Radioisotope Power Systems

An Imperative for Maintaining U.S. Leadership in Space Exploration

Radioisotope Power Systems Committee
Space Studies Board
Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences
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Preface

Radioisotope power systems (RPSs) such as radioisotope thermoelectric generators provide electrical power for spacecraft and planetary probes that cannot rely on solar energy. To support the continued availability of the RPSs required to power NASA space missions, Congress and NASA requested that the National Research Council (NRC) undertake a study of RPS technologies and systems.

The NRC formed the Radioisotope Power Systems Committee to produce this report in response to House Report 110-240 on the Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2008. This report assesses the technical readiness and programmatic balance of NASA's radioisotope power systems technology portfolio in terms of its ability to support NASA's near- and long-term mission plans. In addition, the report discusses related infrastructure, the effectiveness of other federal agencies involved in relevant research and development, and strategies for re-establishing domestic production of ^{238}Pu, which serves as the fuel for RPSs. To put the discussion of RPSs in context, the report includes some information regarding other options (i.e., solar power and space nuclear power reactors), but a detailed assessment of these alternatives is beyond the scope of the statement of task. A complete copy of the statement of task appears in Appendix A.

The Radioisotope Power Systems Committee met four times between September 2008 and January 2009 at NRC facilities in Washington, D.C., and Irvine, California, and at the Jet Propulsion Laboratory in Pasadena, California. In addition, small delegations of committee members and staff visited NASA's Glenn Research Center and the Department of Energy's Idaho National Laboratory and Oak Ridge National Laboratory.

RPS technology has been a critical element in establishing and maintaining U.S. leadership in the exploration of the solar system. Continued attention to and investment in radioisotope power systems will enable the success of historic missions such as Viking and Voyager, and more recent missions such as Cassini and New Horizons, to be carried forward into the future.

William W. Hoover
Ralph L. McNutt, Jr.
Co-Chairs, Radioisotope Power Systems Committee

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

William B. Adkins, Adkins Strategies, LLC,
Carl A. Alexander, Battelle Memorial Institute,
Jimmy L. Allison, Boeing Company (technical fellow),
Mohamed S. El-Genk, University of New Mexico,
Kathleen F. Harer, NASA and DOE (retired),
Anthony K. Hyder, University of Notre Dame,
E. Philip Muntz, University of Southern California,
Zack T. Pate, World Association of Nuclear Operations (chairman emeritus), and
John Spencer, Southwest Research Institute.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J. Lanzerotti, New Jersey Institute of Technology. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

For nearly 50 years, the United States has led the world in the scientific exploration of space. U.S. spacecraft have circled Earth, landed on the Moon and Mars, orbited Jupiter and Saturn, and traveled beyond the orbit of Pluto and out of the ecliptic. These spacecraft have sent back to Earth images and data that have greatly expanded human knowledge, though many important questions remain unanswered.

Spacecraft require electrical energy. This energy must be available in the outer reaches of the solar system where sunlight is very faint. It must be available through lunar nights that last for 14 days, through long periods of dark and cold at the higher latitudes on Mars, and in high-radiation fields such as those around Jupiter. Radioisotope power systems (RPSs) are the only available power source that can operate unconstrained in these environments for the long periods of time needed to accomplish many missions, and plutonium-238 (^{238}Pu) is the only practical isotope for fueling them. The success of historic missions such as Viking and Voyager, and more recent missions such as Cassini and New Horizons, clearly show that RPSs—and an assured supply of ^{238}Pu—have been, are now, and will continue to be essential to the U.S. space science and exploration program.

Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) are the only RPS currently available. MMRTGs convert thermal energy released by the natural radioactive decay of ^{238}Pu to electricity using thermocouples. This is a proven, highly reliable technology with no moving parts.

The Advanced Stirling Radioisotope Generator (ASRG) is a new type of RPS, and it is still being developed. An ASRG uses a Stirling engine (with moving parts) to convert thermal energy to electricity. Stirling engine converters are much more efficient than thermocouples. As a result, ASRGs produce more electricity than MMRTGs, even though they require only one-fourth as much ^{238}Pu. It remains to be seen, however, when development of a flight-qualified ASRG will be completed.

THE PROBLEM

Plutonium-238 does not occur in nature. Unlike ^{239}Pu, it is unsuitable for use in nuclear weapons. Plutonium-238 has been produced in quantity only for the purpose of fueling RPSs. In the past, the United States had an adequate supply of ^{238}Pu, which was produced in facilities that existed to support the U.S. nuclear weapons program. The problem is that no ^{238}Pu has been produced in the United States since the Department of Energy (DOE) shut down those facilities in the late 1980s. Since then, the U.S. space program has had to rely on the inventory of ^{238}Pu that existed at that time, supplemented by the purchase of ^{238}Pu from Russia. However, Russian facilities to produce ^{238}Pu were also shut down many years ago, and the DOE will soon take delivery of its last shipment of ^{238}Pu from Russia. The committee does not believe that there is any additional ^{238}Pu (or any operational ^{238}Pu production facilities) available anywhere in the world. The total amount of ^{238}Pu available for NASA is fixed, and essentially all of it is already dedicated to support several pending missions—the Mars Science Laboratory, Discovery 12, the Outer Planets Flagship 1 (OPF 1), and (perhaps) a small number of additional missions with a very small demand for ^{238}Pu. If the status quo persists, the United States will not be able to provide RPSs for any subsequent missions.

Reestablishing domestic production of ^{238}Pu will be expensive (the cost will likely exceed $150 million). Previous proposals to make this investment have not been enacted, and cost seems to be the major impediment. However, regardless of why these proposals have been rejected, the day of reckoning has arrived. NASA is already making mission-limiting decisions based on the short supply of ^{238}Pu.

NASA is stretching out the pace of RPS-powered missions by eliminating RPSs as an option for some missions and delaying other missions that require RPSs until more ^{238}Pu becomes available. Procuring ^{238}Pu from Russia or other foreign nations is not a viable option because of schedule and national security considerations. Fortunately, there are two viable approaches for reestablishing production of ^{238}Pu in the United States. Both of these approaches would use existing reactors at DOE facilities at Idaho National Laboratory and Oak Ridge National Laboratory with minimal modification, but a large capital investment in processing facilities would still be needed. Nonetheless, these are the best options in terms of cost, schedule, and risk for producing ^{238}Pu in time to minimize the disruption in NASA's space science and exploration missions powered by RPSs.

IMMEDIATE ACTION IS REQUIRED

On April 29, 2008, the NASA administrator sent a letter to the secretary of energy with an estimate of NASA's future demand for ^{238}Pu.[1] The committee has chosen to use this letter as a conservative reference point for determining the future need for RPSs. However, the findings and recommendations in this report are not contingent on any particular set of mission needs or launch dates. Rather, they are based on a conservative estimate of future needs based on various future mission scenarios. The estimate of future demand for ^{238}Pu (which is about 5 kg/year) is also consistent with historic precedent.

The orange line [hollow square data points] in Figure S-1 shows NASA's cumulative future demand for ^{238}Pu in a best-case scenario (which is to say, a scenario in which NASA's future RPS-mission set is limited to those missions listed in the NASA administrator's letter of April 2008, the ^{238}Pu required by each mission is the smallest amount listed in that letter, and ASRGs are used to power OPF 1). The green line [solid square data points] shows NASA's future demand if the status quo persists (which is to say, if OPF 1 uses MMRTGs.)

Once the DOE is funded to reestablish production of ^{238}Pu, it will take about 8 years to begin full production of 5 kg/year. The red and blue lines [triangular data points] in Figure S-1 show the range of future possibilities for ^{238}Pu balance (supply minus demand). A continuation of the status quo, with MMRTGs used for OPF 1 and no production of ^{238}Pu, leads to the largest shortfall, and the balance curve drops off the bottom of the chart. The best-case scenario, which assumes that OPF 1 uses ASRGs and DOE receives funding in fiscal year (FY) 2010 to begin reestablishing its ability to produce ^{238}Pu, yields the smallest shortfall (as little as 4.4 kg). However, it seems unlikely that all of the assumptions that are built into the best-case scenario will come to pass. MMRTGs are still baselined for OPF 1, there remains no clear path to fight qualification of ASRGs, and FY 2010 funding for ^{238}Pu production remains more a hope than an expectation. Thus, the actual shortfall is likely to be somewhere between the best-case curve and the status-quo curve in Figure S-1, and it could easily be 20 kg or more over the next 15 to 20 years.

It has long been recognized that the United States would need to restart domestic production of ^{238}Pu in order to continue producing RPSs and maintain U.S. leadership in the exploration of the solar system. The problem is that the United States has delayed taking action to the point that the situation has become critical. Continued inaction will exacerbate the magnitude and the impact of future ^{238}Pu shortfalls, and it will force NASA to make additional, difficult decisions to reduce the science return of some missions and to postpone or eliminate other missions until a source of ^{238}Pu is available.

The schedule for reestablishing ^{238}Pu production will have to take into account many factors, such as construction of DOE facilities, compliance with safety and environmental procedures, and basic physics. This schedule cannot be easily or substantially accelerated, even if much larger appropriations are made available in future years in an attempt to overcome the effects of ongoing delays. The need is real, and there is no substitute for immediate action.

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[1] Letter from the NASA Administrator Michael D. Griffin to Secretary of Energy Samuel D. Bodman, April 29, 2008 (reprinted in Appendix C).

