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Space Nuclear Power: An Overview

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Nuclear power sources have enabled or enhanced some of the most challenging and exciting space missions yet conducted, including missions such as the Pioneer flights to Jupiter and Saturn; the Voyager flights to Jupiter, Saturn, Uranus, and Neptune; the Apollo lunar surface experiments; the Viking Lander studies of Mars; the Ulysses mission to study the polar regions of the sun; and the Galileo mission to orbit Jupiter. This article surveys the early missions and continues to the present Galileo and Ulysses missions and provides a summary of the power technology that was used in each mission. Current activities aimed at improving the specific power and efficiency of space nuclear power sources are summarized. In addition to radioisotope power sources, this article surveys the U.S. space nuclear reactor program focusing on the flight of the SNAP-10A reactor and the technology developed in the SP-100 space nuclear reactor power system program. The general attributes of space nuclear power sources are described and possible future applications are identified.

Introduction

THE purpose of this article is to provide an overview of the historical use of nuclear power sources in space and to summarize some of the recent programmatic activities. The historical overview will show the wide range of applicability of nuclear power sources such as Earth orbital missions, lunar and planetary surface missions, and outerplanetary and extra-solar-system missions.

Background

Typical electric power source options for space systems include solar (either photovoltaic or thermal-to-electric, such as solar dynamic), batteries, fuel cells, and nuclear (radioisotope or reactor). Generally, the selection of the power source is dictated by the overall requirements of the mission.

Figure 1 is an illustrative example of the qualitative regimes of power source applicability. What the figure shows is that nuclear power sources (NPS) are particularly applicable to long-duration missions and, in the case of reactors, to high-powered missions.

In general, a nuclear power source consists of 1) a nuclear heat source (either a radioisotope heat source or a nuclear reactor heat source); 2) a conversion system [e.g., thermoelectric, thermionic, thermophotovoltaic (TPV), Brayton, Rankine, Stirling, magnetohydrodynamic, or alkali metal thermal-to-electric conversion (AMTEC)], which changes the thermal power into electrical power; and 3) a thermal management system for removing the unused heat. To date, the U.S. has only used thermoelectric converters because of their proven reliability and the lack of a requirement to provide powers high enough to warrant the use of more efficient conversion systems such as turbine-alternators (e.g., Brayton or Rankine cycle), linear oscillators (e.g., Stirling cycle) or advanced static conversion systems (e.g., TPV or AMTEC). (The Russians have reportedly used thermoelectric conversion systems on all but two of their NPS missions.) More information on the state-of-the-art radioisotope thermoelectric generators (RTGs) currently in use on the Galileo and Ulysses spacecraft and planned for use on the Cassini spacecraft will be provided in the next section.

Nuclear power sources are attractive for use in space under a number of conditions:

1) *Lifetime*. Nuclear power is the only currently available alternative to solar power for a spacecraft that must operate for a long period of time (see Fig. 1). Unlike solar cells, reactors can provide essentially constant power over the life of

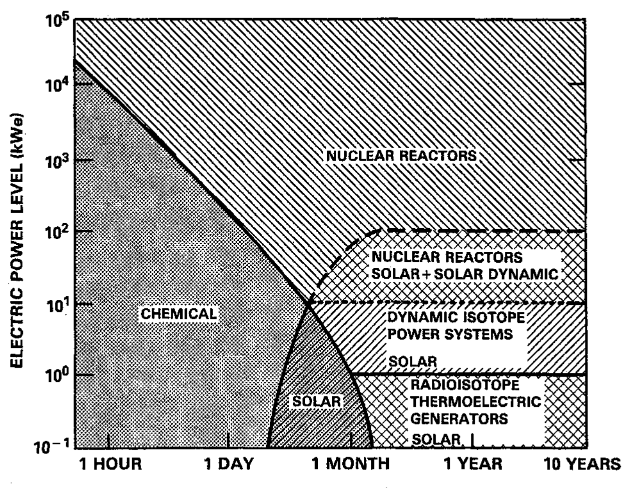

Fig. 1 Diagram of the qualitative regimes (power and duration) where the different space power systems are generally applicable.

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Table 1 Summary of space nuclear power systems successfully launched by the United States

