Space Reactors, A Prospective for the Future

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ABSTRACT

The power requirements for future space missions are increasing and alternate power systems will be required to meet these needs. Therefore, in the early 1980's a tri-agency space reactor program, the SP-100, was initiated that is capable of meeting the higher power requirements. To understand the current space reactor program, it is important to review it in the context of past space nuclear programs--including radioisotopes, nuclear rockets and reactors. Initial effort on these programs began in the mid-1950's. Radioisotope generators have been flown on a variety of missions and are continuing to be used. The space reactor and nuclear rocket programs were technically successful but were both terminated in 1973. The current SP-100 program builds on those earlier programs.

INTRODUCTION

In October 1983, the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE) signed a Memorandum of Agreement to jointly pursue the development of a space reactor for the power range of 10's to 100's of kilowatts-electric (kWe). The program was named the SP-100. To fully understand the current program it is important to review the past space nuclear programs. Figure 1 shows the development of those programs as a function of time. The radioisotope program, and the past nuclear rocket and space reactor programs are described, followed by a summary of the current space reactor development programs.

SPACE NUCLEAR ISOTOPE POWER SYSTEMS

Isotope power systems derive their energy from the natural decay of radioisotopes and the energy is converted into electrical energy through the use of either static or dynamic power conversion systems. Although the system derives its energy from radioactive decay and not nuclear fission, the isotope material is a product of nuclear fission and therefore is briefly covered in this paper. The isotope power systems are referred to as radioisotope thermoelectric generators (RTGs).

The United States has used 34 RTGs as electrical power supplies for 19 space applications between 1961 and 1977 in support of both the NASA and DoD[1]. Figure 2 illustrates the development history of the RTG program. The technology and design of the RTGs have evolved over the last 25 years as higher power systems have been attained through advancements in the technology. The beginning-of-life power output has been increased since the first unit launched in 1961 from 2.8 watts to the 285 watts produced by current systems. RTGs have enabled many key space missions which would not have been possible without the autonomous operation of the radioisotope system and have played a significant role in the exploration of space.

The RTG program began in 1955 upon a request by DoD to the AEC to begin work on space nuclear power systems for potential Air Force (AF) applications. The Space Nuclear Auxiliary Power (SNAP) program was initiated to develop both isotope and reactor power systems. The even-numbered SNAP systems were reactors and the odd-numbered were radioisotope systems. To help place this in historical context, it was not until 1957 that the Soviets launched the first satellite, Sputnik. In 1956 the AEC initialized a low level effort at the Martin Company to develop an isotope power system for military satellites.[2] Over the past thirty years RTGs have been designed and built by both the Martin Company (currently Teledyne) and General Electric. The RTGs used in space have used Pu-238 fuel with thermoelectric power conversion systems.