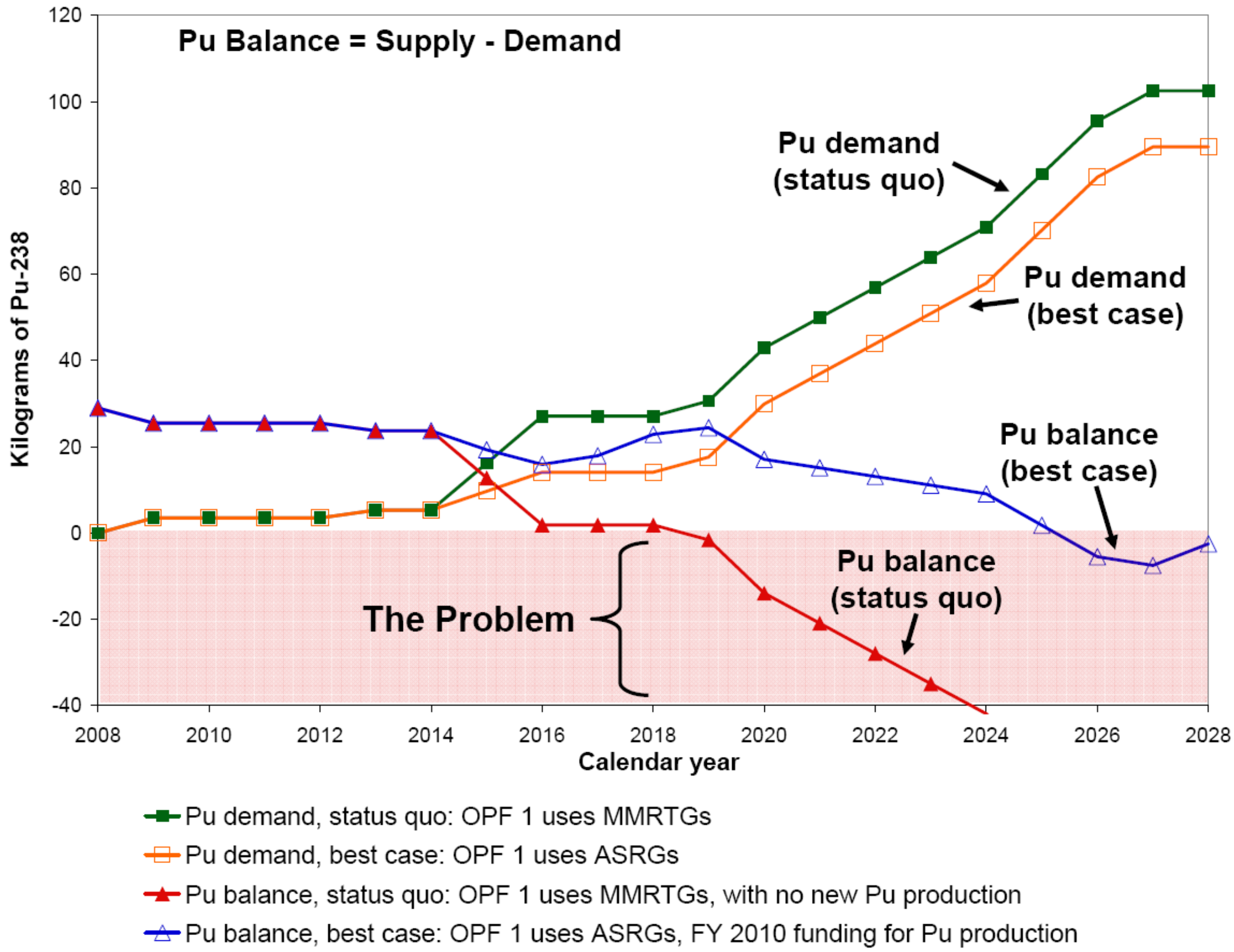

FIGURE S-1 Potential ^{238}Pu demand and net balance, 2008 through 2028.

HIGH-PRIORITY RECOMMENDATION. Plutonium-238 Production. The fiscal year 2010 federal budget should fund the Department of Energy (DOE) to reestablish production of ^{238}Pu.

- As soon as possible, the DOE and the Office of Management and Budget should request—and Congress should provide—adequate funds to produce 5 kg of ^{238}Pu per year.
- NASA should issue annual letters to the DOE defining the future demand for ^{238}Pu.

DEVELOPMENT OF A FLIGHT-READY ASRG

Advanced RPSs are required to support future space missions while making the most out of whatever ^{238}Pu is available. Until 2007, the RPS program was a technology development effort. At that time, the focus shifted to development of a flight-ready ASRG, and that remains the current focus of the RPS program. The program received no additional funds to support this new tasking, so funding for several other important RPS technologies was eliminated, and the budget for the remaining RPS technologies was cut. As a result, the RPS program is not well balanced. Indeed, balance is impossible given the current (FY 2009) budget and the focus on development of flight-ready ASRG technology. However, the focus on ASRG development is well aligned with the central, and more pressing, issue that threatens the future of RPS-powered missions: the limited supply of ^{238}Pu. The RPS program should continue to support NASA's mission requirements for RPSs while minimizing NASA's demand for ^{238}Pu. NASA should continue to move the ASRG project forward, even though this has come at the expense of other RPS technologies.

Demonstrating the reliability of ASRGs for a long-life mission is critical—but has yet to be achieved. The next major milestones in the advancement of ASRGs are to freeze the design of the ASRG, to conduct system testing that verifies that all credible life-limiting mechanisms have been identified and assessed, and to demonstrate that ASRGs are ready for flight. In lieu of any formal guidance or requirements concerning what constitutes flight readiness, ongoing efforts to advance ASRG technology and demonstrate that it is flight ready are being guided by experience gained from past programs and researchers' best estimates about the needs and expectations of project managers for future missions. While this approach has enabled progress, the establishment of formal guidance for flight certification of RPSs in general and ASRGs in particular would facilitate the acceptance of ASRGs as a viable option for deep-space missions and reduce the impact that the limited supply of ^{238}Pu will have on NASA's ability to complete important space missions.

RECOMMENDATION. Flight Readiness. The RPS program and mission planners should jointly develop a set of flight readiness requirements for RPSs in general and Advanced Stirling Radioisotope Generators in particular, as well as a plan and a timetable for meeting the requirements.

RECOMMENDATION: Technology Plan. NASA should develop and implement a comprehensive RPS technology plan that meets NASA's mission requirements for RPSs while minimizing NASA's demand for ^{238}Pu. This plan should include, for example:

- A prioritized set of program goals.
- A prioritized list of technologies.
- A list of critical facilities and skills.
- A plan for documenting and archiving the knowledge base.
- A plan for maturing technology in key areas, such as reliability, power, power degradation, electrical interfaces between the RPS and the spacecraft, thermal interfaces, and verification and validation.
- A plan for assessing and mitigating technical and schedule risk.

RECOMMENDATION. Multi-Mission RTGs. NASA and/or the Department of Energy should maintain the ability to produce Multi-Mission Radioisotope Thermoelectric Generators.

HIGH-PRIORITY RECOMMENDATION. ASRG Development. NASA and the Department of Energy (DOE) should complete the development of the Advanced Stirling Radioisotope Generator (ASRG) with all deliberate speed, with the goal of demonstrating that ASRGs are a viable option for the Outer Planets Flagship 1 mission. As part of this effort, NASA and the DOE should put final-design ASRGs on life test as soon as possible (to demonstrate reliability on the ground) and pursue an early opportunity for operating an ASRG in space (e.g., on Discovery 12).

1
The Problem

For nearly 50 years, the United States has led the world in the scientific exploration of space. U.S. spacecraft have circled Earth; landed on the Moon and Mars; flown to and beyond Jupiter, Saturn, Uranus, and Neptune; and traveled beyond our solar system. The spectacular images and data sent back to Earth by these spacecraft have greatly expanded human knowledge. Even so, there is much yet to learn from continued space exploration.

Spacecraft require electrical energy. This energy must be available in the outer reaches of the solar system where sunlight is very faint. It must be available through lunar nights that last for 14 days, through long periods of dark and cold at the higher latitudes on Mars, and in high radiation fields such as those around Jupiter. Radioisotope power systems (RPSs) are the only available power source that can operate unconstrained in these environments for the long periods of time needed to accomplish many missions.

RPSs generate electricity by converting heat from the natural decay of the plutonium-238 (^{238}Pu) radioisotope into electricity. Plutonium-238 has been produced in quantity only for the purpose of fueling RPSs; unlike ^{239}Pu, it is unsuitable for use in nuclear weapons. In the past, the United States had an adequate supply of ^{238}Pu, which was produced in facilities that existed to support the U.S. nuclear weapons program. The problem is, no ^{238}Pu has been produced in the United States since the Department of Energy (DOE) shut down those facilities in the late 1980s. Since then the U.S. space program has had to rely on the inventory of ^{238}Pu that existed at that time, supplemented by the purchase of ^{238}Pu from Russia. However, Russian ^{238}Pu production facilities were also shut down many years ago, and the DOE will soon take delivery of its last shipment of ^{238}Pu from Russia. The committee does not believe that there is any additional ^{238}Pu (or any operational ^{238}Pu production facilities) available anywhere in the world. The total amount of ^{238}Pu available for the National Aeronautics and Space Administration (NASA) is fixed, and essentially all of it is already dedicated to support several pending missions.[1]

Reestablishing domestic production of ^{238}Pu will be expensive; the cost will likely exceed $150 million. Previous proposals to make this investment have not been enacted, and cost seems to be the major impediment. However, the day of reckoning has arrived. NASA has been making mission-limiting decisions for some time because of the short supply of ^{238}Pu. Moreover, NASA has been eliminating RPSs as an option for some missions and delaying other missions that require RPSs until more ^{238}Pu becomes available. Unless and until a new source of ^{238}Pu is established, the restricted supply of ^{238}Pu will increasingly limit both the quality and quantity of U.S. space science in many mission areas, and continued U.S. leadership in these areas will be at risk.

The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is the only specific RPS currently available. Like all prior RPSs, MMRTGs convert the thermal energy produced by the radioactive decay of ^{238}Pu to electricity using thermocouples. This is a proven technology. RPSs that use thermocouples have no moving parts and have demonstrated high reliability and long life, albeit with low energy-conversion efficiency.

The Advanced Stirling Radioisotope Generator (ASRG) is a new type of RPS, and it is still being developed. It uses a Stirling engine (with moving parts) to convert thermal energy to electricity. Stirling

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[1]This report focuses on large quantities of ^{238}Pu (measured in kilograms) necessary to fuel RPSs. It is not concerned with small quantities of ^{238}Pu (measured in grams, milligrams, or micrograms) that are produced for research or other purposes.

engine converters are much more efficient than thermocouples. As a result, ASRGs produce more electricity than MMRTGs, even though they require only one-fourth as much ^{238}Pu. ASRG development efforts have made good progress thus far, but it remains to be seen when a flight-qualified ASRG will be available.

FINDING. Production of ^{238}Pu. The United States has not produced ^{238}Pu since the Department of Energy shut down its nuclear weapons production reactors in the late 1980s.

Chapter 2 provides background information on space exploration, the case for using RPSs and ^{238}Pu, NASA and DOE roles and responsibilities, and nuclear safety. Chapter 3 examines ^{238}Pu supply and demand and the importance of immediate action to reestablish domestic production of ^{238}Pu. Chapter 4 reviews the performance of various RPSs, related research and development, and the importance of completing the development of ASRGs with all deliberate speed.

BOX 1.1

What is a Radioisotope Power System?

Radioisotope Power Systems (RPSs) are compact, rugged spacecraft power systems that provide reliable, long lived power in harsh environments where other power systems such as solar arrays are not practical. RPSs are not nuclear reactors. They do not use nuclear fission or fusion to produce energy. Instead, they produce heat through the natural radioactive decay of plutonium-238 (^{238}Pu). All U.S. RPSs launched to date have used solid-state thermoelectric converters to convert this heat into electricity. Such RPSs have supported 26 NASA and DoD missions since 1961. Advanced Stirling Radioisotope Generators (ASRGs), which are still under development, use a more-efficient dynamic energy conversion system to generate electricity.