Power source[a]	Number of NPS	Initial average power/NPS, We	Spacecraft (mission type)	Launch date[b] (launch site)	Initial orbit	Status
SNAP-3B7	1	2.7	Transit 4A (navigational)	June 29, 1961 (ETR)	~890 × 1,000 km 67.5 deg, 104 min	RTG operated for ~15 yr. Satellite now shut down but operational.
SNAP-3B8	1	2.7	Transit 4B (navigational)	Nov. 15, 1961 (ETR)	~960 × 1,130 km 32.4 deg, 106 min	RTG operated for 9 yr. Satellite operation was intermittent after 1962 high-altitude nuclear test. Last reported signal in 1971.
SNAP-9A	1	>25.2	Transit 5BN-1 (navigational)	Sept. 28, 1963 (WTR)	~1,090 × 1,150 km 89.9 deg, 107 min	RTG operated as planned. Non-RTG electrical problems on satellite caused satellite to fail after 9 months.
SNAP-9A	1	26.8	Transit 5BN-2 (navigational)	Dec. 5, 1963 (WTR)	~1,080 × 1,110 km 90.0 deg, 107 min	RTG operated for >6 yr. Satellite lost navigational capability after 1.5 yr.
SNAP-10A	1	>500	SNAPSHOT (experimental)	April 3, 1965 (WTR)	1,296 × 1,329 km 90.2 deg, 111.5 min	Reactor successfully operated for 43 days until shutdown by electrical component failure on spacecraft.
SNAP-19B3	2	28.2	Nimbus III (meteorological)	April 14, 1969 (WTR)	1,070 × 1,131 km 99.9 deg, 107 min	RTGs operated for >2.5 yr (no data taken after that).
SNAP-27	1	73.6	Apollo 12 (lunar)	Nov. 14, 1969 (KSC)	Lunar trajectory	RTG operated for ~8 yr (station was shut down).
SNAP-27	1	72.5	Apollo 14 (lunar)	Jan. 31, 1971 (KSC)	Lunar trajectory	RTG operated for ~6.5 yr (station was shut down).
SNAP-27	1	74.7	Apollo 15 (lunar)	July 26, 1971 (KSC)	Lunar trajectory	RTG operated for >6 yr (station was shut down).
SNAP-19	4	40.7	Pioneer 10 (planetary)	March 2, 1972 (ETR)	Solar system escape trajectory	RTGs still operating. Spacecraft successfully operated to Jupiter and is now beyond orbit of Pluto.
SNAP-27	1	70.9	Apollo 16 (lunar)	April 16, 1972 (KSC)	Lunar trajectory	RTG operated for ~5.5 yr (station was shut down).
Transit–RTG	1	35.6	Transit (TRIAD-01-1X)	Sept. 2, 1972 (WTR)	716 × 863 km 90.1 deg, 101 min	RTG still operating.
SNAP-27	1	75.4	Apollo 17 (lunar)	Dec. 7, 1972 (KSC)	Lunar trajectory	RTG operated for ~5 yr (station was shut down).
SNAP-19	4	39.9	Pioneer 11 (planetary)	April 5, 1973 (ETR)	Solar system escape trajectory	RTGs still operating. Spacecraft successfully operated to Jupiter and Saturn and is now beyond orbit of Pluto. Science data return essentially terminated in late 1995.
SNAP-19	2	42.3	Viking 1 (Mars lander)	Aug. 20, 1975 (ETR)	Trans-Mars trajectory	RTGs operated for >6 yr (lander was shut down).
SNAP-19	2	43.1	Viking 2 (Mars lander)	Sept. 9, 1975 (ETR)	Trans-Mars trajectory	RTGs operated for >4 yr (relay link was lost).
MHW–RTG	2	153.7	LES-8 (communications)	March 14, 1976 (ETR)	35,787 km 25.0 deg, 1,436 min	RTGs still operating.
MHW–RTG	2	154.2	LES-9 (communications)	March 14, 1976 (ETR)	35,787 km 25.0 deg, 1,436 min	RTGs still operating.
MHW–RTG	3	159.2	Voyager 2 (planetary)	Aug. 20, 1977 (ETR)	Solar system escape trajectory	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, Uranus, Neptune, and beyond.
MHW–RTG	3	156.7	Voyager 1 (planetary)	Sept. 5, 1977 (ETR)	Solar system escape trajectory	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.
GPHS–RTG	2	287.1	Galileo (Jupiter orbiter)	Oct. 18, 1989 (KSC)	Trans-Jupiter trajectory	RTGs still operating.
GPHS–RTG	1	~282 (power inferred)	Ulysses (solar orbiter)	Oct. 6, 1990 (KSC)	Solar polar orbit	RTG still operating.

[a]SNAP stands for systems for nuclear auxiliary power. All odd-numbered SNAP powerplants use radioisotope fuel. Even-numbered SNAP powerplants have nuclear fission reactors as a source of heat. MHW–RTG stands for the multihundred watt radioisotope thermoelectric generator. GPHS–RTG stands for the general-purpose heat source radioisotope thermoelectric generator.
[b]Key to launching stations: ETR, eastern test range; WTR, western test range; KSC, Kennedy Space Center.

the mission. Radioisotope power sources follow a very predictable slow decay (about 0.8% per year from the natural decay of the plutonium-238 fuel and less than the decay of most solar cells), that is, for most applications, insensitive to the outside environment. Reactors can be automatically controlled to maintain a constant power or a variable power as dictated by the mission requirements.

2) *Environment.* Nuclear power sources are less vulnerable to external radiation (e.g., the radiation belts around Jupiter) and to other potentially hostile environments (e.g., meteoroids, Martian dust storms, and extreme temperatures, such as those experienced on the lunar surface).

3) *Self-Sufficiency.* Nuclear power sources make the spacecraft more mission independent. For example, with NPS there is no need to be concerned about orienting the spacecraft toward the sun for power or using complicated solar concentrators for missions far from the sun. In addition, since RTGs begin producing power the moment they are assembled, RTGs can be operated on the launch pad for systems checkouts prior to launch or in the orbiting Space Shuttle for checkouts prior to separation from the Shuttle.

4) *Operational.* Space NPS have exhibited extremely high reliability; all of the U.S. NPS have met or exceeded their specified prelaunch requirements. NPS provide a compact source of electrical power with a good power-to-mass ratio. The small exposed area of NPS can reduce the overall size of the spacecraft, simplify attitude control, and reduce structural interactions.

Since 1961, the U.S. has flown 41 RTGs and one reactor to provide power for 25 space systems. As shown in Table 1, 38 of these NPS on 22 space systems are still in space or on other planetary bodies. Four of the 41 RTGs were safely returned to Earth following accidents involving the launch vehicles (Transit 5BN-3 and Nimbus-B1) or the spacecraft (Apollo 13). These accidents were in no way related to the RTGs and the incidents showed that the RTGs met their safety design requirements, thereby demonstrating that it is practical to design, build, and launch safe nuclear power sources. Safety has been the principal design requirement on all flight U.S. nuclear power sources from the very beginning of the program in the 1950s.

The U.S. has also used small radioisotope heater units (RHUs) on some of its RTG-powered science missions and on the Apollo 11 science package to keep sensitive instruments at the correct temperature. Three small RHUs are to be used on the upcoming Mars Pathfinder mission. All of the U.S. RTGs have used plutonium-238 as the source of heat because of its long half-life (87.8 years) and its comparatively low level of radiation emission (primarily alpha particles that are easily absorbed in the heat source to produce the heat). The only U.S. space reactor flown used uranium-235 as the fuel.[1] The first RTGs and space nuclear reactors were described by the general title SNAP, an acronym for systems for nuclear auxiliary power. In those early systems the convention adopted was that RTGs were assigned odd numbers and the reactors were assigned even numbers.

The next two sections will provide a summary of the status of U.S. radioisotope and reactor power sources for space applications. Following these two sections is a section providing an overall summary and conclusions.

Radioisotope Power Sources

Radioisotope power sources have been used to provide RHUs and RTGs. As noted in the previous section, it is also possible to use dynamic conversion systems such as turbine-alternators (Brayton or Rankine cycle), linear oscillators (Stirling cycle), or advanced static conversion systems (e.g., TPV or AMTEC) with radioisotope heat sources to provide electric power. Both the dynamic conversion technology and the advanced static conversion technology have been studied in the U.S. and they will be discussed in later paragraphs. In general, for the benefit of the spacecraft designer and scientist, it can be said that the technology in use today will provide radioisotope power sources with specific powers of over 5.3 We/kg and that the technology exists to at least double this value.