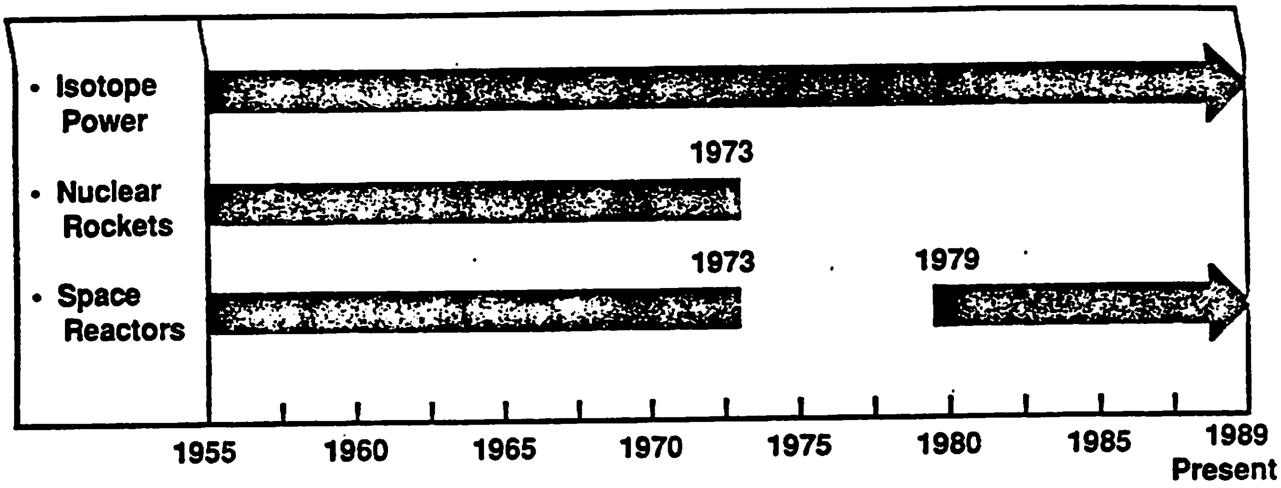

FIGURE 1. PAST SPACE REACTOR HISTORY

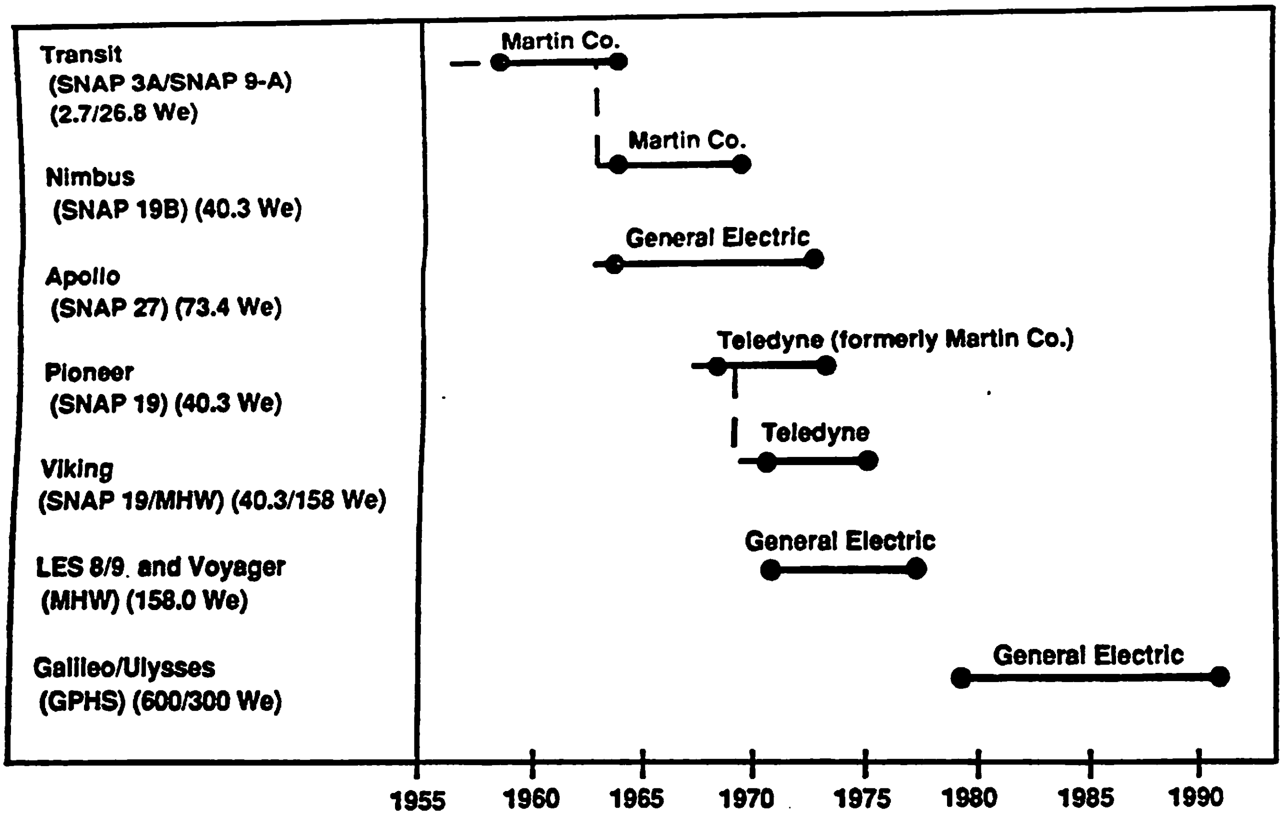

FIGURE 2. ISOTOPE POWER SYSTEMS

The first SNAP isotope system, SNAP-3A, was successfully launched on board a Navy TRANSIT 4A navigational satellite. From 1961 to April 1964, SNAP-3A and SNAP-9A RTGs were used on five Navy Transit navigational satellites. A redesigned RTG was later used for a Naval Transit mission in 1972. A SNAP-19B RTG was used on the NASA Nimbus-III Meteorological satellite in 1969. SNAP-27 RTGs were used to power experimental packages on the lunar surface which were launched aboard the Apollo spacecrafts: Apollo 12, Apollo 13 (mission aborted), Apollo 14, Apollo 15, Apollo 16, and Apollo 17. The SNAP-19 RTGs were used to power the NASA outer planetary spacecraft Pioneer 10 and 11, and the Viking 1 and 2 launched between 1972 and 1977. The Multi-Hundred Watt (MHW) RTGs were used for the AF communication satellites LES 8 and 9, and the NASA outer planetary spacecraft Voyager 1 and 2.[2] An advanced RTG system, the General Purpose Heat Source (GPHS) will be launched with the Galileo and Ulysses spacecraft in 1989 and 1991 respectively.

The RTG program has had the greatest success of all nuclear power systems slated for use in space because of their simplicity and low mass and because in many cases, such as deep space exploration, RTGs represented the only viable solution.

PAST NUCLEAR ROCKET PROGRAM

The nuclear rocket program began in 1955 and ended in 1973 as shown in Figure 3. A total of 21 nuclear reactors were ground tested under the nuclear rocket program and substantial work was completed in the area of nuclear safety. The program ended in 1973 primarily due to a change in national priorities. An estimated total of $1.2 billion dollars was expended on the development and testing of the nuclear rocket systems.

One of the greatest challenges faced by the nuclear rocket program was not the development of technology, but rather trying to continue a viable program in the face of changing program requirements. The initial system required 15 to 30 minutes full power operation, yet, as the program requirements changed commensurate with the changing missions, the final program required 6 to 10 hours of operation with capability for several restarts. The research and development was subjected to the political environment in anticipation of a firm requirement.[3] The ratcheting of program direction offered less time to focus on a single design but resulted in a much broader technology base at the end of the program.