U.S. RPSs have an outstanding safety and reliability record. RPSs have never caused a spacecraft failure, and almost 50 years of effort have been invested in the engineering, safety, analysis, and testing of RPSs. Safety features are incorporated into the design of RPSs, extensive testing has demonstrated that they can withstand severe conditions associated with a wide spectrum of credible accidents, and mission experience has demonstrated that they can operate continuously for decades.

2
Background

WHY SPACE EXPLORATION?

From its very beginning, the exploration of space has brought enormous gains to humanity. At one level it is about seizing the strategic initiative and using space technology for a broad array of activities that enhance our life on Earth. Indeed, weather, communications, reconnaissance, and navigation satellites have revolutionized many aspects of our lives. Spacecraft have also revolutionized our understanding of the solar system and beyond. They have investigated Earth's relationship to the Sun and the larger cosmological system, the context of Earth in relation to other planets, and the fragility of our planet in ensuring our continued existence.

Understanding how and why Earth is an abode of life, understanding the potential for life elsewhere, advancing scientific knowledge of the origins and history of the solar system, and creating a sustainable long-term human presence on the Moon are vital components of the space exploration efforts of the United States. Why is Mars bone dry, virtually airless, and seemingly dead? Why is Venus a hostile world, hidden from view by a hot, heavy atmosphere and a dense layer of clouds? Is Titan an analogue for Earth-like meteorology and geological processes, albeit at frigid temperatures? What causes the dynamic and violent atmospheric conditions of Jupiter? What are the fundamental processes that shaped the origins and evolution of the solar system? Are we alone or is the universe teeming with undiscovered life beyond planet Earth? As John Glenn remarked, "Our spirit as a nation is reflected in our willingness to explore the unknown for the benefit of all humanity, and space is a prime medium in which to test our mettle" (Glenn, 1983).

WHY RADIOISOTOPE POWER SYSTEMS?

Through an investment of considerable resources—engineering and scientific knowledge, human capital, and public funds—the United States has gained undisputed leadership in the exploration of the solar system. This has been made possible since the 1950s by harnessing several core technologies that have enabled the U.S. scientific spacecraft to travel for years on end, engage in extended scientific observations, and relay critical data back to Earth. RPSs are one such technology.

RPSs convert the heat generated by the natural decay of radioactive material (specifically, ^{238}Pu) to electrical energy. In a radioisotope thermoelectric generator (RTG), the heat flows through the thermocouples to a heat sink, generating direct current (dc) electricity in the process. The thermocouples are then connected through a closed loop that feeds an electrical current to the power management system of the spacecraft. All of the RPSs flown to date have been RTGs. They are compact, rugged, and extraordinarily reliable, but the energy conversion efficiency is low (~6 percent).

ASRGs will have much higher efficiency (~29 percent), thereby greatly reducing the amount of ^{238}Pu needed to support future missions. In the Stirling engine converter used by ASRGs, helium gas oscillates in a regenerator, one end of which is heated by radioactive decay of ^{238}Pu, while the other end is cooled by a heat sink. This oscillating gas pushes a piston in a linear alternator that generates alternating current (ac) electricity. The ac is converted to dc electronically, and the current is fed to the power management system of the spacecraft. Although dynamic energy conversion systems have long been considered for RPSs, only recently have technological advances—and the need to minimize future demand for ^{238}Pu—justified development of RPSs with a Stirling engine.

RPSs can provide power for multi-year missions to faraway places where sunlight is either lacking (e.g., missions beyond Jupiter) or where solar power is unreliable (e.g., in Jupiter's radiation belts).[1] At Jupiter, sunlight is 96 percent less intense than at Earth. Continuing outward to Pluto, sunlight is 99.94 percent less intense. RPS-powered *Voyager, Galileo, Cassini*, and *New Horizons* spacecraft have enabled the United States to explore every planet in this dark, outer region of the solar system. Much of their success has been due in large part to having a reliable power source that provides enough power to operate complex instruments at a data rate high enough to optimize the capabilities of the scientific instruments they carry.

RPSs are also useful for missions to the surface of the Moon (especially during the long, cold lunar nights and in the permanently shadowed regions near the lunar poles), for missions to the surface of Mars (with its dust storms and extended winters), for extended missions below Venus's cloud-deck, and for other missions where solar power is not practical, for example, because the dynamic range of solar power would preclude the use of solar arrays.[2]

Space nuclear power reactors are another potential option for missions where solar power is not practical. However, the performance and reliability of space nuclear power reactor systems using current technology remains unproven, especially for missions with long lifetimes. In addition, the committee is not aware of any substantive effort currently underway anywhere in the world to develop space nuclear power reactor systems. The history of space nuclear power reactors suggests that space nuclear reactors, if successfully developed, could meet the needs of some missions and could enable other missions that are not now under consideration because of power limitations. For example, Project Prometheus, which was NASA's most recent attempt to develop space nuclear power reactors, selected a nuclear electric propulsion reactor concept that was scalable from 20 kW_e to 300 kW_e. However, history also shows that the development of a high-power, long-life space nuclear power reactor would be very time-consuming and cost billions of dollars (see Appendix E).

Since 1961, the U.S. has launched 45 RPSs on 26 spacecraft dedicated to navigation, meteorology, communications, and exploration of the Moon, Sun, Mars, Jupiter, Saturn, and elsewhere in the outer solar system (see Table 2-1). This critical work could not have been accomplished without RPSs. Current RPS-powered space missions include the *Cassini* spacecraft, with three RPSs, which is studying Saturn and its moons; and the *New Horizons* spacecraft, with one RPS, which is studying Pluto and the Kuiper Belt. The Mars Science Laboratory spacecraft is scheduled for launch in 2011 with an RPS-powered rover. Over the longer term, RPSs are expected to support continued exploration of extreme environments of the Moon, Mars, and Venus, as well as the dimly lit outer reaches of the solar system and beyond. Such missions will be severely constrained or eliminated unless RPSs are ready and available (see Table 2-2).

FINDING. Importance of RPSs. RPSs have been, are now, and will continue to be essential to the U.S. space science and exploration program.

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[1]For example, the Juno mission to Jupiter will be powered by solar arrays, but it will be in a highly elliptical polar orbit; it will not orbit near the Jovian equatorial plane where the most intense portions of the belts are located. Thus, it will spend little time in the belts themselves.

[2]A specific example is a solar probe mission using Jupiter for a gravity assist in order to pass the Sun in an orbit highly inclined to the plane of the ecliptic. For a mission such as this, the spacecraft experiences such a wide range of solar intensity that current technology is unable to provide the spacecraft with a low-mass solar power system.

TABLE 2-1 U.S. Spacecraft Using Radioisotope Power Systems

Spacecraft	Power Source	No. of RPSs	Mission Type	Launch Date	Location
Transit 4A	SNAP-3B7	1	Navigational	6/29/1961	Currently in orbit
Transit 4B	SNAP-3B8	1	Navigational	11/15/1961	Currently in orbit
Transit 5BN-1	SNAP-9A	1	Navigational	9/28/1963	Currently in Orbit
Transit 5BN-2	SNAP-9A	1	Navigational	12/5/1963	Currently in Orbit
Transit 5BN-3	SNAP-9A	1	Navigational	4/12/1964	Reentered; Burned up
Nimbus B-1	SNAP-19B2	2	Meteorological	5/18/1968	Aborted; Retrieved
Nimbus III	SNAP-19B3	2	Meteorological	4/14/1969	Currently in Orbit
Apollo 12	SNAP-27	1	Lunar/ALSEP	11/14/1969	On Lunar surface
Apollo 13	SNAP-27	1	Lunar/ALSEP	4/11/1970	Reentered in S. Pacific
Apollo 14	SNAP-27	1	Lunar/ALSEP	1/31/1971	On Lunar surface
Apollo 15	SNAP-27	1	Lunar/ALSEP	7/26/1971	On Lunar surface
Pioneer 10	SNAP-19	4	Planetary/Sun escape	3/2/1972	Heliosheath
Apollo 16	SNAP-27	1	Lunar/ALSEP	4/16/1972	On Lunar surface
Triad-01-1X	Transit-RTG	1	Navigational	9/2/1972	Currently in Orbit
Apollo 17	SNAP-27	1	Lunar/ALSEP	12/7/1972	On Lunar surface
Pioneer 11	SNAP-19	4	Planetary/Sun escape	4/5/1973	Heliosheath
Viking 1	SNAP-19	2	Mars Lander	8/20/1975	On Martian surface
Viking 2	SNAP-19	2	Mars Lander	9/9/1975	On Martian surface
LES 8, LES 9	MHW-RTG	2, 2	Communication	3/14/1976	Currently in Orbit
Voyager 2	MHW-RTG	3	Planetary/Sun escape	8/20/1977	Heliosheath
Voyager 1	MHW-RTG	3	Planetary/Sun escape	9/5/1977	Heliosheath
Galileo	GPHS-RTG	2	Planetary (Jupiter)	10/18/1989	Intentionally deorbited into Jupiter
Ulysses	GPHS-RTG	1	Solar and space physics	10/6/1990	Heliocentric, polar orbit
Cassini	GPHS-RTG	3	Planetary (Saturn)	10/15/1997	Operating at Saturn
New Horizons	GPHS-RTG	1	Planetary/Sun escape	1/19/2006	Enroute to Pluto

NOTE: ALSEP, Apollo Lunar Surface Experiments Package; GPHS, General Purpose Heat Source; LES, Lincoln Experimental Satellite; MHW, Multi-hundred Watt; SNAP, Systems for Nuclear Auxiliary Power.
SOURCES: Data from G.L. Bennett, J.J. Lombardo, and B.J. Rock, "Development and Use of Nuclear Power Sources for Space Applications," *Journal of the Astronautical Sciences* 29 (October-December 1981):321-42; N.L. Johnson, "Nuclear Power Supplies in Orbit," *Space Policy*, August 1986, pp.223-33; G.L. Bennett, "Space Nuclear Power: Opening the Final Frontier," AIAA 2006-4191, p. 2, presentation at 4th International Energy Conversion Engineering Conference and Exhibit, San Diego, Calif., June 26-29, 2006.