RTGs

The U.S. Atomic Energy Commission, predecessor to the U.S. Department of Energy, began development of RTG power sources in the mid-1950s. The historical trend in the use of RTGs on U.S. space systems has been toward improved generator performance, efficiency, and specific power (watts per kilogram). Specifically, this technology development has resulted in improvements in the thermoelectric materials from the telluride-based (generally, lead telluride or Pb–Te) alloys used in the early RTG concepts to the silicon–germanium (Si–Ge) alloy used in the more recent RTGs.[2,3]

The first use of an RTG in space was on the U.S. Navy navigational satellite known as Transit 4A that was launched on June 29, 1961 (see Table 1). The 2.1-kg RTG, known as SNAP-3B, was designed to provide about 2.7 We of auxiliary power for five years. In the case of the Transit 4A satellite and the follow-on Transit 4B satellite these requirements were met. This led to the use of the SNAP-9A RTGs, which were designed to provide 25 We for five years in space, on the next-generation Transit 5BN satellites.[3,4]

The success of the SNAP-9A technology development program led to NASA's use of the higher performance SNAP-19 technology beginning with the Nimbus III meteorology satellite and then on the Pioneer 10 and Pioneer 11 outerplanetary missions. The choice of nuclear power was a natural one considering the early concerns about possible debris in the asteroid belt, the high radiation fields surrounding Jupiter, the low temperatures at Jupiter ($\sim$130 K), and the 25-fold reduction in solar energy flux at the distance of Jupiter relative to the flux at the distance of Earth. The Pioneer SNAP-19 RTGs provided an average beginning-of-mission (BOM) power of 40.3 We at a specific power of 3.0 We/kg and a thermal-to-electric conversion efficiency of 6.2%. The SNAP-19 design was modified to operate on the Martian surface and two SNAP-19 RTGs were used to power each of the two Viking Landers that operated on the surface of Mars beginning in 1976. All of these SNAP-9A and SNAP-19 RTGs used telluride-based alloys in the thermoelectric elements.[3,4]

The Pioneer 10 and Pioneer 11 RTGs (four per spacecraft) have operated successfully for over 22 years, well beyond their original two-year design requirements. These were the first spacecraft to be sent into the outer solar system and then beyond the orbit of Pluto. The early success of the Pioneer 10 RTGs enabled Pioneer 11 to be retargeted for a flyby of Saturn, a bonus for these originally planned Jupiter flyby spacecraft. Pioneer 11 continued providing data for over 22 years after launch out to over 6.4×10^9 km from Earth until forced to cease scientific data transmission because a high-voltage relay could no longer be activated. Pioneer 10, which is now about 9.6×10^9 km from Earth, is the most distant object built by humans and it is still sending back data about the Sun's influence in deep space. Pioneer 10 should have enough power to continue providing data until 1999.[4]

The four 42.7-We (average) RTGs on the two Viking Landers easily met the 90-day requirement for the baseline mission on the surface of Mars and they were still operating up to six years after landing when an erroneous command shut down the last lander in November 1982. Both the Pioneer and the Viking SNAP-19 RTGs first demonstrated the operability and usefulness of RTGs in interplanetary spacecraft.[3,4]

Nuclear power sources were used on each of the Apollo landing missions to the moon. Two 15-W RHUs provided heat for the Early Apollo Scientific Experiment Package (EASEP) left on the moon by the Apollo 11 astronauts in July 1969. These RHUs kept the EASEP warm through the long (14-Earth-day) lunar night. The subsequent Apollo flights each carried an RTG, the SNAP-27, which was designed to produce

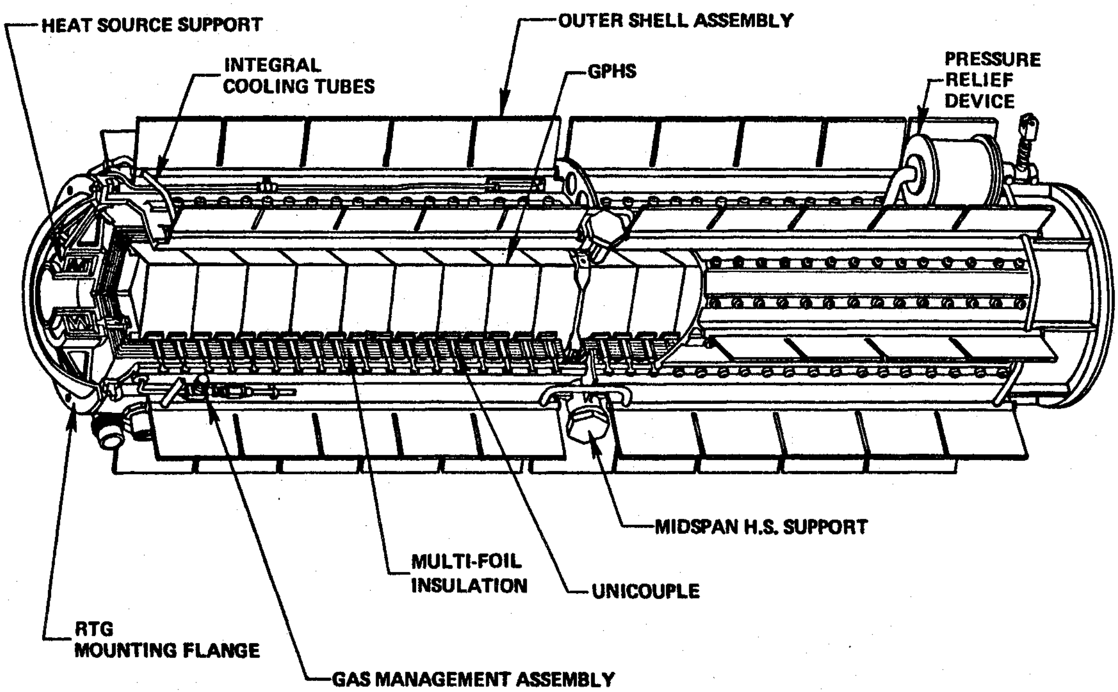

Fig. 2 Cutaway diagram of the general-purpose heat source radioisotope thermoelectric generator (GPHS-RTG) as used on the Galileo and Ulysses spacecraft. The GPHS-RTG consists of 18 GPHS modules inside a converter with 572 SiGe alloy thermoelectric elements (unicouples). Overall diameter with fins is 42.2 cm, and length is 114 cm. The average mass of a GPHS-RTG is about 55.9 kg. At the time of radioisotope fueling the GPHS-RTG can produce over 300 We.

