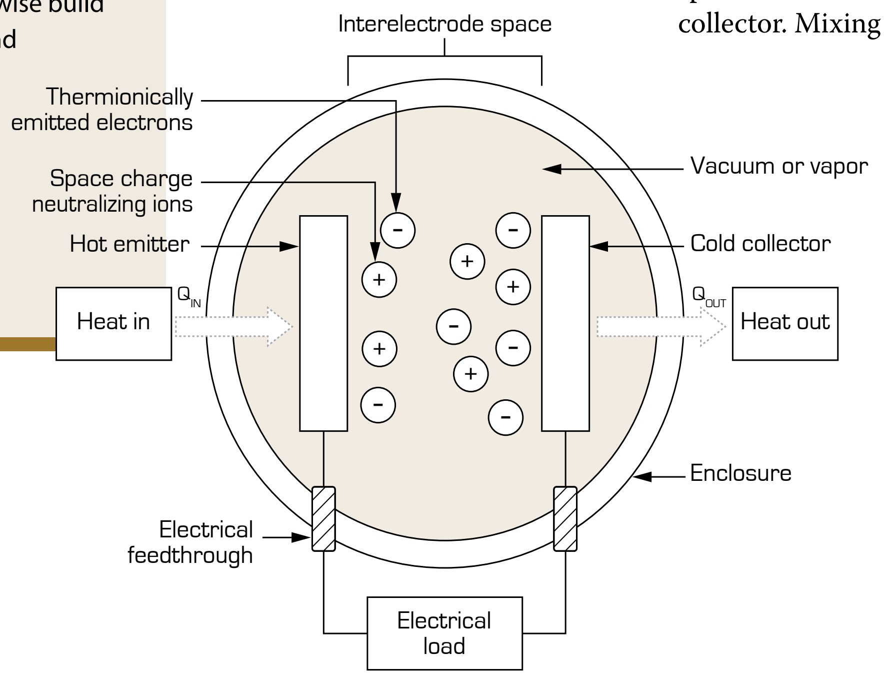
Thermionic Power Conversion

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

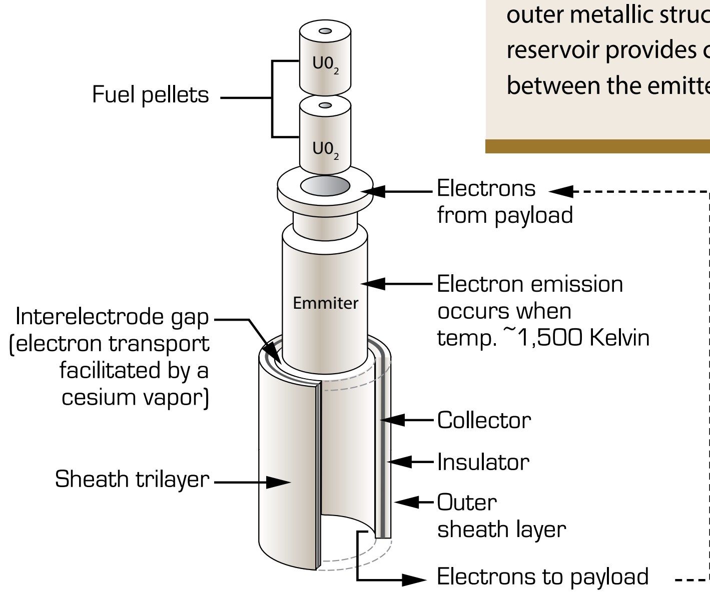


gases with the cesium gas reduced the effectiveness of the space charge provided by the cesium.[2]

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 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)

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.