The missions for the nuclear rocket evolved from the initial AF Intercontinental Ballistic Missile (ICBM) to NASA missions including: the second stage for a lunar flight, manned Mars flight, orbit-to-orbit transfer,[4] the Saturn V third stage for unmanned planetary probes, nuclear flight propulsion module (LFPM) for a lunar logistic carrier and a reusable nuclear shuttle.[5] The primary impetus for the development of the nuclear rocket was its ability to provide an increase in specific impulse which in turn provides a substantial increase in deliverable payload mass. Specific impulse is defined as the effectiveness by which propellant flow is converted into thrust.[6] The nuclear rocket has roughly twice the specific impulse of the best chemical rocket.[4] It was predicted that using a nuclear rocket could provide 70% improved payload performance for low velocity missions compared to a chemical system, and would reduce the transportation costs for a reusable earth-to-orbit shuttle.[5] The program support was based upon these large potential gains over conventional chemical systems.

The nuclear rocket program was officially initiated in 1955. Both Los Alamos National Laboratory (LANL) and Lawrence Livermore Laboratory (LLL) were funded to investigate the design and construction of a nuclear rocket capable of meeting the ICBM design requirements. The program was given the code name Rover.

Work continued at both LLL and LANL laboratories until 1957 when DoD recommended that the AEC lower the funding and change the program objectives from concentrating on a single mission to one capable of meeting many missions. This change was primarily due to the earlier than anticipated availability of chemical ICBM's.[4] In response to the reduction in funding the program was reduced to a single laboratory. LANL was given the sole responsibility for Rover. LANL concentrated their efforts on a hydrogen cooled, graphite reactor.

The first proof-of-concept test reactor series was termed Kiwi after the flightless New Zealand kiwi bird. The Kiwi reactors were not designed as flight units, but rather were concept feasibility and test reactors. The Kiwi reactors were tested from July 1959 to October 1960.