at least 63.5 We during the first year of operation for the Apollo Lunar Surface Experiments Package (ALSEP). All of the RTGs exceeded their mission requirements in both power and lifetime. This performance was achieved by the RTGs despite the variable duty cycle and the temperature extremes of the lunar day–night cycle. All five RTG-powered ALSEPs were operating when NASA shut down the stations on Sept. 30, 1977 for budgetary reasons.[3,4]

A variant on the telluride–alloy thermoelectric technology was employed on the Transit RTG that was flown on the Navy TRIAD navigational satellite launched on September 2, 1972. The Transit RTG heat source was based on the SNAP-19 design, but the conversion system consisted of a series of panels using Pb–Te thermoelectric elements that could operate without the cover gas sealed within the SNAP-19 generator. The Transit RTG operated well beyond its five-year requirement, enabling the Navy to perform a number of navigational and scientific experiments.[1,3,4]

RTG technology took a dramatic turn upward with the launch on March 14, 1976 of the two U.S. Air Force (USAF) experimental communications satellites LES 8 and LES 9 (Lincoln Experimental Satellite). LES 8 and 9 were the first spacecraft to use the new, >150-We multihundred watt (MHW) RTG, which employed 312 SiGe-alloy thermoelectric elements (called unicouples) per RTG. The LES 8 and 9 satellites required 125 We per RTG with an output voltage of 26 V at the end of mission (EOM), an operational life of at least five years after launch. Each spacecraft carried two RTGs. These RTGs are still operating over 20 years after launch, which enabled LES 9 to be used during the Gulf War and for recent communications with a polar exploration team.[3,4]

While LES 8 and 9 provided the first use of the MHW-RTGs, Voyager 1 and 2 provided the most publicly dramatic use of this technology. Launched on Sept. 5, 1977 and Aug. 20, 1977, respectively, these two spacecraft are still operating well beyond their original four-year requirement thanks to the outstanding performance of the three MHW-RTGs on each spacecraft. The success of the MHW-RTGs enabled Voyager 2 to perform an extended mission to Uranus and Neptune. Now both spacecraft are exiting the solar system. The Voyager MHW-RTGs averaged 158 We at the beginning of mission (BOM) with a conversion efficiency of 6.6% and a specific power of 4.2 We/kg.[3,4]

The success of the LES 8 and 9 and Voyager 1 and 2 missions led to the use of the SiGe-alloy technology in the higher-powered RTGs now in operation on the Galileo and Ulysses spacecraft and planned for use on the Cassini spacecraft that is scheduled to be launched in 1997. Figure 2 is a cutaway of this RTG, which is termed the general-purpose heat source (GPHS) RTG, showing the positioning of the 18 modules comprising the GPHS within the converter assembly. Like the MHW-RTG, the heat is transported radiatively from the heat source to the thermoelectric elements of the converter; there is no contact between the heat source and the thermoelectric elements. Figure 3 shows the location of the two GPHS-RTGs on the Galileo spacecraft and Fig. 4 shows the location of the single GPHS-RTG on the Ulysses spacecraft. The power requirement for the Galileo RTGs as revised because of launch delays following the Challenger accident is to provide 470 We (235 We per RTG) at EOM (71,000 h after BOM). In the case of Ulysses the revised power requirement is to provide 245 We after 42,000 h. However, at the time of fueling, the GPHS-RTG can provide over 300 We at a specific power of over 5.3 We/kg.[2,4]

Reference 2 provides more information on the testing of the GPHS-RTG. The two GPHS-RTGs in use on the Galileo spacecraft and the one GPHS-RTG on the Ulysses spacecraft have met all power performance requirements to date and they are expected to meet their remaining power performance requirements. Three GPHS-RTGs are planned to be used on the Cassini spacecraft that is to orbit Saturn.

In general, the flexibility of RTGs that can provide powers from milliwatts to close to a kilowatt provides the spacecraft and science community with a proven source of long-lived power.

Improved Static Conversion Systems

Improvements in radioisotope power source conversion system performance have been studied for a range of future missions. The static conversion system concepts have included the

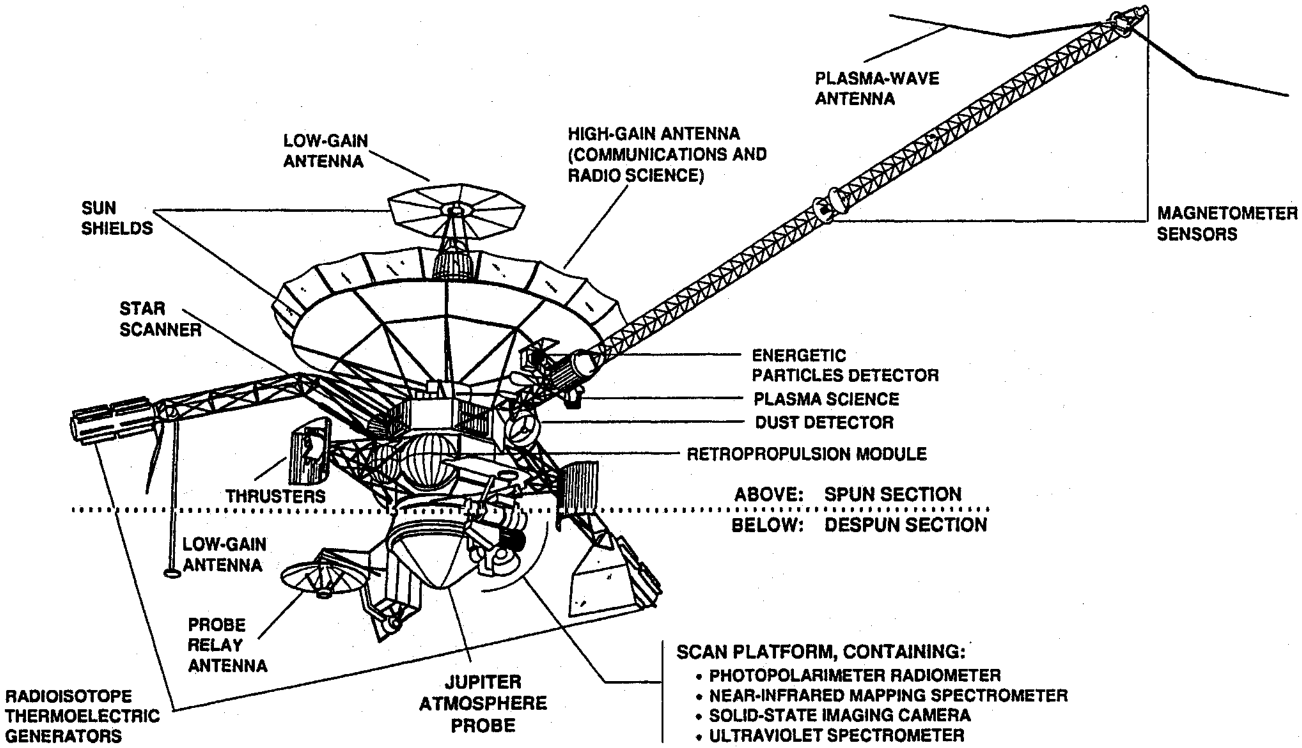

Fig. 3 Diagram of the Galileo spacecraft orbiter and probe with the two GPHS–RTGs shown mounted on the two booms.