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-

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.

power oscillations. The other 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]

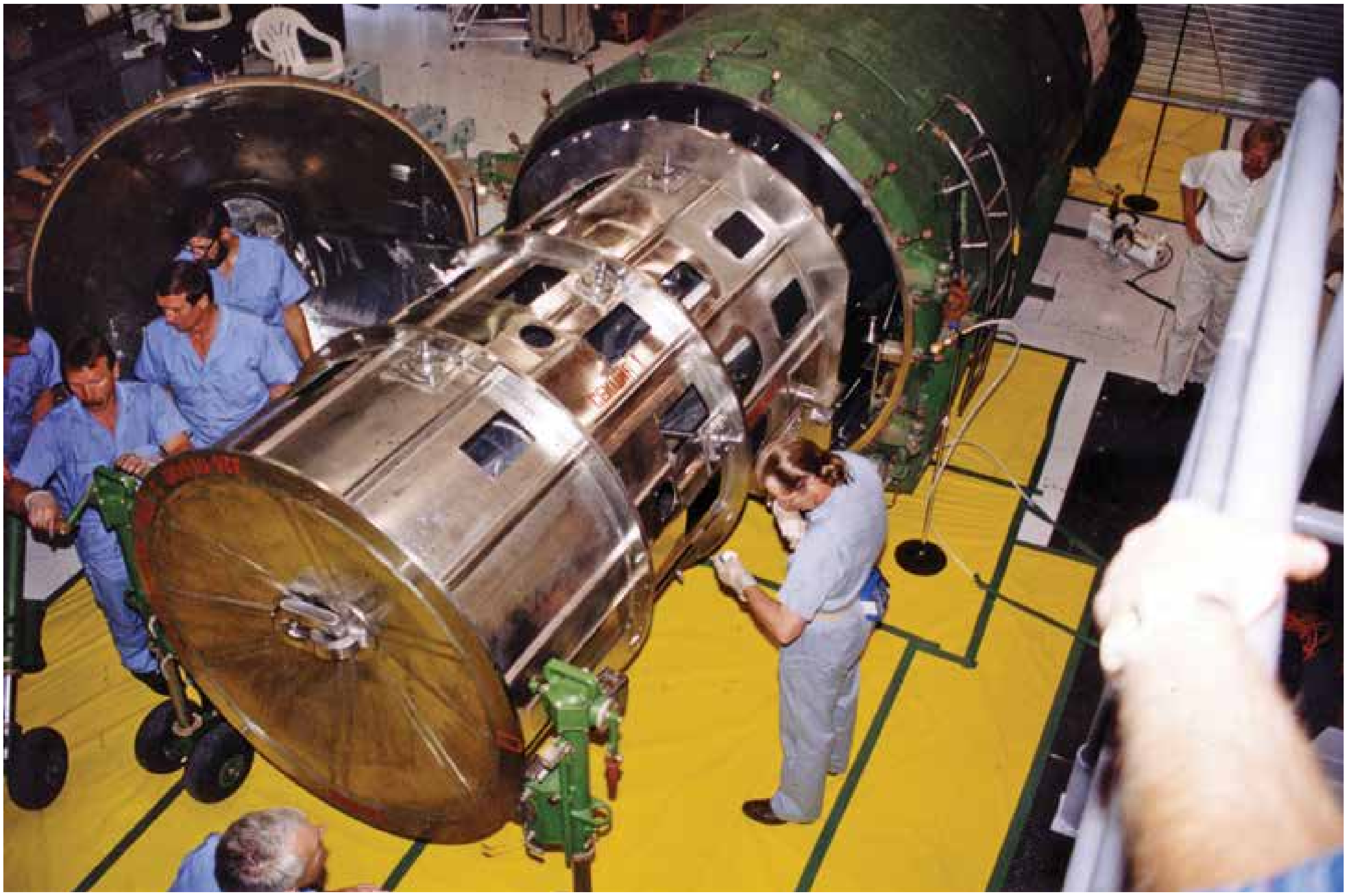
Safety considerations gave rise to yet additional design changes. A preliminary nuclear safety assessment, performed to demonstrate compliance with guidelines for a U.S.-based launch, identified the need for several safety features to ensure nuclear safety of the reactor system during the planned mission.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