During this time a Memorandum of Understanding was signed between NASA and the Atomic Energy Commission (AEC) that established a joint nuclear program office, the Space Nuclear Propulsion Office.[4]

In 1961, the Rover program was reoriented at the completion of the Kiwi-A test series to include the integration of a propulsion system. Four Kiwi-B tests were planned from which a reactor core design was to be selected for the Nuclear Engine Rocket Vehicle Application (NERVA) program.[3] LANL continued as lead of the reactor development, Westinghouse Electric Corporation and Aerojet General Corporation had the lead on the flight engine-NERVA and

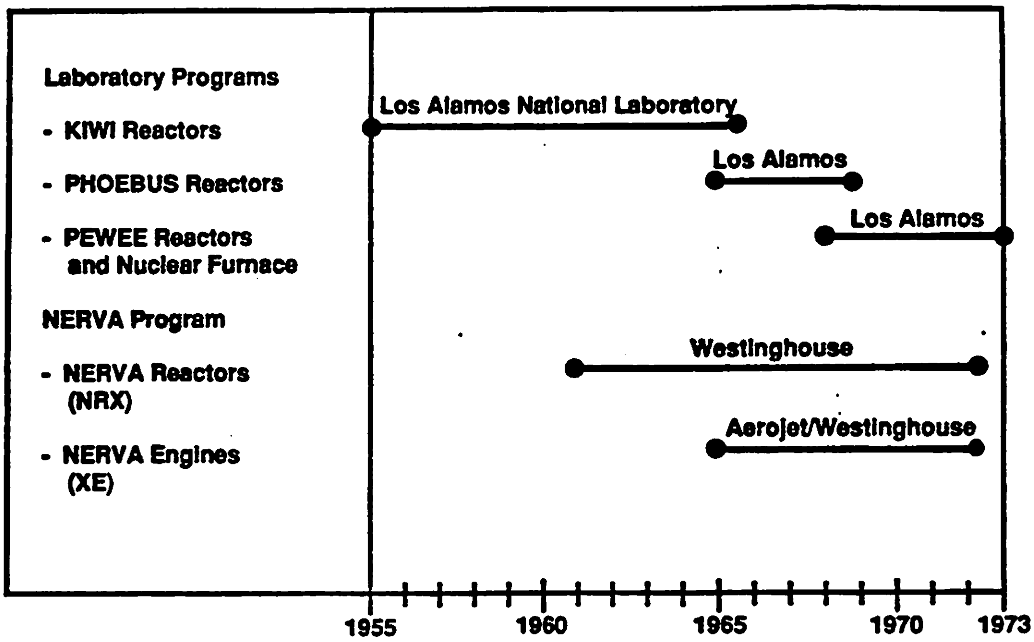

FIGURE 3. PAST NUCLEAR ROCKET PROGRAM

Lockheed had the lead on the Reactor in Flight Test (RIFT).[7]

The RIFT program initiated an intensified effort to solve safety problems associated with flight operations. The RIFT program was canceled in December 1963, however, work continued on the flight safety.

The Kiwi-B series was then initiated at LANL. A total of 5 Kiwi-B reactors were tested between 1961 and 1964. This test series reflected the evolution of the reactor design as a series of technical issues were resolved. One of the most famous tests during this period was the Kiwi-TNT (Transient Nuclear Test-TNT), performed January 12, 1965. The Kiwi-B type reactor was deliberately placed on a fast excursion which caused it to self-destruct. The purpose of the test was to obtain information to reduce the uncertainties in accurately predicting potential accidents.[3]

Development of a new class of reactors, the Phoebus test series, was begun by LANL at the close of the Kiwi-B series. The Phoebus reactors were based on the Kiwi technology, but further pushed the technology by going to higher outlet temperatures, power densities and power levels. A total of three reactors were ground tested under the Phoebus series, the first in mid-year 1965, and the last in 1968. The last reactor in the LANL test series was the Pewee reactor. One Pewee reactor system was tested in 1968 and in many ways represented the culmination of technology development within the Rover development program.

The NERVA Reactor Experiment (NRX) test series was begun parallel to the Kiwi-B series. A total of six developmental reactors were tested under this program, with the first test starting in 1964 and the last test ending in December 1967. The final engine test, the XE, was the first down-firing prototype nuclear engine. The XE was operated in March 1968 at various power levels. The NRX and XE verified the flight readiness of the NERVA flight unit.[8]

Three major events occurred during 1968 and 1969 that had an impact on the nuclear rocket program. The first was the cancellation of the Saturn V program in 1968 which would have been the prime launch vehicle for NERVA. Second, was the enactment of the National Environmental Protection Act (NEPA) in 1969 which deterred further open air testing of the nuclear rockets at the Nevada Test Site. And finally, the advent of the NASA space shuttle forced reexamination of NASA's funding priorities.