TABLE 2-2 RPS Contribution to Space Science and Exploration Missions

	Discovery				New Frontiers						Flagship					Lunar		Mars		Exploration	
Major Questions and Objectives (Adapted from 2006 NASA Solar System Exploration Roadmap)	SB	Moon	Venus	Mercury	SPABSR	CSSR	VISE	IO	GO	S/M NET	EE	TE	VME	EAL	NTE	ILN 1&2	ILN 3&4	MSL	MSR	ATHLETE	PR #1,2,3
How did the Sun's Family of planets and minor bodies originate																					
Understand the initial stages of planetary and satellite formation	○●	○●	○▲	○▲	○●	▲		○●	○●	○●	✕▲	✕▲	✕▲		✕●	○▲	○▲	✕▲			
Study the processes that determine the original characteristics of bodies in the solar system	○●	○●		○▲	○▲	○●		○▲	○▲	○▲	✕▲	✕▲			✕●	○▲	○▲	✕▲			
How did the Solar System evolve to its current diverse state?																					
Determine how the processes that shape planetary bodies operate and interact	○▲	○▲	○▲	○▲	○▲	▲	○▲	○▲	○▲		✕●	✕●	✕●	✕●	✕●	○▲	○▲	✕●	○▲		
Understand why the terrestrial planets are so different from one another			○●				○●	○▲	○▲	○●			✕●					✕▲	○▲		
Learn what our Solar System can tell us about extrasolar planetary systems											✕▲	✕▲	✕●		✕▲						
What are the characteristics of the Solar System that led to the origin of life?																					
Determine the nature, history, and distribution of volatile and organic compounds in the Solar System	○▲					○●	○▲				✕●	✕●	✕●	✕●	✕●			✕●	○●		
Determine evidence for a past ocean on the surface of Venus			✕▲				○▲						✕●								
Identify the habitable zones in the outer solar system											✕●	✕●		✕●	✕●						
How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?																					
Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life	○▲										✕▲	✕●		✕●	✕▲			✕●	○●		
Evidence for life on Europa, Enceladus, and Titan											✕▲	✕●		✕●							
Evidence for past life on Venus													✕▲								
Identify environmental hazards and resources enabling human presence in space																					
Determine the inventory and dynamics of objects that may pose an impact hazard to Earth	●																				
Inventory and characterize planetary resources that can sustain and protect human explorers	●				○▲	●				○▲						○▲	○▲		○▲	○●	○●

Science contribution: ● **Major return;** ▲ **Secondary return** **RPS dependence:** ✕ **Not possible without RPS;** ○ **RPS use enhances science return**

NOTE: SB, small bodies; SPABSR, South Pole-Aitken Basin Sample Return; CSSR, Comet Surface Sample Return; VISE, Venus In-Situ Explorer; IO, Io Observer; GO, Ganymede Observer; S/M NET, seismological/meteorological network science; EE, Europa Explorer; TE, Titan/Enceladus Exp; VME, Venus Mobile Exp; EAL, Europa Astrobiology Lander; NTE, Neptune-Triton Explorer; ILN, International Lunar Network; MSL, Mars Science Laboratory; MSR, Mars Sample Return; ATHLETE, All-Terrain Hex-Legged Extra-Terrestrial Explorer (rover); PR, Pressurized Rover.

SOURCE: T.J. Sutliff, NASA, "Space Science and RPSs, What Missions Cannot be Accomplished without RPSs," presentation to the Radioisotope Power Systems Committee, January 12, 2009, Irvine, California.

WHY ^{238}Pu?

Plutonium-238, which does not occur in nature, is created by irradiating ^{237}Np targets in a nuclear reactor. Although many studies over the past 50 years have assessed the advantages and disadvantages of using a wide variety of isotopes as a fuel for RPSs, every U.S. RPS launched into space has been fueled by ^{238}Pu.[3] Studies examined by the committee demonstrate that the longstanding decision by the DOE and NASA to rely on ^{238}Pu is correct and well-justified. No other radioisotope meets or exceeds the safety and performance characteristics of ^{238}Pu, particularly for long-duration, deep-space exploration missions (see Appendix D). Plutonium-238, which has a half-life of 88 years, is the only isotope that meets all of the general criteria for RPS fuels, as follows:

- It generates heat for a sufficient length of time (i.e., it has a radioactive decay half-life of sufficient length).
- The type and quantity of the emissions produced by the radioactive decay of the fuel allow it to be handled safely.
- It has high specific power (heat per mass) and high power density (heat per volume).
- It has a fuel form that is non-corrosive, water-insoluble, chemically stable, and demonstrates good engineering properties at high temperatures.
- It can be produced in sufficient quantity at an affordable cost.

FINDING. Plutonium-238 Supply. Plutonium-238 is the only isotope suitable as an RPS fuel for long-duration missions because of its half-life, emissions, power density, specific power, fuel form, availability, and cost. An assured supply of ^{238}Pu is required to sustain the U.S. space science and exploration program.

NASA AND DOE ROLES AND RESPONSIBILITIES

The Atomic Energy Act of 1954 (as amended) establishes comprehensive requirements regarding the possession, use, and production of nuclear materials and facilities. Other federal legislation allocates responsibilities for regulating nuclear materials between the DOE and the Nuclear Regulatory Commission. In the United States, only the DOE is authorized to own space nuclear power systems. Therefore, NASA must team with the DOE to manufacture, launch, and operate RPSs in space.

The DOE also owns and operates the nuclear facilities that are used to develop, fabricate, assemble, and test RPS systems and hardware that involve nuclear fuels. Although the DOE always retains ownership of RPSs, NASA may have custody. The nuclear fuel is integrated with other RPS components at DOE facilities located at several DOE sites. In addition, DOE regulations apply to the RPS storage, handling, and checkout facility at Kennedy Space Center.

The NASA-DOE partnership to provide RPSs for space exploration has been extremely successful, with decades of mission success (see Appendix E). Scientific results of RPS missions have often greatly exceeded initial expectations because the RPSs powering those missions have far exceeded their design lifetimes.[4]

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[3]The SNAP-3 Program used both ^{210}Po and ^{238}Pu as nuclear fuel for RTGs during ground tests (Dieckamp, 1967). Over the years, some papers have erroneously reported that SNAP-3 RTGs fueled with ^{210}Po were operated in space. That is not the case.

[4]The Voyager 1 and 2, originally designed for a 5-year mission to the Saturn system, are still sending back scientific data 31 years after launch. Voyager 2 became the first and only spacecraft to fly by Uranus and Neptune,

The DOE writes nuclear safety requirements applicable for the operations they perform. These requirements are similar to those established by the Nuclear Regulatory Commission and other agencies that regulate other types of nuclear operations. For example, regulations specify that safety should be engineered into systems during their design and development, and systems and processes should be designed and implemented with the goal of reducing radiation exposures to as low as reasonably achievable.

Agreements between NASA and the DOE

A memorandum of understanding between the secretary of energy and the NASA administrator defines NASA's and DOE's roles and responsibilities regarding research, technology development, design, production, delivery, space-vehicle integration, launch, and operation of RPSs (DOE, 1991).

DOE's responsibilities include the design, development, fabrication, evaluation, testing, and delivery of RPSs to meet NASA system-performance and schedule requirements. In accordance with the National Environmental Policy Act (NEPA), the DOE assesses potential environmental impacts from activities related to nuclear material operations, transportation, and storage. The DOE also provides nuclear risk assessments in support of environmental impact statements (EISs) that NASA prepares to comply with NEPA for the launch of a spacecraft utilizing an RPS system. The DOE is also responsible for specifying minimum radiological, public-health, and safety criteria and procedures for the use of RPSs; providing safeguards and security guidance for NASA facilities and services; supporting NASA operational plans, mission definition, environmental analysis, launch approval, and radiological contingency planning; affirming the flight readiness of RPSs with respect to nuclear safety; participating in the nuclear launch approval process; jointly investigating and reporting nuclear incidents; and assuming legal liability for damages resulting from nuclear incidents and accidents involving RPSs.

NASA provides the DOE with overall system requirements, specifications, schedules, and interfaces; provides data to support DOE safety analyses in accordance with NEPA; supports nuclear launch approval (e.g., launch-vehicle databooks); complies with minimum radiological occupational and public health and safety criteria and procedures specified by the DOE; provides adequate facilities for safe and secure storage, assembly, and checkout of RPSs while in NASA custody; and provides tracking, command, and data services required to monitor RPSs during and subsequent to launch.

The 2006 National Space Policy directs the United States to develop and use space nuclear power systems where such systems safely enable or significantly enhance space exploration. This policy reaffirms DOE's role in maintaining nuclear infrastructure as well as the ability to conduct nuclear safety analyses to support the nuclear launch approval process.

Historically, the DOE or its predecessor agencies (the Atomic Energy Commission and the Energy Research and Development Administration) bore the cost of establishing and maintaining the infrastructure to produce ^{238}Pu and to develop RPS technology and systems. NASA would then reimburse the DOE for the incremental costs of producing the ^{238}Pu that NASA used and for the flight hardware that it launched. Consistent with this historic precedent, NASA is reimbursing the DOE for the full cost of the ^{238}Pu that the DOE is purchasing from Russia, because all of that ^{238}Pu is being used for NASA missions.

If the United States is to continue using RPSs for space science and exploration, it is appropriate for the DOE to continue the maintenance and operation of the nuclear facilities required for the fabrication and testing of fueled RPS components and systems. Because of the DOE's statutory responsibilities, it is also appropriate for the funding of these facilities to be included in the DOE budget rather than passing these funds through NASA's budget. These facilities are required to operate according to DOE rules and regulations. The DOE's budget has funding to continue the maintenance and operations of the nuclear facilities required to support the fabrication of RPSs—but no funds are included for

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and both spacecraft are now out of the ecliptic plane. The Voyager RPSs are projected to provide enough power for these spacecraft to operate until approximately 2020.

production of ^{238}Pu. If the production of ^{238}Pu is not reestablished, these DOE facilities could be shut down after they process the last available ^{238}Pu.

FINDING. Roles and Responsibilities. Roles and responsibilities as currently allocated between NASA and the Department of Energy are appropriate, and it is possible to address outstanding issues related to the short supply of ^{238}Pu and advanced flight-qualified RPS technology under the existing organizational structures and allocation of roles and responsibilities.

RPS NUCLEAR SAFETY

Safety is an integral part of any nuclear system, and it encompasses the entire system life cycle. Nuclear safety for RPSs encompasses design, development, assembly, checkout, testing, handling, transport, storage, ground checkout, integration with payload, mating with launch vehicle, pre-launch activities, launch, ascent, orbital insertion, trajectory insertion, in-flight checkout, mission operations, and final disposition. RPS safety includes the protection of the public, the environment, workers, property, and other resources from undue risk of injury or harm. To achieve these goals, three objectives must be met: (1) design safety into each RPS at the outset, (2) demonstrate the safety of RPSs through testing and analysis, and (3) assess the level of risk for each RPS-powered space mission as required to support the launch approval process.

Processes have been established to address all of these objectives. The DOE has well-established rules, specifications, and procedures for the safe design, development, testing, transport, and handling of RPSs. The DOE also has developed sophisticated tools to conduct safety and risk analyses to support the flight safety review and launch approval process.