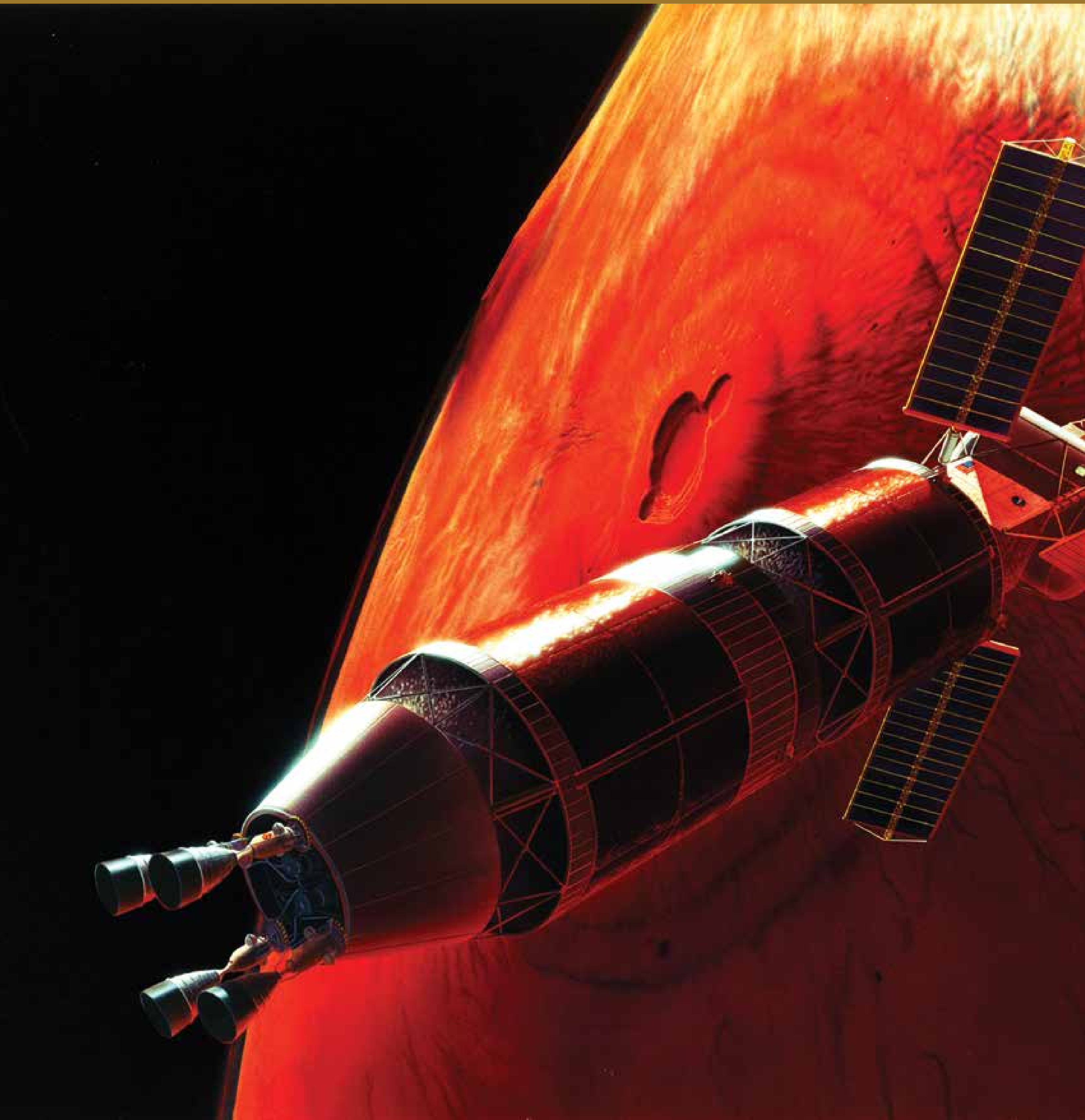
In 1996, the beleaguered TOPAZ-II International Program was officially terminated. The termination came in part due to findings from the GAO audit but also from the lack of a defined DoD or NASA mission and changing priorities within the defense agency. Following its termination, the six TOPAZ-II reactors 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.