The final reactor ground test of the nuclear rocket program was the Nuclear Furnace-1 (NF-1). The NF-1 was designed as a reusable test bed for the testing of advanced fuels and materials. One special feature of the test was the evaluation of a reactor effluent cleanup system to remove radioactive contaminants from the effluent reactor gas.[4]

In January of 1973 the nuclear rocket program was terminated. The nuclear rocket technology provided a basis for the civilian graphite reactor development.

PAST SPACE REACTOR PROGRAM

The past space reactor program encompassed several parallel reactor system technology programs. The early space reactor program can be divided into three primary system categories: the SNAP reactors based upon Zirconium-Hydride (ZrH) fuel technology; fast reactors which included the SNAP-50, the Medium Power Reactor Experiment (MPRE), and the gas cooled-710 reactor; and the in-core thermionic (TI) reactor concept. The primary emphasis of past efforts was on the SNAP program under which both RTGs and nuclear reactor systems were developed. An estimated $850 M was spent between 1955 and 1973 on the space reactor program depicted in Figure 4.[9]

SNAP Reactor Program

The SNAP program was begun in 1955 and was terminated in 1973. During that period over $490 million (then-year dollars) was spent to develop the SNAP systems.[9] A broad technology base was developed during the SNAP reactor program that encompassed a wide range of materials and power conversion systems.

The beginning of the SNAP program can be traced to 1948 when the AF began to look at the possibility of reconnaissance satellites. As a result of their studies, space power needs were identified. A joint AF-AEC committee was established and developed specifications for nuclear power in space. The AEC was responsible for the development of the nuclear power system, and the AF provided mission requirements and support.[10] In 1957, Atomics International (AI) was selected as the primary contractor for the development of the SNAP reactor systems. AI chose a ZrH epi-thermal reactor design. A total of six reactors were tested during the SNAP program.

The first reactor ground test, the SNAP Experimental Reactor (SER), began in 1959 and operated for a total of 5300 hours with an outlet temperature of 482°C. The follow-on unit, the SNAP 2 Developmental Reactor (S2DR) was ground tested in 1961. The SNAP 2 system was designed to be a 3 kWe ZrH reactor coupled to a mercury (Hg) Rankine cycle combined unit with NaK working fluid. The Hg Rankine system