Because ^{238}Pu emits alpha particles, U.S. RPSs only pose a biological hazard if the ^{238}Pu is somehow released into the environment and is then either ingested or inhaled. Ingestion is only plausible through the food chain, where foods contaminated with ^{238}Pu are consumed. This requires that the ^{238}Pu be released and vaporized or pulverized into small particles (less than ~100 microns in diameter), and then transported through the atmosphere so they can deposit on or within food stuffs. Similarly, inhalation is only plausible if ^{238}Pu is released and vaporized or pulverized into respirable particles (less than ~3 microns in diameter), and then transported through the atmosphere where it can be inhaled. U.S. RPSs are fueled with ^{238}Pu in the form of a ceramic oxide ($^{238}PuO_2$) that has a high melting point and very low solubility to (1) minimize fuel vaporization and transport in the atmosphere and (2) minimize fuel retention within the human body, if it should occur.

RPSs are designed with multiple fuel containment barriers (i.e., defense in depth) to prevent release and, if a release should occur, to limit the dispersal of ^{238}Pu into the biosphere in credible accident scenarios that could occur during a space mission. For U.S. RPSs on the Galileo mission to Jupiter (October 1989) and on all subsequent missions to date, each $^{238}PuO_2$ fuel pellet is encapsulated in a ductile, high-temperature iridium-based alloy. Two encapsulated $^{238}PuO_2$ fuel pellets are packaged within a cylindrical graphite impact shell constructed of a carbon-carbon composite. Two graphite impact shells are packaged within a reentry aeroshell that is also constructed of a carbon-carbon composite. This assembly, which is approximately 4in x 4in x 2in, is called a general purpose heat source (GPHS) module. This is the standard RPS fuel module now used in all U.S. RPSs, and it reflects many improvements in materials and packaging that have been introduced over time.[5]

Testing and analysis must be performed to determine the response of all RPSs to credible accident environments. Testing validates analysis models and establishes and demonstrates the level of

[5] It is possible to conceive of an RPS design that uses a different approach to packaging the ^{238}Pu fuel. However, any new approach would require demonstrating, through analysis and testing, that the new approach will be safe during normal operating conditions and credible accident scenarios. This would be very expensive and time-consuming, in part because some of the facilities used to develop the current fuel system no longer exist.

safety built into the design. A tremendous amount of testing has been conducted on the GPHS fuel, materials, and hardware since its original design and development in the mid-to-late 1970s.

The efficacy of the U.S. RPS design safety approach was demonstrated during the launch of the Nimbus B-1 meteorological satellite, with two SNAP-19B2 RPSs on board, from Vandenberg Air Force Base, California, on May 18, 1968. During this launch, range safety destruct of the launch vehicle and upper stage was initiated by the range safety officer, because the launch vehicle was ascending erratically. Although the launch vehicle and payload were totally destroyed by the explosion, the RPSs were recovered intact. No release of ^{238}Pu occurred, and the $^{238}PuO_2$ fuel was used on a later mission.

Nevertheless, the use of RPSs does create some risk that ^{238}Pu could be released into the biosphere, however low that risk may be. To assess this risk, the Unites States has established a flight safety review and launch approval process for RPS-powered missions. This process is structured to ensure that the radiological risk for each mission is characterized in detail and independently evaluated so that an informed launch decision can be made, based on sound risk-benefit considerations.

The U.S. flight safety review and launch approval process for space nuclear power systems is established by Presidential Directive/National Security Council Memorandum 25 (PD/NSC-25, 1977). As part of this process, the DOE prepares a series of increasingly detailed Safety Analysis Reports that characterize the radiological risk for the each mission.

For each NASA mission, the NASA administrator requests establishment of an Interagency Nuclear Safety Review Panel (INSRP) comprised of coordinators from the Department of Defense, Environmental Protection Agency, NASA, and the DOE, with a technical advisor from the Nuclear Regulatory Commission. The INSRP coordinators and the technical advisor are appointed by senior management from within each agency's safety oversight office. They are, therefore, independent of the mission and associated RPS development efforts, and they have the responsibility and authority to identify and address issues at any level. Each INSRP is supported by technical experts, as needed, typically in six working groups: Launch Abort, Reentry, Power Systems, Meteorology, Biomedical and Environmental Effects, and Risk Integration and Uncertainty.

The Final Safety Analysis Report is reviewed in great depth by the INSRP, which often performs additional independent analyses. The INSRP then prepares a Safety Evaluation Report. These reports identify and characterize credible accident scenarios, including the probabilities that ^{238}Pu will be released and the postulated health effects for each accident scenario, to determine overall mission risk and the uncertainties associated with that risk.

NASA uses the Final Safety Analysis Report and the Safety Evaluation Report to determine whether it will formally request launch approval from the White House. If it does, both reports are provided to the director of the Office of Science and Technology Policy (within the Executive Office of the President), who may grant launch approval, deny launch approval, or defer the decision to the President.

The entire launch approval process typically takes 3 years (including the resolution of legal challenges that are sometimes raised), although it could take as long as 8 years. The process usually takes longer than average if a mission uses a launch vehicle, upper stage, launch complex, launch trajectory, and/or spacecraft combination that has not previously been characterized and analyzed. In such cases, extra effort is needed to prepare the Launch Vehicle Databook, which identifies and characterizes accident sequences and environments that could occur during pre-launch, launch, ascent, and trajectory insertion.

FINDING. RPS Nuclear Safety. The U.S. flight safety review and launch approval process for nuclear systems comprehensively addresses public safety, but it introduces schedule requirements that must be considered early in the RPS system development and mission planning process.

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3
Plutonium-238 Supply

This chapter addresses NASA's ^{238}Pu needs and how they can be satisfied.

FOREIGN OR DOMESTIC ^{238}Pu?

When U.S. nuclear weapons production facilities were shut down in 1988 and subsequently decommissioned, the United States lost the ability to produce ^{238}Pu (except for very small amounts for research). The substantial cost of maintaining those facilities could not be justified solely on the basis of producing ^{238}Pu, especially given the large ^{238}Pu stockpile that existed at the time. That stockpile was sufficient to support RPS missions through the 1990s and into the early 2000s.[1] To supplement the DOE's dwindling stockpile of ^{238}Pu, the DOE executed an agreement with Russia in 1992 to purchase ^{238}Pu from Russia. The DOE has taken delivery of 20 kgs to date. There are three more orders to be delivered, totaling less than 20 kg.[2]

To the best of the committee's knowledge, ^{238}Pu is no longer being produced in Russia (or anywhere else), and there is not a substantial amount of ^{238}Pu left in Russia (or anywhere else) available to meet NASA's needs, beyond that which Russia has already agreed to sell to the United States. Purchasing ^{238}Pu was intended as a stop-gap measure until U.S. production was reestablished, and continued procurement from Russia cannot serve as a long-term solution to U.S. needs unless Russia itself reestablishes a ^{238}Pu production capability. Such a move would require a major investment in Russian production facilities—an investment that Russia seems unlikely to make unless the United States pays for it.

Restarting production of ^{238}Pu in Russia would take longer than restarting domestic production, because of the long time it would take to negotiate an agreement with Russia and to complete the NEPA process, which would apply to Russian production of ^{238}Pu if it were funded by the U.S. government. Based on prior experience, it would probably take 2 or 3 years just to negotiate and finalize an agreement with Russia before work could begin. In addition, ^{238}Pu obtained from Russia can only be used for civil applications and cannot be used to satisfy U.S. national security applications, should they arise. Russia has agreed to sell ^{238}Pu to the United States with the limitation that it be used only for peaceful space missions, and that same stipulation would presumably apply to future purchases.

A similar situation would likely exist if the United States attempted to obtain ^{238}Pu from a nation other than Russia: a large capital investment would be needed to construct new facilities and/or refurbish existing facilities; the work would need to comply with NEPA if it were funded by the United States; and the long time necessary to negotiate an agreement, obtain funding, and start work would create a substantial shortfall in ^{238}Pu available for NASA missions.

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[1]Because of radioactive decay, ^{238}Pu cannot be stored indefinitely. However, with a half-life of 88 years, ^{238}Pu decays rather slowly. After a storage period of 20 years, 85 percent of the original amount will still remain.

[2]The DOE did not provide an exact estimate of how much ^{238}Pu it expects to have on hand after the deliveries of Russian ^{238}Pu are complete. Based on available information, the committee estimates that there will be a total of approximately 30 kg of ^{238}Pu available for NASA, including the ^{238}Pu that has already been used to fuel the RPS for the Mars Science Laboratory, whose launch date has been postponed from 2009 to 2011.

FINDING. Foreign Sources of ^{238}Pu. No significant amounts of ^{238}Pu are available in Russia or elsewhere in the world, except for the remaining ^{238}Pu that Russia has already agreed to sell to the United States. Procuring ^{238}Pu from Russia or other foreign nations is not a viable option.

HOW MUCH DO WE NEED?

On April 29, 2008, the NASA administrator sent a letter to the secretary of energy with an estimate of NASA's future demand for ^{238}Pu (see Appendix C).[3] The committee has chosen to use this letter as a conservative reference point for determining the future need for RPSs (see Table 3-1). However, the findings and recommendations in the report are not contingent upon any particular set of mission needs or launch dates. Rather, they are based on a conservative estimate of future needs. The estimate of future needs is also consistent with historic precedent. For example, the mission set described in the Administrator's letter is consistent with the mission set in the current Agency Mission Planning Model, although the latter includes three additional RPS-powered missions: two International Lunar Network missions (that could be launched in 2013 and 2016) and a Mars Lander mission (that could be launched in 2016). These additional missions are not included in Table 3-1, but the total amount of ^{238}Pu required to fuel these additional missions is estimated to be 3.6 kg or less. As noted below, even if the ^{238}Pu required by these missions is not considered, the DOE should take immediate action to reestablish domestic production of ^{238}Pu. Including the International Lunar Network and Mars Lander missions in the demand estimate would only increase the projected ^{238}Pu shortfall.

The administrator's letter requests that the DOE maintain the capability to provide NASA with fueled RPS assemblies for 12 missions during the 20-year period from 2009 to 2028. These missions have electrical power requirements ranging from 100 to 2,000 watts (see Table 3-1).

The amount of ^{238}Pu required to meet the needs of these 12 missions will depend upon the type of RPS used to convert the thermal energy of the ^{238}Pu fuel to electrical energy. The Mars Science Laboratory is equipped with an MMRTG, and the MMRTG is also currently baselined for use on the Outer Planets Flagship (OPF) 1 mission. As Chapter 4 describes in more detail, this is the only type of RPS that is currently available, and it has a low energy-conversion efficiency (of just 6.3 percent). The ASRG's energy conversion efficiency is predicted to be 28 to 30 percent, and an ASRG will produce more electricity than an MMRTG even though it will be powered by just 2 GPHS modules instead of the 8 modules used by an MMRTG.