8 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]

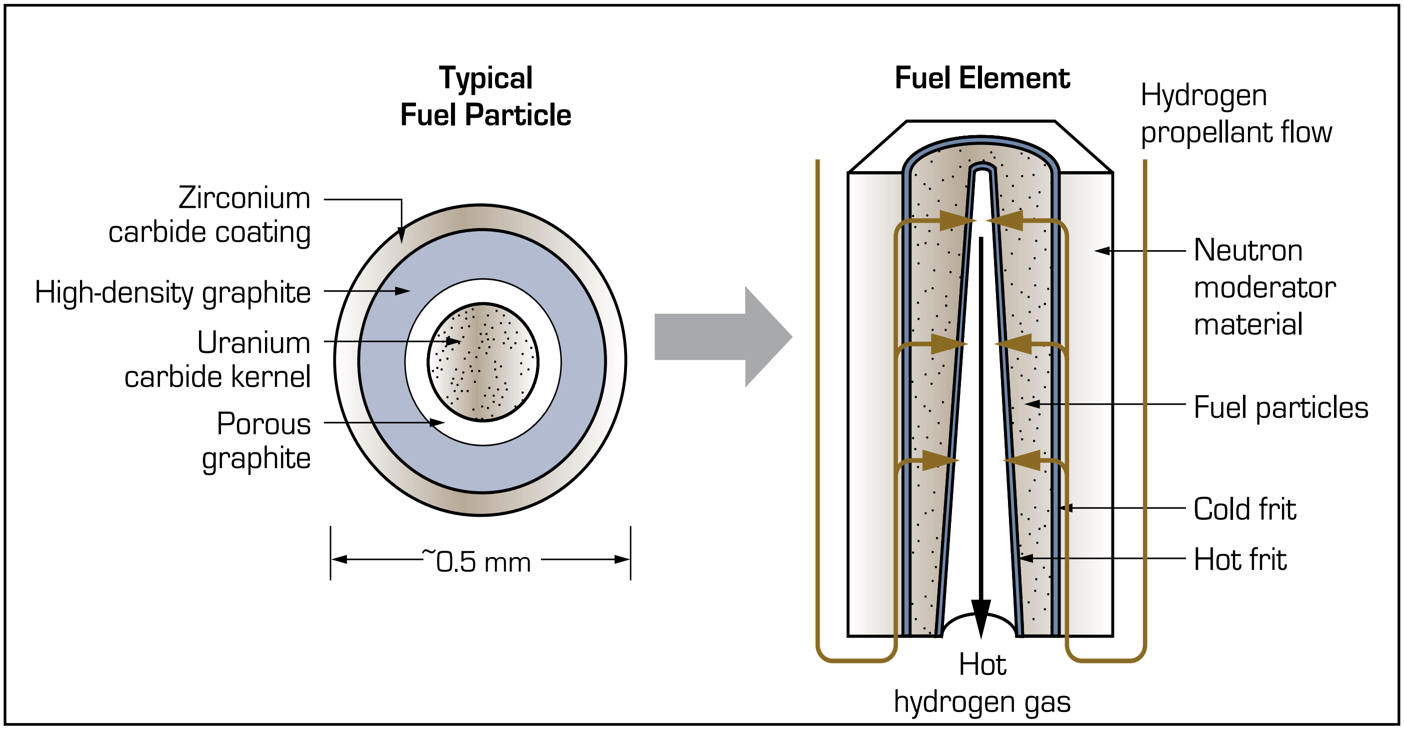
PBR Feasibility

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]

Annular core research reactor at SNL. (Photo: SNL Flickr)

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 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. Of

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.