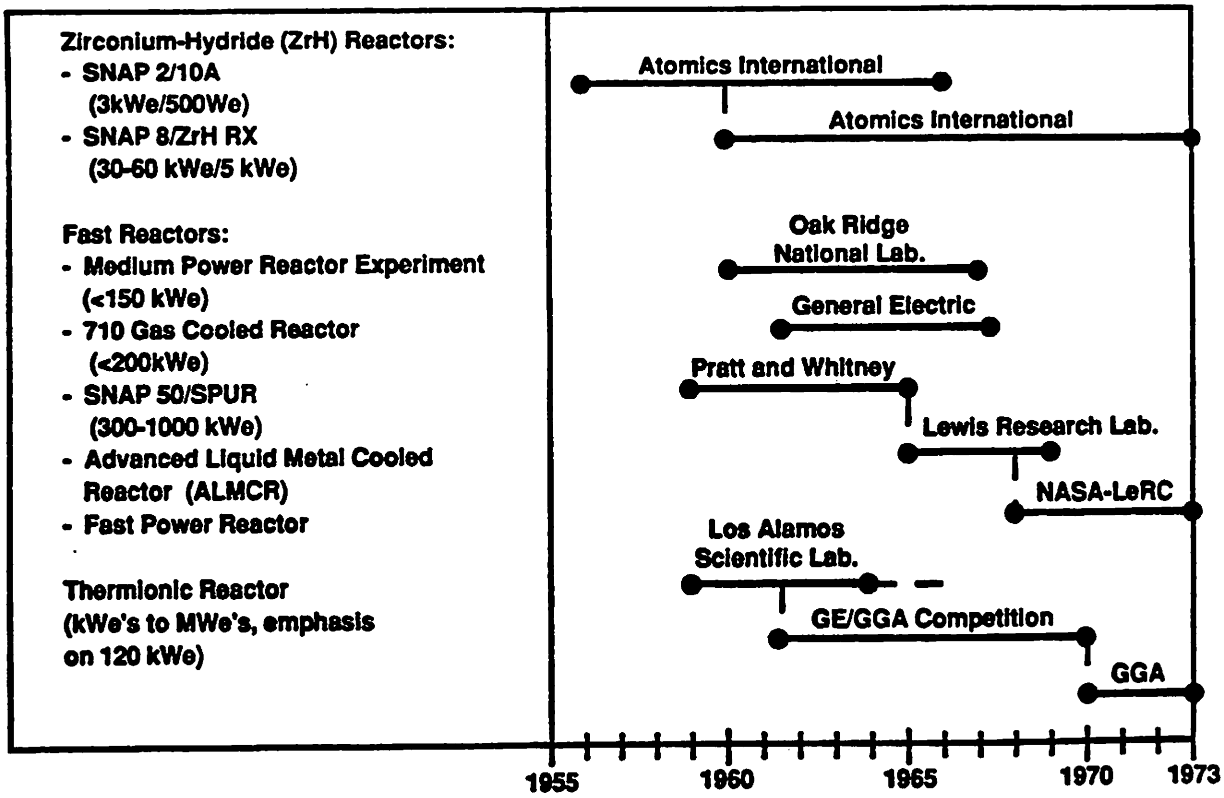

FIGURE 4. PAST SPACE REACTOR HISTORY

was being developed by TRW. The SNAP 2 program was canceled in 1964 due to changing AF requirements but the development of the ZrH technology and the power conversion were continued. The Hg Rankine effort was later terminated in FY67.[11]

The SNAP 10 development ran parallel to the SNAP 2. The SNAP 10 program was initiated at the request of the AF in 1959 to meet a firm requirement to develop a 200w(e) power system. The initial SNAP 10 design was a direct radiating thermoelectric (TE) conversion system with SNAP 2 reactor technology for a reconnaissance satellite. The system was later changed to a flowing NaK coolant system with TE power conversion. In 1960 the AEC and AF jointly initiated the SNAPSHOT program for which a total of four flights were scheduled.[11] In 1963 the AF withdrew their requirement for both the SNAP 2 and SNAP 10A power systems, primarily due to program delays in the AF mission and the advancements in solar technology.

The AEC recommended that the SNAP 10A be flown as a proof-of-principle flight unit, to help lesson the "chicken-and-the egg" syndrome by demonstrating the technology for the user in a space environment. The Joint Committee on Atomic Energy supported the launch and included the funding within its budget. The SNAPSHOT spacecraft, with the SNAP 10A Flight System (FS-4) on-board, was launched April 3, 1965 on a modified Atlas-Agena launch vehicle from Vandenberg Air Force Base on a polar trajectory. The SNAPSHOT achieved a nominal orbit (705/695 nautical miles) with a lifetime of greater than 3500 years.[10] The system started up and operated as planned for 43 days before a malfunction, believed to be within the supporting bus apart from the reactor system, caused a sudden and unexpected reactor shutdown. The system operated half of its planned demonstration time of 90 days. Overall, the SNAPSHOT was considered a success since the US demonstrated that it could safely launch and operate a nuclear reactor in space.

The SNAP 10A (FS-3), a complete power system, was put on a parallel ground test on January 22, 1965. The ground test operated flawlessly at power for over 10,000 hours until the test was ended in March 1966.

The SNAP 8 program was initiated in FY60 to develop a 30-60 kWe system for both space power and electric propulsion. The AEC sponsored the reactor development and NASA was responsible for the development of the dynamic power conversion system. Some of the missions identified for the SNAP 8 reactor were: a manned space station, radar systems, reconnaissance systems, meteorological satellites, lunar base power plant, communication satellite and the Manned Orbiting Laboratory.[11] The SNAP 8 reactor was based upon a modified SNAP 2 reactor with a Hg Rankine power conversion system and NaK working fluid. In the late 1960's, the SNAP 8 program was broadened to consider the use of several alternative power conversion systems.