The ASRG or some other type of Stirling radioisotope generator (SRG) is baselined for all other missions listed in the administrator's letter.[4] All 12 missions will require a total of 105 to 110 kg of ^{238}Pu, which is equivalent to an average production rate of 5.3 to 5.5 kg per year over 20 years.

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[3]During the late 1980s and early 1990s, NASA periodically sent similar letters to DOE to update DOE regarding NASA's requirements for ^{238}Pu.

[4]As described in Chapter 4, the International Lunar Network missions, if they take place, would likely be powered by a third type of RPS: a yet-to-be-defined "Small RPS."

TABLE 3-1 NASA's demand for ^{238}Pu, 2009-2028 (as of April 2008)

Pu (kg)	Mission	Launch Date	Watts	Type of RPS
3.5	Mars Science Laboratory	2009[a]	100	MMRTG
1.8	Discovery 12/Scout	2014	250	ASRG
24.6	Outer Planets Flagship 1	2017	600-850	MMRTG
3.5	Discovery 14	2020	500	ASRG
5.3	New Frontiers 4	2021	800	ASRG
14	Pressurized Rover 1	2022	2000	High Performance SRG[b]
14	ATHLETE Rover	2024	2000	High Performance SRG
1.8-5.3	New Frontiers 5	2026	250-800	ASRG
3.5	Discovery 16	2026	500	ASRG
14	Pressurized Rover 2	2026	2000	High Performance SRG
5.3-6.2	Outer Planets Flagship 2	2027	700-850	ASRG
14	Pressurized Rover 3	2028	2000	High Performance SRG
105-110	Total demand for Pu, 2009-2028 (kg)			
5.3-5.5	Annual demand (20-year average in kg/year)			

NOTE: ATHLETE = All-Terrain Hex-Legged Extra-Terrestrial Explorer.
[a]The launch date for the Mars Science Laboratory mission is currently 2011.
[b]A high performance SRG is a yet-to-be-developed concept that would use ASRG technology to meet the high power requirements of the lunar rovers.
SOURCE: Letter from the NASA Administrator Michael D. Griffin to Secretary of Energy Samuel D. Bodman, April 29, 2008 (reprinted in Appendix C).

PLUTONIUM-238 PRODUCTION PROCESS

Production of ^{238}Pu is a complex process. At the top level, this process involves the following steps:

1. Processing of materials prior to irradiation.
   a. Purify neptunium (^{237}Np).
   b. Fabricate ^{237}Np targets.

2. Irradiation of targets in a nuclear reactor to transform ^{237}Np into ^{238}Pu.

3. Processing of materials after irradiation.
   a. Extract, separate, and purify ^{238}Pu and the remaining ^{237}Np from the irradiated targets.
   b. Recycle the extracted ^{237}Np so that it can be used to make more targets.
   c. Process the ^{238}Pu so that it can be used to fabricate RPS fuel pellets, which are then assembled into GPHS modules.

The capabilities of existing facilities and the expertise of existing staff at the DOE's Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) make them the best places to carry out the above steps. In particular, there are just two operational reactors in the United States that can enable the production of large amounts of ^{238}Pu (on the order of kilograms per year) in a timely fashion: the Advanced Test Reactor (ATR) at INL and the High Flux Isotope Reactor (HFIR) at ORNL.

The ATR and HFIR reactors are light-water fission reactors that use enriched uranium as fuel. Both have numerous cylindrical voids at various locations in and around the reactor core where targets can be inserted and irradiated. The rate at which ^{237}Np is transformed into ^{238}Pu will vary greatly according to the location of the ^{237}Np targets in the reactor.

There are nine primary test positions (flux traps) in the ATR.[5] Six of these are dedicated full-time to the DOE's Office of Naval Reactors. This office is responsible for developing reactors to power submarines and aircraft carriers for the U.S. Navy. Naval Reactors is the primary customer for the ATR and the primary source of funds used to sustain the ATR.

There are also many other usable positions in the ATR where ^{237}Np targets could be irradiated, although the outer positions have neutron and gamma fields that are an order of magnitude lower than the positions nearest the center of the core. If ^{237}Np targets are placed in all of the core positions except for the six flux traps that are dedicated to Naval Reactors, ATR is thought capable of creating up to 4.6 kg of ^{238}Pu per year using proven, cylindrical ^{237}Np targets and standard reactor operating conditions. Advanced targets with a more complex geometry, which could be introduced later as a process improvement, would increase the yield, perhaps as high as 5.8 kg/year. A yield of 3 to 4 kg/year would allow ATR to produce ^{238}Pu while still supporting the Office of Naval Reactors as well as other users, such as the National Scientific User Facility.

Like the ATR, HFIR also has multiple positions where targets can be irradiated. The DOE's Office of Science is HFIR's primary user. Assuming that HFIR will continue to support its primary mission of neutron science, HFIR can create, at most, about 2 kg/year of ^{238}Pu using standard target designs and reactor operating conditions. However, this would reduce the amount of support that it can provide to secondary activities, such as production of medical and industrial isotopes.

Some test positions tend to produce unacceptably high concentrations of an unwanted Pu isotope (^{236}Pu) in irradiated targets. Unlike ^{238}Pu, the natural decay of ^{236}Pu produces significant gamma radiation, which makes handling and processing of irradiated targets much more difficult and hazardous. Because ^{236}Pu has a half-life of just 2.9 years, if irradiated targets are determined to have too much ^{236}Pu, they are stored until the ^{236}Pu decays sufficiently so that radiation levels are within acceptable limits.

Ultimately, the total amount of ^{238}Pu that the United States can easily produce is limited by the availability of ^{237}Np. Trace amounts of ^{237}Np occur naturally in uranium ores, but as a practical matter, ^{237}Np used for ^{238}Pu production must be artificially produced. ^{237}Np is not currently being produced in the United States, and it would not be easy to restart production. (The existing stockpile was created as a byproduct of Cold War production of nuclear weapons material.) However, the United States has enough ^{237}Np in storage at INL to produce 5 kg of ^{238}Pu per year for more than 50 years.

Programmatic Options for Domestic Production

There are four primary options for initiating domestic production of ^{238}Pu in a timely fashion. All of these options (1) rely exclusively on existing reactors (ATR and/or HFIR) to irradiate ^{237}Np targets, (2) would require new or refurbished processing facilities to fabricate ^{237}Np targets and extract ^{238}Pu from the irradiated targets, and (3) would ship extracted ^{238}Pu to Los Alamos National Laboratory for encapsulation in fuel pellets.[6]

Option 1. Use HFIR alone to irradiate ^{237}Np targets, with processing of targets primarily at ORNL.

The HFIR, as currently configured, could yield 1 to 2 kg of ^{238}Pu per year and still accommodate current, high priority customers for that facility. If the HFIR were wholly dedicated to support ^{238}Pu production—and if it were configured with a new beryllium reflector—the DOE estimates that it could

[5] Flux traps are areas with high levels of thermal neutron radiation, which is ideal for converting ^{237}Np to ^{238}Pu with minimal impurities.

[6] The ^{238}Pu encapsulation facilities at Los Alamos National Laboratory are currently operational and have been used to prepare fuel for past missions as well as the Mars Science Laboratory. All four programmatic options for domestic production of ^{238}Pu assume that ^{238}Pu encapsulation facilities will remain at Los Alamos National Laboratory because it would not be cost-effective to relocate them to another location such as INL.

yield at least 3 kg of ^{238}Pu per year.[7] However, like the ATR, the HFIR is a unique facility, and it is not realistic to expect that the DOE would displace all current users of that facility in order to dedicate the HFIR wholly to ^{238}Pu production.

Option 2. Use ATR alone to irradiate ^{237}Np targets, with processing of targets primarily at INL.

It may be technically possible to get 5 kg/year from just the ATR, but only at the cost of displacing virtually all other users except for the Office of Naval Reactors, and at the cost of production flexibility when the ATR is out of service for routine or corrective maintenance.

Option 3. Use ATR and HFIR to irradiate ^{237}Np targets, with processing of targets primarily at INL

If both the ATR and HFIR reactors are used to support ^{238}Pu production, a yield of 5 kg/year could be achieved without displacing the primary customers of either facility, and ^{238}Pu production would continue even when one of the reactors is shut down for routine or corrective maintenance. Under this option, ^{237}Np targets would be fabricated at INL. Irradiation of ^{237}Np targets would occur at both INL and ORNL. Plutonium-238 recovery and purification would occur at INL.

Option 4. Use ATR and HFIR to irradiate ^{237}Np targets, with processing of targets primarily at ORNL

This option is the same as Option 3, except that the processing of targets before and after irradiation would be conducted primarily at ORNL. With this option, INL would continue to store the existing stockpile of ^{237}Np, shipping it to ORNL as needed for fabrication of ^{237}Np targets.

If and when the DOE is funded to reestablish ^{238}Pu production, the DOE's first task will be to decide which of the above options to use. The committee believes that both Options 3 and 4 are viable approaches for initiating domestic production of ^{238}Pu, and the differences between these two options, in terms of cost, schedule, etc., pale in comparison to the negative consequences of continued inaction to implement either option.

The major cost of implementing either Option 3 or 4 would be for capital improvements at the site where most of the processing operations would take place. For both approaches, previous, preliminary estimates by the DOE indicate that capital costs at the primary laboratory would be about \$150 million over 5 to 7 years. The cost of capital improvements at the supporting center was estimated to be approximately \$10 million to \$12 million. The DOE will undoubtedly update these estimates as part of its site selection process. A reliable estimate of the incremental cost of producing each new kilogram of ^{238}Pu, after capital improvements are completed, is not available.

Option 4 would allow fabrication of ^{237}Np targets to start earlier than with Option 3.[8] Thus, Option 4 would allow testing of targets in the ATR and HFIR reactors to start sooner than with Option 3. This testing is necessary to validate predictions regarding the yield of ^{238}Pu and the presence of undesirable isotopes in targets irradiated at various locations in the reactors.

From 1998 to 2000, the DOE prepared a broad EIS concerning its nuclear facilities that included reestablishing ^{238}Pu production in the United States. This EIS, entitled *Final Programmatic Environmental Impact Statement for Accomplishing Expanded Civilian Nuclear Energy Research and Development and Isotope Production Missions in the United States, Including the Role of the Fast Flux Test Facility*, is commonly referred to as the Nuclear Infrastructure Programmatic Environmental Impact Statement (NI PEIS) (DOE, 2000). This EIS established the need to produce 5 kg/year of ^{238}Pu to meet

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[7]Most of the neutrons produced in fission reactors appear as high-energy ("fast") neutrons. The beryllium reflector increases the rate at which fast neutrons slow down, thereby increasing the level of low-energy ("thermal") neutron radiation in the reactor.