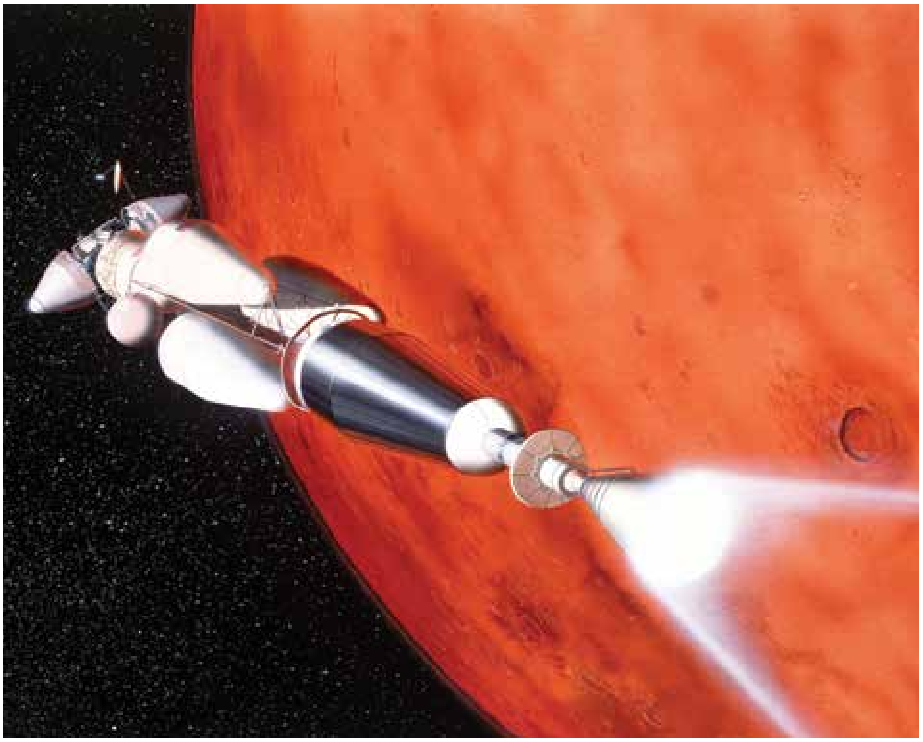
Nuclear electric propulsion systems use a nuclear reactor to generate electricity that provides power to an electric thruster system. Unlike nuclear thermal propulsion systems, nuclear reactors used in electric propulsion systems are designed to operate at lower temperatures over a period of several 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]

interest to Chairman Howard 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.

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

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.

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

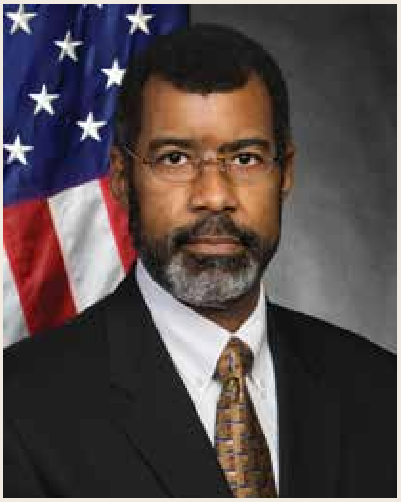
Following the resurgence in space nuclear reactor development between 1983 and 1993, U.S. investment in space reactor research and development largely waned. Although some small study and technology efforts continued, the focus was on solar, chemical, and radioisotope systems to meet the power and propulsion 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]

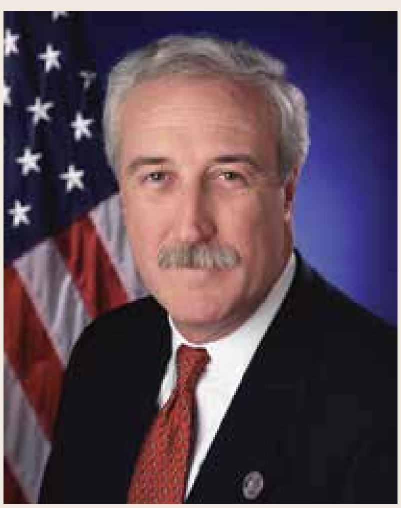
A Project Takes Flight

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 the next breakthough in space exploration, whether human or robotic, would require space nuclear power, as noted years later by John Casani, JPL Project Manager. That conviction gave rise to project Prometheus.[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]

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]

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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