Two reactors were tested under the SNAP 8 program, the SNAP 8 Experimental Reactor (S8ER) and the SNAP 8 Developmental Reactor (S8DR). The S8ER was used as a proof-of-concept test reactor and was ground tested from May 1963 to April 1965. The S8DR testing began in January 1969 and ended December 1969. Problems occurred during the testing of both reactors.[11] Several design changes were proposed to correct the problems encountered during the SNAP 8 program and were used in conceptual design studies, including the ZrH reactor concept. The SNAP program was terminated in 1973.

MPRE

The MPRE program was initiated in 1959 at Oak Ridge National Laboratory (ORNL) and continued until 1966 when the program was canceled in order to allocate the funding to other advanced reactor systems. An estimated $13 M dollars was spent on the MPRE development program.[9] The MPRE program focused on power needs of up to 150 kWe to fill the gap between the SNAP ZrH systems and the more advanced SNAP 50 system. The purpose of the MPRE program was to investigate the feasibility of direct boiling potassium in a compact fast spectrum reactor which was then passed directly to a Rankine cycle turbine[10].

SNAP 50/SPUR

The SNAP 50 nuclear system development continued the technology development of the earlier Aircraft Nuclear Propulsion (ANP) program which ended in 1961.[10] The technology effort continued due to DoD and NASA interest in the development of a high power nuclear system for space applications. In FY62, the program was directed toward the AF SPUR concept utilizing a 2000°F, fast, lithium-cooled, refractory-alloy reactor coupled to a potassium Rankine cycle power conversion system.[9] The SNAP 50/SPUR was expected to meet power needs from 300 to 1000 kWe for either electric propulsion or electric power.

A SNAP 50 office was established at the AEC headquarters with an AF officer as program manager and with NASA, AF and AEC deputy managers.[9] Pratt and Whitney was the primary contractor for the program development. Upon completion of the development phase in 1965, the primary program was terminated and the technology program transferred to LLL. In 1967 the funding was further reduced and in 1968 the program was terminated.[2] A total of $82.8 M was spent on the SNAP 50 program between 1961 and 1965, with the total program funding being approximately $99 M.[9]

710-Gas Cooled Reactor

The 710 program was initiated in 1961 under the ANP program by the AEC as an advanced system design for power and propulsion applications. The primary contractor, General Electric (GE), proposed a high temperature, gas cooled refractory metal-fuel cermet reactor core that could be used open cycle for direct propulsion or closed cycle with a Brayton cycle to produce electricity. The power system was to produce 200 kWe for up to 10,000 hours of operation.[10] In 1965 the program was reduced in scope to a power system only, in 1967 the program was reoriented towards just fuels development and in 1968 the program was canceled, again to focus the funds on the two primary programs. An estimated $14 M dollars was spent on the program from 1963 to 1968.

Thermionic Reactor

The thermionic reactor program, known as the plasma thermocouple, was started at LANL in 1959. In 1964 the AEC reoriented the program to emphasize industry participation, and both GE and General Atomics (GA) began work on the concept with continued research at LANL. In 1970 GA was selected to develop a thermionic fuel element (TFE) and a thermionic reactor test. In 1971, the NASA and AEC thermionic efforts were combined. NASA was responsible for systems studies and support technology and the AEC was responsible for the reactor concept. In January of 1973, all thermionic effort was ended.

The thermionic system was considered viable for several different power levels and for many different missions. The total program costs exceeded $70 million between 1964 and 1972.[9]

Conclusion

A great deal of research and development was completed during the early space reactor program. The resulting data base was reviewed and evaluated during the selection of the concept to be pursued for the current SP-100 nuclear power program. It is hard to pin down exactly why the space nuclear power program did not gain greater success in space when it had so many successes in technology development and within the ground test program. Contributing factors include: exaggerated near-term space power requirements, advancements in solar technology, a reduction in the number of large-scale space exploration missions, and the reorientation of national priorities including the space shuttle and space station.

CURRENT U.S. SPACE REACTOR PROGRAMS

Low level design studies on the potential of space reactors were reinitiated as early as 1979. Initial work was done between 1979 and 1983 at LANL on a heat pipe cooled reactor called the Space Power Advanced Reactor (SPAR). These studies led to the establishment of the SP-100 program in 1983 which was opened up to industry participation and concept competition.