[8]Options 3 and 4 would both require existing facilities to be upgraded. Option 3 would also require some new construction at INL before ^{237}Np targets could be fabricated.

national needs for RPSs. A record of decision was issued that approved the NI PEIS (Federal Register, 2001). To date, no Administration has requested and Congress has not provided funds necessary to implement the work described in the NI PEIS. The DOE could implement option 3 or option 4 using (1) a modification of an existing EIS for INL and (2) a separate existing EIS for ORNL (without modification).

In addition to the four options described above, other, less practical options also exist. For example, building a new reactor similar to HFIR or ATR would enable production rates substantially higher than 5 kg/year. This could completely eliminate ^{238}Pu availability as a constraint on NASA missions and RPS designs. However, this approach would probably cost on the order of a billion dollars—much more than the cost of using existing reactors. In addition, it would probably take 10 to 15 years to complete the necessary reviews and construct a new reactor—too long to satisfy NASA's future needs without a long hiatus in RPS-powered missions.

Another approach would be to build multiple, large TRIGA reactors,[9] but the effectiveness of this approach has not been demonstrated. In any case, this option would take much longer than any option that uses the existing HFIR and ATR reactors, and it may not be possible to generate neutron flux levels in a TRIGA reactor high enough for useful ^{238}Pu production rates.

It is also possible to produce ^{238}Pu using a commercial light water reactor (CLWR) operated by an electric utility. Such a reactor could yield 5 kg of ^{238}Pu/year while still producing electricity. However, aluminum-clad ^{237}Np targets, which have been used in the past and could be used with ATR and HFIR, would not be suitable for the high operating temperatures of a CLWR. Thus, this option would require development of new ^{237}Np targets with Zircaloy or stainless steel cladding (DOE, 2000). It would take years to develop, test, and validate the performance of new target designs in specific locations in a particular commercial reactor. The Record of Decision for the NI PEIS notes that CLWR options for producing ^{238}Pu "were not selected because of uncertainties in the target design, development and fabrication. The design and fabrication technology of ^{237}Np targets for irradiation in ATR and HFIR is much more mature" (DOE, 2001). Given that nothing has been done to address these uncertainties since the Record of Decision was issued in 2001, CLWRs are not a viable option for addressing the need to reestablish ^{238}Pu production as soon as possible.

If funding becomes available, the DOE could issue a university solicitation to consider innovative concepts for ^{238}Pu production. This research would be directed at possible improvements over the long term, but it would not mitigate the need to provide an assured supply of ^{238}Pu in the near term.

In summary, there are many different options that, in principle, could be used to restart domestic production of ^{238}Pu. Given enough time and money, many approaches could likely be made to work. But given NASA's ongoing need for RPSs; given the technical, cost, and schedule uncertainties associated with other approaches; and given the schedule and budgetary constraints that exist, the only timely and practical approaches for restarting domestic production of ^{238}Pu involve the use of the DOE's ATR and HFIR reactors. These are also the lowest risk approaches, because they rely on proven processes and technologies to a much larger extent than any other option.

The committee believes that it is reasonable to establish 5 kg/year as the goal for domestic production of ^{238}Pu for several reasons:

- The NI PEIS established that a production rate of 5 kg/year would meet national needs for ^{238}Pu.
- NASA's need for domestic production of ^{238}Pu through 2028 is on the order of 5 kg/year.

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[9]TRIGA reactors are a class of small nuclear reactors designed and manufactured by General Atomics. TRIGA is an acronym for "Training, Research, Isotopes, General Atomics." TRIGA reactors are pool-type reactors that can be installed without a containment building, and they are designed for use by scientific institutions and universities for undergraduate and graduate education, private commercial research, non-destructive testing, and isotope production. General Atomics has built TRIGA reactors in a variety of configurations and capabilities, with steady state power levels ranging from 20 kilowatts to 16 megawatts (GA, 2009).

- It would be difficult to produce ^{238}Pu at a rate substantially higher than 5 kg/year using existing reactors (i.e., the ATR and HFIR) because of technical factors and because these reactors meet currently subscribed and funded needs by other users.

Even so, over the longer term, the national need for ^{238}Pu could exceed 5 kg/year, and long-term efforts to enhance ^{238}Pu production capabilities should consider the need for higher production rates, perhaps in concert with an assessment of long-term national needs and capabilities for the production of key radionuclides.

FINDING. Domestic Production of ^{238}Pu. There are two viable approaches for reestablishing production of ^{238}Pu, both of which would use facilities at Idaho National Laboratory and Oak Ridge National Laboratory. These are the best options, in terms of cost, schedule, and risk, for producing ^{238}Pu in time to minimize the disruption in NASA's space science and exploration missions powered by RPSs.

FINDING. Alternate Fuels and Innovative Concepts. Relying on fuels other than ^{238}Pu and/or innovative concepts for producing ^{238}Pu as the baseline for reestablishing domestic production of ^{238}Pu would increase technical risk and substantially delay the production schedule. Nevertheless, research into innovative concepts for producing ^{238}Pu, such as the use of a commercial light water reactor, may be a worthwhile investment in the long-term future of RPSs.

IMMEDIATE ACTION IS REQUIRED

DOE's inability to produce ^{238}Pu and its limited ability to sustain its ^{238}Pu stockpile using foreign sources is inconsistent with NASA's current plans and future ambitions. Because of the short supply of ^{238}Pu, NASA has baselined future space missions with an RPS that has yet to be flight qualified. In addition, NASA has been making mission-limiting decisions based on the short supply of ^{238}Pu. NASA has been eliminating RPSs as an option for some missions and delaying other missions that require RPSs until more ^{238}Pu becomes available. For example, the New Frontiers 3 Announcement of Opportunity is not open to RPS-powered missions. This will likely eliminate from consideration some of the missions described in the report, *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (NRC, 2008), because solar power is not feasible for some of the missions described in that report.

The report *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (NRC, 2003), describes the solar probe mission as the "highest priority in the large mission category," with implementation recommended as soon as possible. The Solar Probe mission, now scheduled for launch in 2015, has been rescoped to eliminate the need for an RPS. The rescoped mission will spend more time near the Sun, but the closest point of approach will be 8.5 solar radii from the surface of the Sun instead of 3 (JHU, 2008).

Similar considerations affect other missions. The mission planning teams for OPF 1 have been directed to minimize power and consider the use of ASRGs. The use of a mixed package of RPSs has also been considered. For example, MMRTGs could be used to provide a basic level of power, and ASRGs could be used for additional power for full mission capability. For the OPF 1 mission, concurrent science operations will have to be limited unless there are at least 4 or 5 MMRTGs (or the equivalent number of ASRGs).

The decadal survey for solar and space physics identifies the interstellar probe as another high-priority mission, although it has been deferred until necessary propulsion capabilities are available (NRC, 2003; 2004). Given the demise of Project Prometheus (NASA's space nuclear reactor power and propulsion program), the interstellar probe is not possible without RPSs (which are far less expensive than space nuclear reactors).

TABLE 3-2 Best-Case Estimate of ^{238}Pu Shortfall through 2028: ^{238}Pu Demand Versus Supply Subsequent to OPF 1

Mission	Pu (kg)	
Discovery 14	3.5	
New Frontiers 4	5.3	
Pressurized Rover 1	14.0	
ATHLETE Rover	14.0	
New Frontiers 5	1.8-5.3	
Discovery 16	3.5	
Pressurized Rover 2	14.0	
Outer Planets Flagship 2	5.3-6.2	
Pressurized Rover 3	14.0	
	75.4-79.8	Total ^{238}Pu demand subsequent to OPF 1
	−13.0	Remaining inventory of ^{238}Pu after OPF 1 (with ASRGs)
	62.4-66.8	Best case estimate of ^{238}Pu production needed
	−58.0	Total ^{238}Pu production if work starts in FY 2010
	4.4-8.8	Best case estimate of ^{238}Pu shortfall

The DOE's budget does not currently include funds to reestablish production of ^{238}Pu. Yet, even if funding does become available in FY 2010, full-scale production of ^{238}Pu (5 kg/year) is unlikely to be possible until 2018, and that will be too late to meet all of NASA's needs. In fact, if the OPF 1 mission uses MMRTGs, as is currently baselined, even if the DOE starts work immediately to restore its ^{238}Pu production capability, there will be a substantial shortfall in meeting NASA's needs for ^{238}Pu through 2028.

While it remains to be seen whether ASRGs can and will be flight qualified in time for OPF 1, if ASRGs can be used, NASA estimates that there will be 13 kg of ^{238}Pu left from the available stockpile (including future deliveries of Russian ^{238}Pu) to power missions after OPF 1. Those missions (through 2028) and their demand for ^{238}Pu are listed in Table 3-2. They will require a total of 75.4 to 79.8 kg of ^{238}Pu. Thus, the required production from now through FY 2028 is at least 62.4 to 66.8 kg.

Assuming that the DOE begins work in FY 2010 to establish the capability to produce 5 kg of ^{238}Pu per year, it will be able to produce 1 kg of ^{238}Pu in 2016, 2 kg in 2017, and 5 kg in 2018 and in each year thereafter. This amounts to a total production of 58 kg through the end of FY 2028. The net result is a shortfall of 4.4 to 8.8 kg. Thus, even in a "best case" scenario that minimizes ^{238}Pu demands and maximizes ^{238}Pu supply—which is to say, even if it is optimistically assumed that (1) NASA's future RPS mission set is limited to those missions listed in the NASA administrator's letter of April 2008,[10] (2) the ^{238}Pu required by each mission is the smallest amount listed in that letter (for missions with a demand for ^{238}Pu that is listed as a range of values), (3) ASRGs are flight qualified in time to use them instead of MMRTGs on OPF 1, and (4) funds for ^{238}Pu production are included in the DOE's budget for FY 2010—it would not be possible for the DOE to meet NASA's total demand for ^{238}Pu. Immediate action is required to minimize the mismatch between NASA needs and the DOE capabilities and to avoid a potential hiatus in U.S. capability to launch RPS-powered spacecraft. Continued inaction will force NASA to make additional, difficult decisions to reduce the science return of some missions and to postpone or eliminate other missions until a source of ^{238}Pu is available.

It has long been recognized that the United States would need to restart domestic production of ^{238}Pu in order to continue producing RPSs. The problem is that the United States has delayed taking action to the point where the situation has become critical, and the dwindling inventory of ^{238}Pu—and

[10] Letter from the NASA Administrator Michael D. Griffin to Secretary of Energy Samuel D. Bodman, April 29, 2008 (reprinted in Appendix C).

uncertainty about the future supply of ^{238}Pu—is now a major constraint on planning the future of the U.S. space program. In recent years, each time a proposal has been made to restore production of ^{238}Pu, action has been deferred. However, the day of reckoning has arrived, and continued delays in taking action to reestablish domestic production of ^{238}Pu will exacerbate the effect of current shortfalls, as detailed in Figure 3-1.