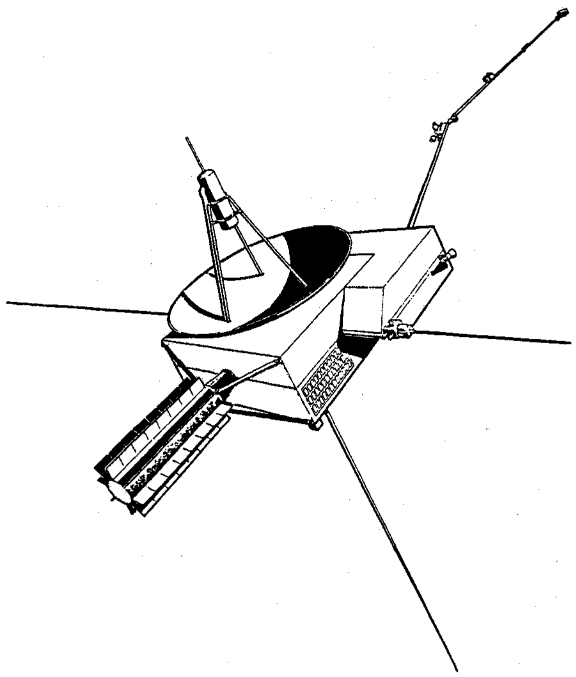

Fig. 4 Diagram of the Ulysses spacecraft with the GPHS–RTG mounted on the side.

use of advanced thermoelectric materials; thermophotovoltaics or TPV [essentially infrared-sensitive solar cells such as gallium antimonide (GaSb) photovoltaic cells used in the radioisotope power source in place of thermoelectric elements]; and alkali metal thermal-to-electric conversion or AMTEC [essentially a thermally regenerated sodium concentration cell that uses beta″-alumina solid electrolyte (BASE) in effect to separate sodium ions and electrons, the latter traveling through an external circuit to produce the power].[5–7]

For example, a number of options have been examined for the proposed Pluto Express mission showing the advantages of radioisotope power for this challenging mission and that specific power improvements ranging from double to triple that of the GPHS–RTG can be achieved with improved conversion technologies.[5–11] As currently defined, the proposed Pluto Express Sciencecraft, which, for planning purposes, is assumed to have a launch date in 2001, will require 74 We at EOM (~12 years after launch), although it would be desirable to have 104 We.[7,8] The mass of the power source should be no greater than 9.5 kg.[6,8] Preliminary studies show that radioisotope-heated TPV and AMTEC power sources can meet these goals with masses in the range of 8 kg while state-of-practice thermoelectric unicouples would lead to an RTG with a mass on the order of 18 kg.[5–13] Experimental studies are under way to determine if TPV and AMTEC will meet these projections. In the next section a Stirling option for Pluto Express will be discussed.

Recently, a study has been completed of a small (20-We) radioisotope TPV system that could be integrated with NASA's proposed New Millennium spacecraft. Depending upon the desired parameters, a 20-We radioisotope TPV system could come in with a mass under 2 kg and a specific power in the range of 12 We/kg.[14]

For comparison purposes, an advanced solar photovoltaic/battery power system would have a specific power in the range of 10 We/kg in Earth orbit[15] and end-to-end orbital efficiencies in the range of 4%.[16] Thus, existing and advanced radioisotope power sources are competitive with advanced solar photovoltaic/battery power systems at 1 AU from the sun. As a spacecraft is sent beyond 1 AU, the decreasing solar energy flux (which falls off as the reciprocal of the square of the distance) rapidly makes the nuclear option the best (and often the only) choice from a mass, volume, efficiency, and operational viewpoint.

Dynamic Isotope Power Systems

The foregoing section described static conversion systems in which there are no moving parts. System efficiencies for such static conversion systems typically are in the range of 5–10% (with some advanced concepts going to 15–20%). The dynamic isotope power system (DIPS) was originally devel-

