Space Nuclear Power: Key to Outer Solar System Exploration

An AIAA Position Paper
Prepared by the Aerospace Power Systems Technical Committee

Approved by the AIAA Board Of Directors

American Institute of Aeronautics and Astronautics
1801 Alexander Bell Drive
Reston, VA 20191
703/264-7500

March 1995

Summary

The U.S. space nuclear power program is at a critical juncture. The Department of Energy (DoE) is not planning to fund any work after NASA's Cassini mission to Saturn. This planned termination of support by DoE jeopardizes all future NASA outer-planet missions, particularly those that will require a light, efficient power source.

If the United States is going to continue exploration of outer space beyond the Cassini mission, space nuclear power is a critically important technology. Yet the current Administration is withdrawing funding for the required infrastructure and for development of improved space nuclear power technologies. AIAA believes that this is unwise because space nuclear power enables outer planet missions that enrich world

culture, stimulate students, and help us understand the origins of humanity.

Nuclear power is the enabling technology for outer-planet missions where there is very little sunlight (see **Figure 1**). The basic nuclear power source consists of a nuclear source of heat (either radioisotope or reactor) and a means of converting that heat into useful electrical power (the thermal-to-electric conversion system, sometimes referred to as the "conversion system" or "converter"). The DoE support for the nuclear infrastructure has been critical to the development and production of nuclear power sources, most particularly the nuclear heat sources, which require the special facilities and expertise of the DoE laboratories and contractors. Advanced thermal-to-electric conversion technologies being investigated by NASA, DoE, and DoD are essential to producing lighter, more efficient nuclear power sources. There are also opportunities to exploit advanced technology developed in other countries such as Russia.

To meet future mission requirements there must be a continuing interactive program that blends thermal-to-electric conversion technology with nuclear heat source development. The program must maintain the essential nuclear laboratory and production capabilities to produce the nuclear power sources. We cannot afford to let pressures to reduce overall government expenditures erase the nation's ability to carry out missions requiring space nuclear power, including exploration of the outer planets and beyond.

Because the AIAA recognizes that maintenance of nuclear power source technology is the key to the nation's capability to conduct outer-planet missions, the Institute recommends that the government agencies, Congress, and industry strongly support the national space nuclear power technology effort.

Introduction

As shown in **Figure 2**, nuclear power is one of the options for providing power to a spacecraft. Other options include solar (photovoltaics and solar dynamics) and chemical (batteries and fuel cells) power systems. The choice of the power source is generally dictated by the mission. For example, all of the spacecraft that have flown beyond the orbit of Mars have been powered by nuclear power sources because there is not enough sunlight for photovoltaic arrays and the missions are too long for chemical power sources. Generally speaking, the history of space nuclear power shows that, except for certain experiments, nuclear power has been used only when there was no other viable alternative.

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

- Lifetime. Nuclear power is the only currently available alternative to solar power for a spacecraft which must operate for a long period of time (see Figure 2). Unlike solar cells, reactors provide essentially constant power over the life of 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, less than the decay rate of most solar cells). That decay rate, for most applications, is insensitive to the outside environment.

- 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, extreme temperatures such as are experienced on the lunar surface).
- Self-Sufficiency. Nuclear power sources make the space craft more independent. For example, with a nuclear power source 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 radioisotope thermoelectric generators (RTGs) begin producing power the moment they are assembled, RTGs can be operated on the launch pad for system checkouts prior to launch or in the orbiting Space Shuttle for checkouts prior to separation from the Shuttle.
- Operational. Space nuclear power sources, have exhibited extremely high reliability -- all of the U.S. nuclear power source have met or exceeded their pre-launch requirements. Nuclear power source provide a compact source of electrical power with a good power-to-mass ratio. The small exposed area of nuclear power source can reduce the overall size of the spacecraft, simplify attitude control, and reduce structural interactions. They also provide thermal energy to protect electronics and mechanical joints.
- High Power. Nuclear power is the only practical source of continuous high power levels in space.

This is due to an economy of scale that results in little added size or mass as power levels increase. For example, nuclear sources were cited as critical technologies for a manned mission to Mars and have been considered for the next generation of space-based communications systems.

Ongoing space nuclear activities include:

- Cassini - this mission to Saturn is currently under development and scheduled for launch in 1997. The Cassini spacecraft will require three of the Galileo-class RTGs plus a number of radioisotope heater units.
- Pluto Express -- this mission is currently in the planning stages but it will require a new, lower power and more efficient RTG (one for each of the two proposed spacecraft).
- Advanced thermal-to-electric conversion systems -- DoD, DoE, and NASa are conducting studies on improved thermal-to-electric conversion systems that could dramatically reduce the mass of nuclear power sources.
- TOPAZ II -- this is a DoD-sponsored program to exploit the potential of the Russian-designed TOPAZ II thermionic reactor.