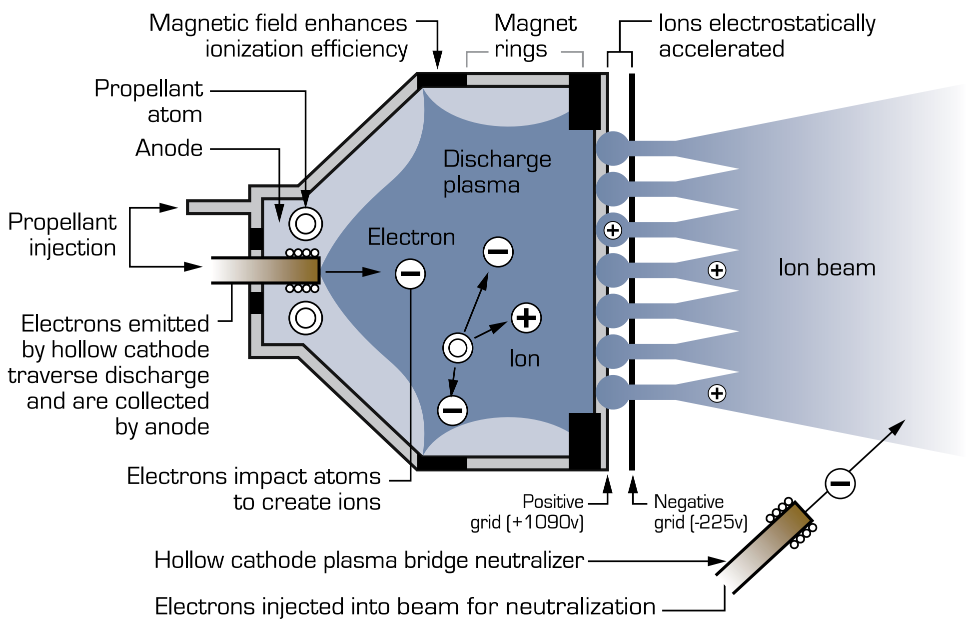
Five candidate reactor plant concepts were eventually developed and evaluated for overall capability, reliability, deliverability, cost, and safety.

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

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

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.

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]

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]

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

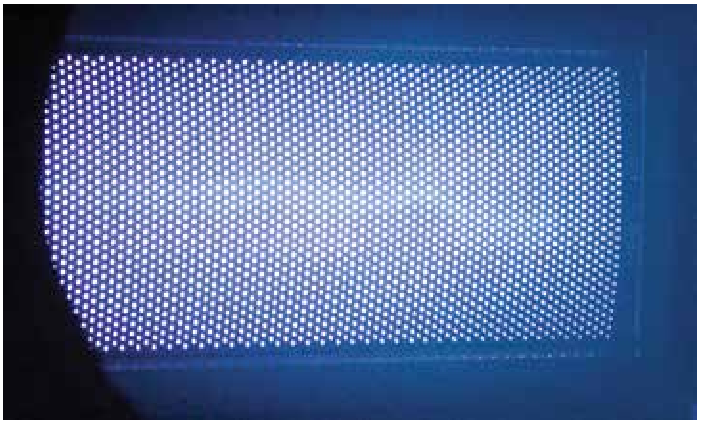
A Vision Fades

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.

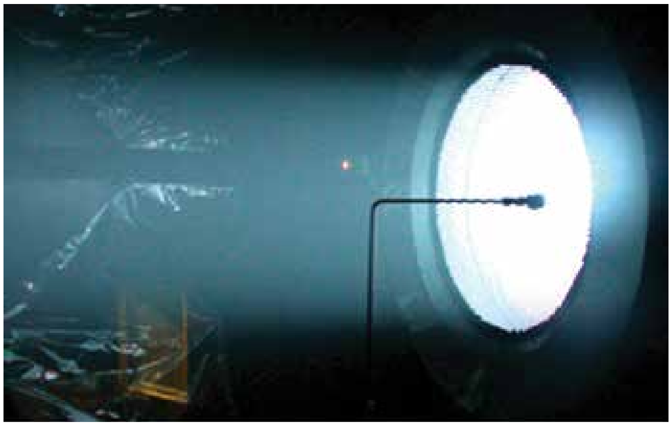
In 2005, after re-evaluating its priorities in light of anticipated budgets, NASA determined that its highest priorities were returning the space shuttles to service, completing the International Space Station, and building the new space vehicle that would replace the shuttle. Those priorities were aligned 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 4,300-volt 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)