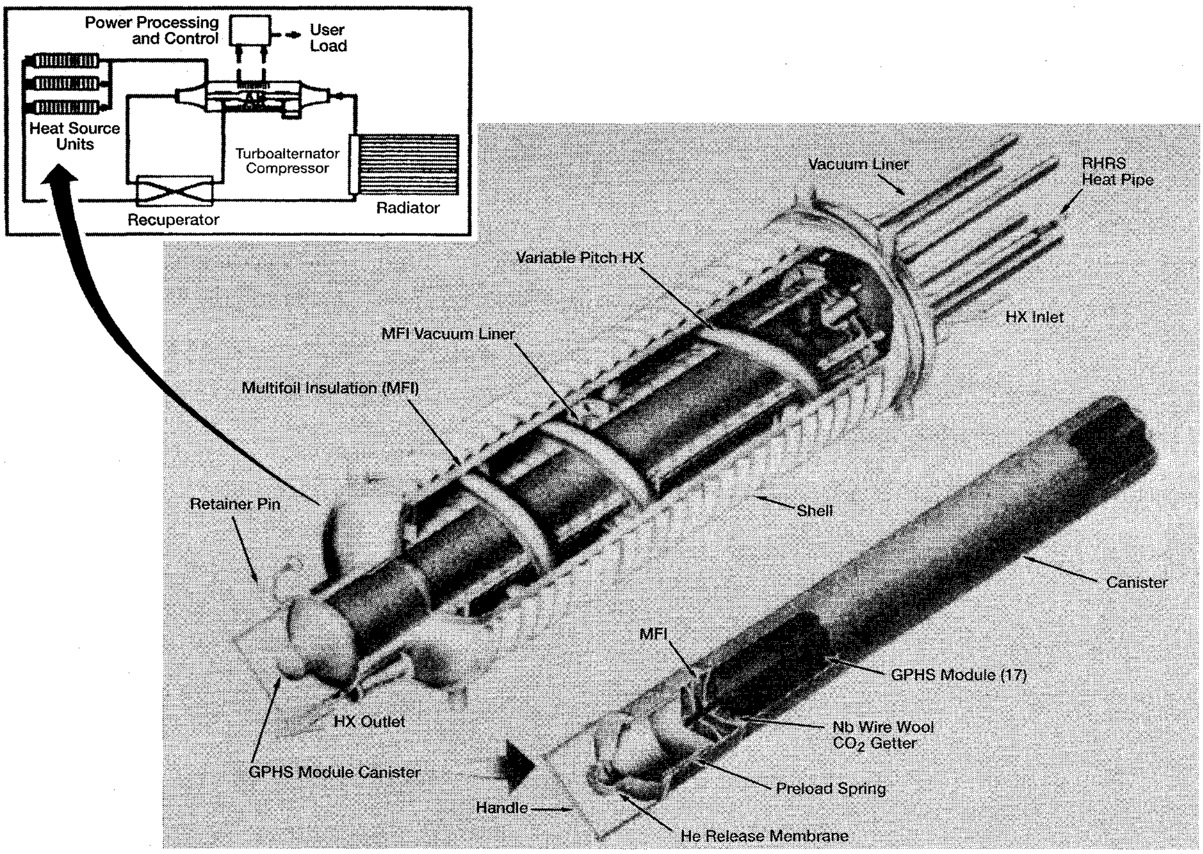

Fig. 5 Cutaway view of the HSU for a 2.5-kWe closed Brayton cycle DIPS. The HSU is designed to provide sufficient thermal power (~4.1 kWe or 17 GPHS modules) for the power conversion assembly to generate approximately 1 kWe. The working gas is heated by the HSU as it passes through a helical coil, variable pitch heat exchanger on the way to the turbine–alternator–compressor.

oped to improve the efficiency of thermal-to-electric conversion by at least a factor of 2, and perhaps 3, compared to current thermoelectric systems, and so reduce the mass (and fuel inventory) for higher-powered missions requiring radioisotope power sources. The dynamic conversion is achieved by using a conversion system based on moving parts such as a rotating turbine–alternator (Brayton cycle or Rankine cycle) or linear oscillator (Stirling cycle). In general, the Brayton and Rankine cycles show their best efficiencies at higher powers while the Stirling cycle scales down nicely with good efficiency to lower powers. Studies have shown that DIPS is the lowest mass nuclear power option in the range from about 1 to at least 10 kWe.[17]

In the mid-1970s the Department of Energy (DOE) sponsored studies of the Brayton and Rankine systems for possible application to Department of Defense (DoD) and NASA missions that required increases in power conversion efficiency for reduced mass and volume. Ground demonstration systems of both conversion cycles were built and tested, proving the basic designs.[18,19] The Rankine cycle was selected for further development at that time, although when the program was restarted in 1987, the Brayton cycle was selected.[20] Both cycles have extensive technology development dating back to the early 1960s, including thousands of hours of operation.[21] Because of this background of feasibility demonstration and technology development, the dynamic conversion systems are judged more mature than the advanced static conversion systems described in the preceding section.

While the second DIPS program was stopped for financial reasons and changing national priorities in the early 1990s, the Brayton cycle, which is a key element of DIPS, is currently being tested in a simulated solar heated mode as part of the Space Station program.[16] The results to date have been very encouraging.[22] System studies have shown that both the Brayton and organic Rankine systems are equally advantageous when compared against solar-array/battery power in the context of the total spacecraft design.[23] A special design study showed that an optimized 2.5-kWe DIPS module could meet a range of applications on the lunar and Martian surface.[24] Figure 5 illustrates a 2.5-kWe power module heat source unit (HSU) for a Brayton DIPS.[25]

Separately, NASA has sponsored research on free-piston Stirling power converters.[26] In a recent study showing the benefits of small Stirling engines to the proposed Pluto Express (then called the Pluto Fast Flyby or PFF) mission it was noted that (Ref. 27)

> Stirling engines, like other dynamic systems offer much higher conversion efficiencies than thermoelectric systems. Tripling or quadrupling the efficiency of current RTGs would greatly reduce the cost and mass of the required fuel loading. Unlike other dynamic conversion systems, Stirling engines retain their high efficiencies at very low output powers, which is important for low-power applications like PFF.

The mass of a radioisotope Stirling system using four Stirling engines for redundancy would be about 12 kg for a mission like Pluto Express compared to about 18 kg for the mass of an equivalent state-of-practice thermoelectric system.[11] While this is a greater mass than equivalent TPV or AMTEC systems, it must be noted that the Stirling technology is much more mature. EOM system efficiencies on the order of 23% can be achieved and EOM specific powers of over 8 We/kg are predicted.[11]

Based on work undertaken in a number of programs, the technology to provide radioisotope dynamic power systems has been developed. Various studies have shown that radioisotope dynamic power systems are an attractive power source for future NASA missions such as outerplanetary spacecraft and lunar and Martian rovers.[11,24,27] Radioisotope dynamic power systems also represent the next logical step in increased NPS power beyond radioisotope power sources using static conversion.

Reactor Power Sources

For higher powers (≥10 kWe) and/or for special applications space nuclear reactor power systems are the preferred NPS option. Nuclear reactors can be used to power electric propulsion systems, thereby enabling or enhancing whole new classes of science missions such as outer planet orbiters and grand tours of the satellites of the outer planets. Over the years a number of technologies have been examined; however, in the interests of technical focus the following sections will discuss the most mature U.S. space reactor technologies: SNAP-10A and SP-100. The reader interested in other technologies is advised to review the various proceedings or transactions of the annual symposia on space nuclear power and propulsion that are currently being published by the American Institute of Physics. The Russians have used mostly reactors (with thermoelectric conversion except for two experiments involving thermionics) in their NPS missions and some of the thermionic technology is beginning to become available to the U.S.[28]

SNAP-10A Reactor Flight

SNAP-10A, which was the first nuclear reactor to be flown in space, was placed into a 1288- by 1307-km polar orbit by an Atlas/Agena launch vehicle on April 3, 1965. Included among the objectives of the SNAP-10A flight test program were to[29] 1) demonstrate, proof test, and flight qualify SNAP-10A for subsequent operational use; 2) demonstrate the adequacy and safety of ground handling and launch procedures; and 3) demonstrate the adequacy and safety of automatic reactor startup in orbit.