The national space nuclear power program that was developed and partially implemented in the 1980s provided technologies that are applicable across the whole spectrum of power levels shown in Figure 2. These programs included:

- Radioisotope thermoelectric generators for the Galileo and Ulysses missions
- SP-100 space nuclear reactor power system for a range of NASA and DoD missions, including nuclear electric propulsion for outer-planet orbits and surface power for lunar and Mars bases
- Dynamic isotope power system for proposed missions such as lunar and Mars rovers and the former Boost Surveillance and Tracking System
- Multi-megawatt space nuclear reactor program for high-powered strategic defense applications
- NASA High-Capacity Power Program to develop highly efficient Stirling conversion systems and advanced thermoelectric elements
- DoE work on advanced thermoelectric materials and RTGs
- DoD initiatives to improve thermionic converters

Continuing support for the space nuclear power program is needed to ensure that the U.S. has the capability to send spacecraft into the outer reaches of the solar system and other hostile places.

Background

Since 1961, the United States has flown 41 RTGs and one reactor to provide power for 25 space systems. Thirty-eight of these nuclear power sources on 22 space systems are still in space or on other planetary bodies. The U.S. has also used small radioisotope heater units on some of its RTG-powered science missions and on the Apollo 11 science package to keep sensitive instruments at the correct temperature. 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, which are easily absorbed within the heat source to produce the heat). The only U.S. space reactor flown, a test flight in 1964, used uranium-235 as the fuel. The first RTGs and space nuclear reactors were designated SNAP, an acronym for Systems for Nuclear Auxiliary Power. Odd-numbered SNAPs were RTGs and even-numbered SNAPs were reactors.

In general, the power subsystem (power source, energy storage, and power management and distribution) can take up about 25% of the mass of a spacecraft, so improvements in the power source translate directly into significant gains for the spacecraft. Moreover, improved thermal-to-electric conversion systems in RTGs can reduce the quantity of potentially scarce plutonium-238 needed. (Currently the U.S. is not producing plutonium-238 for space use, so DoE has been buying some plutonium-238 from Russia to supplement the existing inventory.)

The U.S. established a formal process to review the flight safety of its nuclear power sources in the mid 1960s. Every launch of a U.S. nuclear power source, beginning with the very first one in 1961, has required approval from the White House. As currently constituted, the safety review process is focused in an Interagency Nuclear Safety Review Panel (INSRP) composed of independent safety experts from DoE, NASA, DoD, the Nuclear Regulatory Commission (NRC), and the Environmental Protection Agency (EPA). INSRP reviews all phases of the use of a nuclear power source, including pre-launch, launch, ascent, orbital operations, and trajectory insertion. The result of this very thorough review, which can span years and involve up to 50 or more safety reviewers, is documented in a safety evaluation report that is sent to the White House as part of the request for launch approval. Separately there is a public review of the environmental impact statement for the proposed mission. This safety review process has paid off in minimizing risk and ensuring that all nuclear power sources flown to date have met their safety objectives.

The U.S. has also been an active participant in the nuclear power source deliberations of the United Nations (U.N.) Committee on the Peaceful Uses of Outer Space. U.S. objectives have included raising the flight safety standards of other countries so that they are at least equal to those of the U.S. As a result of these deliberations the U.N. adopted a set of principles on the use of nuclear power sources in outer space in 1992. The U.S. continues to participate in U.N. discussions of nuclear power sources.

In addition to the flight programs in the 1960s, there was an extensive technology effort to develop improved nuclear power sources including work on rotating turbine alternators (Brayton cycle and Rankine cycle) and thermionics. This work provides a good starting point for future endeavors.

In the 1980s DoE completed design, development and production of the most powerful RTG ever flown: the general-purpose heat source, radioisotope thermoelectric generator (GPHS-RTG) which currently powers the Galileo mission to Jupiter and the Ulysses mission to explore the polar regions of the Sun. The GPHS-RTG, with a mass of less than 56 kg, provides over 300 watts of electrical power (We) at the time of fueling. Three new GPHS-RTGs are now being fabricated to power the Cassini spacecraft which is scheduled to be launched in 1997 to Saturn. NASA has asked DoE to sponsor design studies on a lower-power RTG that could be used on the proposed Pluto Express mission, which is under very restrictive mass and cost constraints. In order to reduce both mass and the amount of plutonium-238 a number of advanced thermal-to-electric conversion options are being considered, including small Stirling engines, thermophotovoltaics (essentially solar cells tuned to the infrared radiation of the radioisotope heat source), and alkali metal thermal-to-electric conversion (AMTEC). Maintenance of these technology options is essential to meet the power requirements of the new, smaller, cheaper space missions such as the Pluto Express mission.