The SP-100 program was established as a three phase program. The first phase was a feasibility assessment phase and concluded with the selection of the reactor thermoelectric system to be developed in phase two. Phase II is currently scheduled to be completed in late 1995 and will include a ground test of the reactor subsystem at the Hanford Reservation near Richland, Washington. The final phase will be a space flight demonstration that should occur in the mid to late 1990's. The goals and requirements of the SP-100 program are more demanding than the earlier U.S. space reactor program, e.g. 7 versus 1 year life, mass goal of 33 w/gm, survivability against hostile detection or attack.

A schematic of the SP-100 system is shown in Figure 5. It is a fast spectrum reactor using highly enriched uranium nitride fuel. The fuel will be encased in a bonded liner/cladding that uses rhenium and a niobium based material known as PWC-11. Reactor control is accomplished using 12 hinged reflectors that vary the neutron leakage and are operated independently. The system will be liquid metal cooled using lithium in both the primary system that takes the heat from the reactor to the thermoelectric power converters and the secondary system that transfers heat from the converters to the radiators where the excess heat is transferred to space. Pumping power is achieved using thermoelectric electromagnetic pumps that have no moving parts. The reactor coolant outlet and the radiator reject temperatures are 1375 and 850 K, respectively. The radiator is made up of panels of potassium heat pipes.

Lifetime capability will be demonstrated at the component level by individual component development and accelerated testing in conjunction with lifetime models. Significant

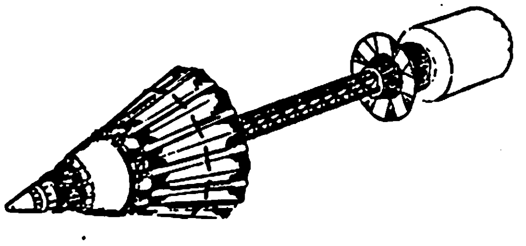

FIGURE 5. CONCEPTUAL ILLUSTRATION OF AN SP-100 SPACE REACTOR POWER SYSTEM

progress has been made to date, e.g. irradiation tests of the fuel and fuel pins have been conducted to the anticipated burnup levels, critical experiments have been completed to verify the neutronic calculations, heat pipes have been placed on life test, fuel development is complete, fuel is being fabricated for the ground system test and the first thermoelectric cell has been fabricated.

Performance of the overall reactor subsystem will be demonstrated through the ground test at Hanford. The test will be conducted in an existing containment facility that is being modified for this test.

A key issue in the eventual use of space reactors will be an assurance that they can be launched and operated safely. Therefore, safety has been an overriding factor in the design process and is based on several key factors, i.e. the reactor will be launched cold so that there will be no buildup of radioactive fission products, it will be designed to prevent the reactor from going critical during launch or ascent, the reactor will only be started after it reaches its operating orbit, it will be designed to remain in a safe condition under accident situations in space, it is intended that the reactor will remain in space, but it will be designed to remain intact and bury itself if it should return to earth in an inadvertent reentry.

The SP-100 technology can be scaled over the range of 10's to 100's of kilowatts-electric. To meet the needs of some missions that may require higher power levels, a program has been started to assess the feasibility of multi-megawatt space reactor systems. Also, because SP-100 may not be optimum for all missions, technology and evaluation efforts are continuing on competing technologies such as thermionics. NASA is also developing a Stirling engine which could extend the capability of the basic SP-100 reactor.

SUMMARY

Space reactors once again are being considered for future U.S. space missions. Manned lunar or Mars bases would require nuclear reactors. SP-100 powered Nuclear Electric Propulsion (NEP) could also open up many new opportunities in space. Civilian missions such as a Jovian Grand Tour or exotic Asteroid orbiter/landers could become a reality. Earth orbit surveillance or communication satellites could be launched using smaller launch vehicles and then raised to their operating orbits using an SP-100 combined with NEP. Nuclear reactors can provide the capability to enhance military satellites survivability.

The program is in place to develop this capability that could be key to the future role of the United States in space. However, there are many forces that could impede this prospect and the United States must exercise great resolve if it is to avoid closing this option once again before it is fully developed.

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