Figure 6 shows a cutaway of the SNAP-10A reactor system that had the shape of a truncated cone with an overall length of 3.48 m and a mounting base diameter of 1.27 m. This configuration was dictated by minimum mass shield requirements, especially the requirement to eliminate neutron scattering around the steel-reinforced lithium hydride shadow shield. The base diameter was established by the Agena launch vehicle payload and the upper diameter was determined by the effective area of the reactor. The length was determined by the total radiator area requirement. The power conversion system basically consisted of 2880 Si–Ge thermoelectric elements. The total system mass of the final flight unit (known as FS-4) was 435 kg, including the shield. The reactor was to provide not less than 500 We with a one-year operating lifetime.[29]

The automatic startup of SNAP-10A was accomplished flawlessly. Net power output ranged from a transient high of 650 We in the early part of the mission to a low of 527 We in the sun after 43 days. On May 16, 1965, after 43 days of successful operation, the reactor was shut down by a spurious command caused by a failure of a voltage regulator on the Agena unregulated bus. There was no evidence of any malfunction in the SNAP-10A system. The FS-3 ground test twin to FS-4 successfully operated at full power for 10,000 h, thereby demonstrating the capability of SNAP-10A to operate unattended for a year.[29]

The SNAP-10A reactor successfully completed most of its objectives, including the following significant achievements[29]: 1) first application of a nuclear reactor in space, 2) first development of a reactor thermoelectric power system and the first use of such a system in space, 3) first remote automatic startup of a nuclear reactor in space, 4) first application of a high-temperature (810 K) liquid metal transfer system in space and the first application of a high-temperature spacecraft in space, 5) first use of a nuclear shadow shield in space, 6) development and application of the highest powered thermoelectric power system to that time and the first use of a thermoelectric power system of that size in space, and 7) first

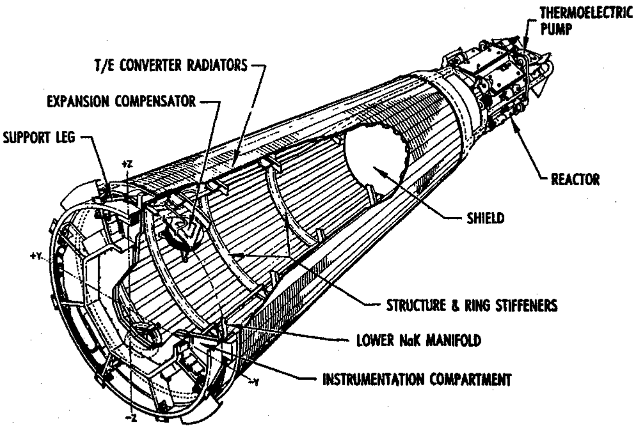

Fig. 6 Cutaway of the SNAP-10A space nuclear reactor system. (Note: the term T/E stands for thermoelectric.)

thermoelectric powered liquid metal pump and the first use of such a pump in space.

The SNAP space reactor program included other reactor concepts that would have led to higher powers, improved efficiencies, and increased specific powers; however, changes in the national space program in the early 1970s prevented any of these concepts from reaching flight status. Nevertheless, the technology base was there to support much improved reactor power sources for space applications.

SP-100 Space Reactor Power System

The SP-100 space reactor power system technology development program was carried out from 1983 to 1994 with a goal to develop a space nuclear reactor technology that could support a range of projected future missions including planetary surface operations and nuclear electric propulsion for science missions. The generic flight system (GFS) configuration shown in Fig. 7 was established to support operational missions requiring relatively high power (100 kWe class) for 10-year mission durations, but scalable from about 10 to 1000 kWe and with high specific power. The diameter and length of the main body (less the radiator panels) are 3.5 and 6 m, respectively, and the design mass is 4575 kg for the 100-kWe GFS. A deployable boom is used to maintain a separation distance of 22.5 m between the reactor and the payload plane to keep the neutron and gamma doses within specified values. First-generation technology is available to support near-term science missions requiring powers in the range of 20–40 kWe. Depending upon the technology and power level, the SP-100 design has projected specific powers ranging from 8 We/kg (current technology at 20 kWe) to 26 We/kg (mature thermoelectric technology at 100 kWe).[30,31]

As shown in Fig. 7, the SP-100 space reactor power system GFS is composed of two major assemblies[30]:

1) The Reactor Power Assembly, including the lithium-cooled reactor, reactor instrumentation and control (I&C) components, radiation shield, and forward portions of the primary heat transport subsystem (PHTS) and auxiliary cooling and thaw (ACT) hydraulic loops.

2) The Energy Conversion Assembly, consisting of 12 pump/power converter assembly (PCA) thermoelectric segments, 12 fixed radiator panels, and a supporting structure.

The advantage of the SP-100 approach is that it places the conversion system external to the nuclear reactor (the source of heat and radiation) so that the converter is not overly stressed and, perhaps more importantly, it allows for the interchange of different conversion systems (e.g., thermoelectric, Brayton, Rankine, Stirling, TPV, AMTEC, and out-of-core thermionic), depending upon application and power requirements.

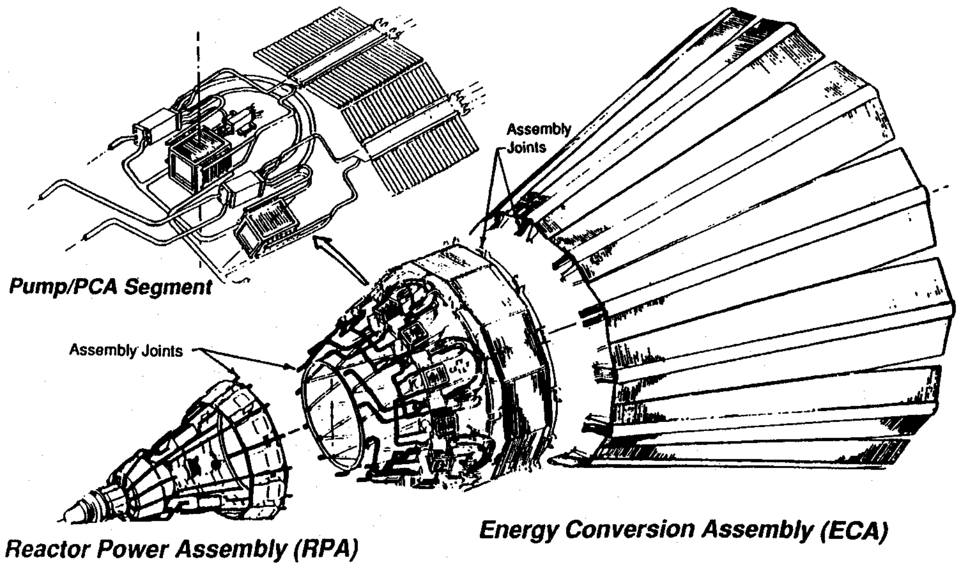

Fig. 7 System physical configuration of the SP-100 space nuclear reactor power system.