The SP-100 space nuclear reactor power system program began officially in 1983 as a jointly managed program under DoD, DoE, and NASA 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. A generic flight system configuration was established to support operational missions requiring relatively high power (100 kWe class) for a 10-year mission duration. That configuration was scalable from about 10 kWe to 1,000 kWe with high specific power (up to 26 We/kg). Because the conversion system is external to the reactor, the SP-100 reactor could be coupled with a range of conversion systems such as thermoelectric, Brayton, Rankine, Stirling or thermionic as the mission dictated. Considerable work was completed on the reactor, and a first-generation thermoelectric module was developed before the program was terminated in 1993. The NASA high-capacity power program complemented the SP-100 program.

Beginning in 1985 a program was undertaken by DoD and DoE to develop electric power in the multi-megawatt range for neutral particle beams, free electron lasers, electromagnetic launchers, and orbital transfer vehicles. The major development activities in this Multi-Megawatt Program were concerned with testing reactor fuels. The program was discontinued in 1990 because of a shift in emphasis within the Strategic Defense Initiative.

Also, in the 1980s, DoD sponsored a number of studies on space nuclear reactors, including the thermionic fuel element verification program, the advanced thermionics initiative and the TOPAZ II thermionic system evaluation test program. DoD, working with DoE, also initiated in 1992 a 40kWe thermionic power system program.

In the use of nuclear reactors in space, the former Soviet Union was the most prolific. They orbited approximately 33 thermoelectric reactor power systems for their radar ocean reconnaissance satellites (RORSATs) and two experimental thermionic reactors now called TOPAZ I. The RORSAT reactors each produced several kilowatts of power, and TOPAZ I delivered 5kWe to 6kWe. Another Russian design team developed a 6kWe thermionic reactor which the U.S. designated TOPAZ II, and which has been purchased by DoD for unfueled testing and evaluation. Both TOPAZ I and TOPAZ II are reported to have been operated in Russia for a year or more in full-up tests.

During the 1960s and early 1970s several other nations, including France, Germany, and the United Kingdom (U.K.) examined space nuclear reactor power systems. In the 1980s some studies were done by Japan and the U.K. The French government assembled a design team that worked on a reactor concept employing a Brayton cycle to convert reactor heat into electrical power. The French, Japanese, and Chinese now have small programs to explore the use of space nuclear technologies.

Currently, NASA is planning a series of smaller spacecraft that are to be built and operated "faster, cheaper, better." To meet these objectives for outer-planet missions, where nuclear power is required, a program is needed to develop new, low-mass, more efficient nuclear power sources. However, the U.S. nuclear space power program to develop and manufacture such sources is in serious jeopardy. For example, it is reported that DoE has no budget plans for any nuclear powered missions after the Cassini mission to Saturn. The SP-100 space nuclear reactor power system program was terminated abruptly by the new Administration early in 1993. NASA is no longer supporting space nuclear technologies, even though the agency recognizes that there is no other way to power outer-planet spacecraft. DoD has sharply cut its program for non-nuclear electrical tests of the TOPAZ II reactor and for technology work on advanced static conversion systems (mostly thermionic).

Conclusions

If the U.S. backs away from maintaining its nuclear power option for spacecraft, we will see the end of all future outer-planet missions, because in today's environment terminating the nuclear power source option means dismantling the infrastructure (people and facilities) that enable nuclear power sources to be built and tested. There are simply no other DoE nuclear or defense programs that need these nuclear power resources. DoE is also closing down its reactor test facilities, which means that there will be no place to test future space nuclear reactor fuel concepts.

Unfortunately, current budget allocations show a steep decline in the space nuclear program. Unless this trend is reversed, it will lead to complete termination of the program. Without corrective action, the nation will be limited only to sending spacecraft to the inner solar system or to very high-risk, very limited missions to the closest of the outer planets.

In summary, with current funding trends the U.S. space nuclear power program will disappear. This in turn eliminates outer-planet and extra-solar-system missions. Hence, space nuclear power technology and infrastructure need real support during the next decade to maintain the U.S. capability for solar system exploration. Historically, the power system technology base lead time for new system development has been at least 10 years, so support now would carry us into the 21st century.

Recommendations

Recognizing that space nuclear power is vital to maintaining the U.S. capability to perform outer planet missions,

- DoE, NASA, and DoD should develop and support an integrated program that maintains the nuclear option and develops the needed high- payoff technologies while avoiding unnecessary duplication of effort. There must be a continuing interactive program that blends thermal-to-electric conversion technology with nuclear heat source developments while maintaining the essential nuclear laboratory and production capabilities to produce the nuclear power sources.

- Congress should provide strong, continuing financial and political support for the agencies' program throughout the next decade. We cannot afford to let national complacency and pressures for reduced overall government expenditures erase the nation's ability to carry out missions to the outer planets and beyond.
- Government and industry leaders should voice their advocacy for a strong space nuclear power program to support future system requirements.
- The U.S. should continue to maintain its cooperation and technical interchanges with other countries to advance nuclear power source technology and to promote nuclear safety.