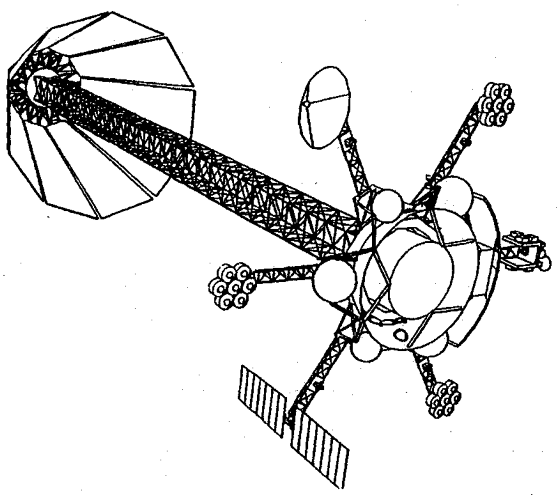

Fig. 8 Possible configuration for a spacecraft using a 40-kWe version of the SP-100 space nuclear reactor power system to power axially thrusting ion engines on a planetary spacecraft. The SP-100 reactor is shown in the upper left, and the spacecraft with ion thrusters is shown in the lower right. The boom provides separation between the reactor and the spacecraft to minimize the radiation dose (and to minimize the mass of the reactor shield).

Of particular interest to the planetary science community is the capability provided by the SP-100 technology to perform a range of missions that are generally not possible with other existing technologies. Figure 8 shows one possible configuration for a nuclear electric propulsion (NEP) planetary science mission.[31] Coupling SP-100 with ion thrusters allows near-term payloads of over 2000 kg to be used in a Mars orbiter with Phobos and Deimos rendezvous, multiple main belt asteroid exploration, and asteroid sample returns. Using more mature technology with powers up to 100 kWe, missions such as the Jupiter minigrand tour, Saturn ring rendezvous, Uranus orbiter/probe, Neptune orbiter/probe, and Pluto orbiter/probe can be accomplished with payloads up to 2000 kg.[31]

By 1993, the SP-100 program had essentially completed most of its nuclear component performance development phase, including validation of the critical technologies and fabrication techniques required to build a space reactor power system. Most of the component development work for the nuclear subsystem (the reactor, reactor instrumentation and control, and shield) and space subsystem (the converter, heat transport, and heat rejection) was completed. The reactor design and computer codes were verified through cold critical testing in the Zero Power Physics Reactor and through separate hydraulic tests. All of the uranium nitride fuel pellets for a 100-kWe space reactor thermoelectric power system were fabricated.[32,33] Tests of the high-power conductively coupled thermoelectric multicell are continuing, showing that the basic concept is feasible and that it is an improvement over unicouple thermoelectric designs.[34] A number of the technologies developed in the SP-100 program have applications to industrial and government programs.[35]

Additional U.S. Space Reactor Programs

From 1985 to 1990, the DoD and DOE sponsored a program called the Multimegawatt Program to develop electric power in the range from tens of megawatts to hundreds of megawatts for neutral particle beams, free electron lasers, electromagnetic launchers, and orbital transfer vehicles. Most of this work focused on design studies and limited fuel testing.[36]

In 1992, DOE and DoD initiated a program to develop the technology for a 40-kWe thermionic reactor power system. Two concepts were selected, one building upon the Russian TOPAZ (called TOPAZ I in the U.S.) multicell thermionic converter technology and the other building upon the Russian ENISY (called TOPAZ II in the U.S.) single-cell thermionic converter technology. (TOPAZ I and TOPAZ II were designed to provide about 5–6 kWe.) The 40-kWe thermionic reactor program also built upon an earlier thermionic fuel element (TFE) verification program initiated in 1986 to resolve the technical issues that contributed to the nonselection of thermionic conversion for the SP-100 space nuclear reactor program.[36]

In parallel with the foregoing thermionic activities, DoD initiated in 1990 the Thermionic System Evaluation Test (TSET) program [later called the TOPAZ International Program (TIP)]. Under this program U.S. and Russian researchers have assembled a Russian-built, electrically heated (i.e., nonnuclear) TOPAZ II reactor system for testing and for training U.S. experts on the operation of space nuclear power systems.[37] Before any flight, modifications to the TOPAZ II design would be needed to meet U.S. standards. Both TOPAZ I and TOPAZ II are limited in lifetime and performance, having lifetimes, conversion efficiencies, and specific powers that are less than U.S. RTGs or the proposed U.S. SP-100 space nuclear reactor power system.[36]

Evaluations are proceeding on bimodal nuclear reactor powerplants that can perform both power and nuclear thermal propulsion functions within a single nuclear reactor for a space vehicle.[38,39] Among the desired characteristics of a bimodal powerplant would be a mass ≤1000 kg for 10 kWe and ≤2000 kg for 20 kWe with a thrust of 80 N and a specific impulse of 7.5 km/s (770 lbf-s/lbm).[38] Such a bimodal system may allow 1) the use of smaller, cheaper launch vehicles through the use of improved orbital transfer and on-orbit maneuvering propulsion and 2) increased satellite capabilities through the availability of higher power.[39]

Summary and Conclusions

The successful use by the U.S. of 38 NPS on 22 space systems has clearly demonstrated the reliability and performance of NPSs. NPSs have successfully operated for over 22 years in space and they are the only viable option available for missions to the outer planets and/or in hostile environments. NPSs with specific powers greater than 5.3 We/kg have been flown and near-term technologies can double or triple that value. NPS technology is available to support a wide range of proposed science missions, including scientifically exciting missions such as outer planet orbiters and probes. In many cases these missions can only be accomplished with NPSs.

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