The top part of Figure 3-1shows three options for future ^{238}Pu supply: (1) funding for ^{238}Pu production is included in the DOE's FY 2010 budget (red line [square data points]), (2) funding for ^{238}Pu production is included in the DOE's FY 2012 budget (orange line [triangular data points]), or (3) no ^{238}Pu production (black line [circular data points]).

The middle part of Figure 3-1 shows two options for future ^{238}Pu demand: (1) OPF 1 uses MMRTGs (green line [square data points])or (2) OPF 1 uses ASRGs (blue line [triangular data points]). This plot assumes that ^{238}Pu must be available 1or 2 years before a mission launch date. It also assumes that missions are launched in accordance with the NASA Administrator's letter of April 28, 2008. Of course, mission launch dates are always subject to change. For example, the best estimate for the OPF 1 launch date is now 2020, not 2017 as indicated in the Administrator's letter. Although changes such as this will change the shape of the middle portion of the demand and balance curves, they do not change the end result, which is that NASA is facing a shortfall in ^{238}Pu that will be difficult to overcome.

The bottom part of Figure 3-1 shows the future ^{238}Pu balance for several combinations of ^{238}Pu supply and demand. The blue lines [triangular data points] depict combinations where OPF 1 uses ASRGs. The green lines [square data points] depict combinations where OPF 1 uses MMRTGs. Every possible combination of ^{238}Pu supply and demand, including those not shown in the figure, results in a future shortfall of ^{238}Pu.

A continuation of the status quo (no production of ^{238}Pu and OPF 1 uses MMRTGs) results in the largest shortfall, with all available ^{238}Pu consumed by 2019. The best case scenario has the smallest shortfall. However, it seems unlikely that all of the assumptions that are built into the best case scenario will come to pass. MMRTGs are still baselined for OPF 1, there remains no clear path to fight qualification of ASRGs, and FY 2010 funding for ^{238}Pu production remains more of a hope than an expectation. Thus, the actual shortfall is likely to fall somewhere between the best-case curve and the status-quo curve, and it could easily be 20 kg or more instead of the 4 to 9 kg calculated in Table 3-2.

Continued inaction is also a problem because of schedule requirements. Space science and exploration missions and spacecraft design vary according to the type of power systems available for use. Mission planners require assurance, early in the planning process, that the ^{238}Pu required by a prospective mission will be there when it is needed. All available ^{238}Pu will be essentially consumed by the Mars Science Laboratory, Discovery 12, and OPF 1 missions (assuming MMRTGs are used for OPF 1, in accordance with NASA's current plans). NASA is unlikely to initiate competitive procurements or develop additional RPS-powered spacecraft until the DOE begins construction of the facilities required to produce the ^{238}Pu needed by those addional missions. As shown in Figure 3-2, if the DOE receives funding in FY 2010 for ^{238}Pu production, the DOE should be able to begin construction of new facilities and/or modification of existing facilities, as necessary, by the end of FY 2013, which would enable the next set of RPS-powered missions (Discovery 14, New Frontiers 4, and the first pressurized lunar rover) to proceed on schedule. However, a delay of one year could force a delay in the New Frontiers 4 schedule, and delay of two years or more could force a delay in the schedule of Discovery 14, the first lunar rover, and subsequent missions.

FINDING. Current Impact. NASA has already been making mission-limiting decisions based on the short supply of ^{238}Pu.

FINDING. Urgency. Even if the Department of Energy budget for fiscal year 2010 includes funds for reestablishing ^{238}Pu production, some of NASA's future demand for ^{238}Pu will not be met. Continued delays will increase the shortfall.

HIGH-PRIORITY RECOMMENDATION. Plutonium-238 Production. The fiscal year 2010 federal budget should fund the Department of Energy (DOE) to reestablish production of ^{238}Pu.

- As soon as possible, the DOE and the Office of Management and Budget should request—and Congress should provide—adequate funds to produce 5 kg of ^{238}Pu per year.
- NASA should issue annual letters to the DOE defining the future demand for ^{238}Pu.

RPS MISSION LAUNCH RATE

Late in the study process—after the committee had completed all scheduled meetings—a new issue was raised about the DOE's ability to support the high launch rate for future RPS missions that NASA currently anticipates.

The United States has launched a total of 26 RPS missions since 1961, but only 4 have been launched since 1977 (Galileo, Ulysses, Cassini, and Pluto/New Horizons). The NASA administrator's letter of April 2008 anticipates 12 RPS missions in the next 20 years, with 9 of those missions launched during the 9-year period ending in 2028.[11] Current DOE facilities used for fueling, processing, testing, and shipping RPS units—as well as the DOE workforce needed to conduct radiological contingency planning—can accommodate the relatively low RPS launch rate of recent decades, but some improvements may be needed to accommodate a sustained launch rate of one mission per year.

To address this issue comprehensively, it would be useful to identify all constraints that the DOE and NASA must overcome to increase the launch rate for RPS missions, and how those constraints could be overcome. Relevant information would include a comparison of historic and future launch rates for space nuclear systems and missions. For example, 15 RPS missions were launched during a period of 8½ years from April 1969 through September 1977. Those missions included 31 RPSs of four different designs (see Table 2-1). It would be useful to know what it took to accomplish this feat, in terms of staff, facilities, and facility usage at the DOE and at NASA, especially at JPL and Kennedy Space Center.

Assessments of workforce issues related to radiological contingency planning associated with the Safety Review and Launch Approval Process under PD/NSC-25 should also consider the demands of additional missions that use radioisotope heater units (RHUs) but not RPSs (e.g., the Mars Pathfinder mission and the Mars Exploration Rover A and B missions).[12] Also, not all launch reviews are equal.

Although Galileo and Ulysses were launched one year apart, and even though both used the same launch system and the same RPS design, the Ulysses review was just as involved as the Galileo review because the Ulysses GPHS-RTG was oriented 90 degrees from those on the Galileo spacecraft. In contrast, for the Apollo missions, the first safety review was exhaustive, but subsequent Apollo safety reviews were abbreviated, focusing on mission and system differences. Pioneer 10 and 11 were reviewed together, as were Viking 1 and 2, LES 8 and 9, and Voyager 1 and 2.

Although the committee did not have the time or information necessary to assess launch rate issues, the committee is confident that the short supply of ^{238}Pu is by far the most urgent issue that must be addressed to carry out NASA's plans for RPS missions. Still, a detailed investigation of launch rate issues would be advisable because inattention could eventually allow them to become a mission-limiting factor.

[11] Letter from the NASA Administrator Michael D. Griffin to Secretary of Energy Samuel D. Bodman, April 29, 2008 (reprinted in Appendix C).

[12] RHUs provide small amounts of heat (on the order of 1 W) to keep selected spacecraft components warm. They are used when mass and electrical power are at a premium for providing spacecraft thermal control. RHUs produce heat from the natural decay of radioactive material, but they do not produce electricity.

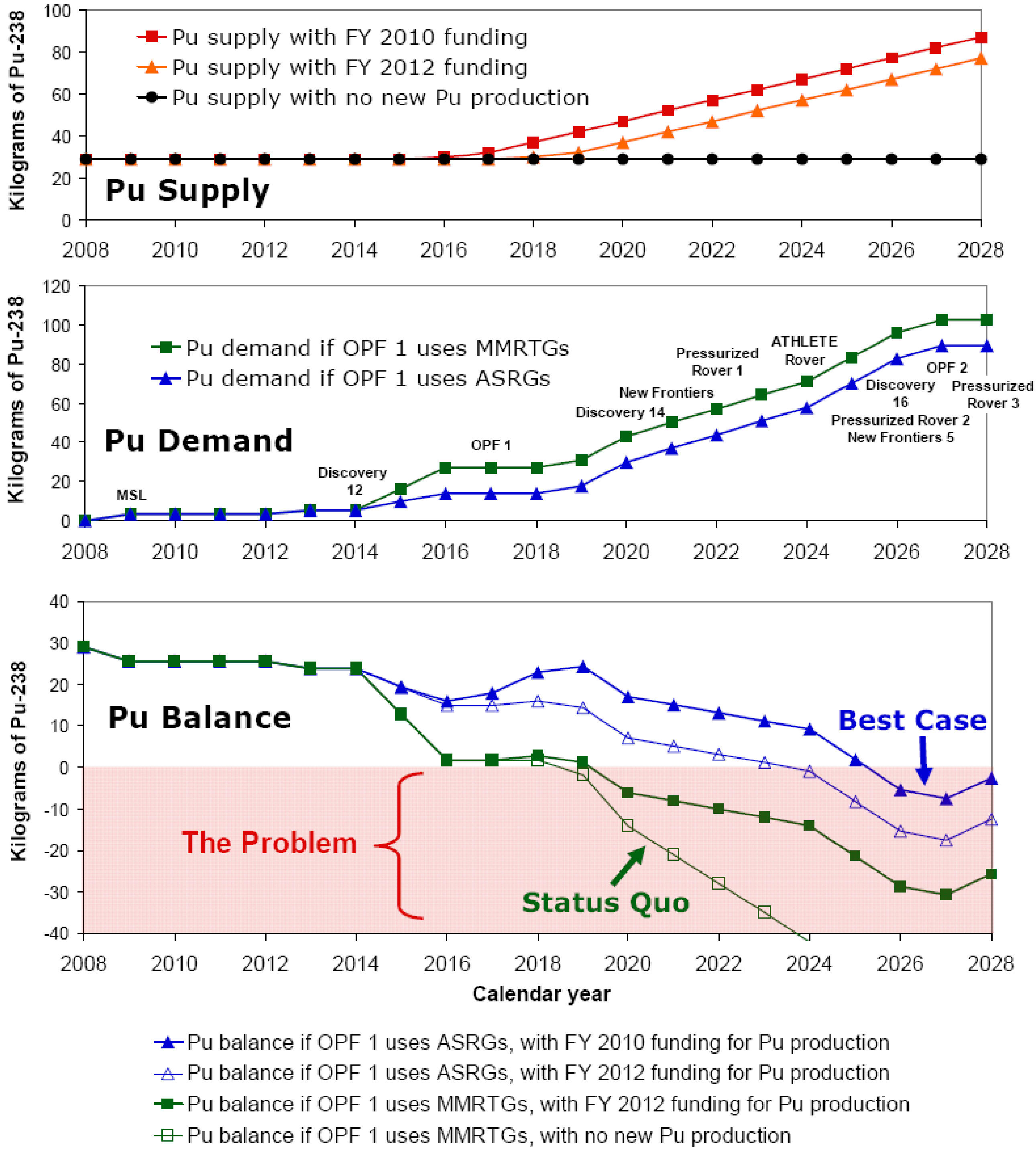

FIGURE 3-1 Potential ^{238}Pu supply, demand, and net balance, 2008 through 2028.

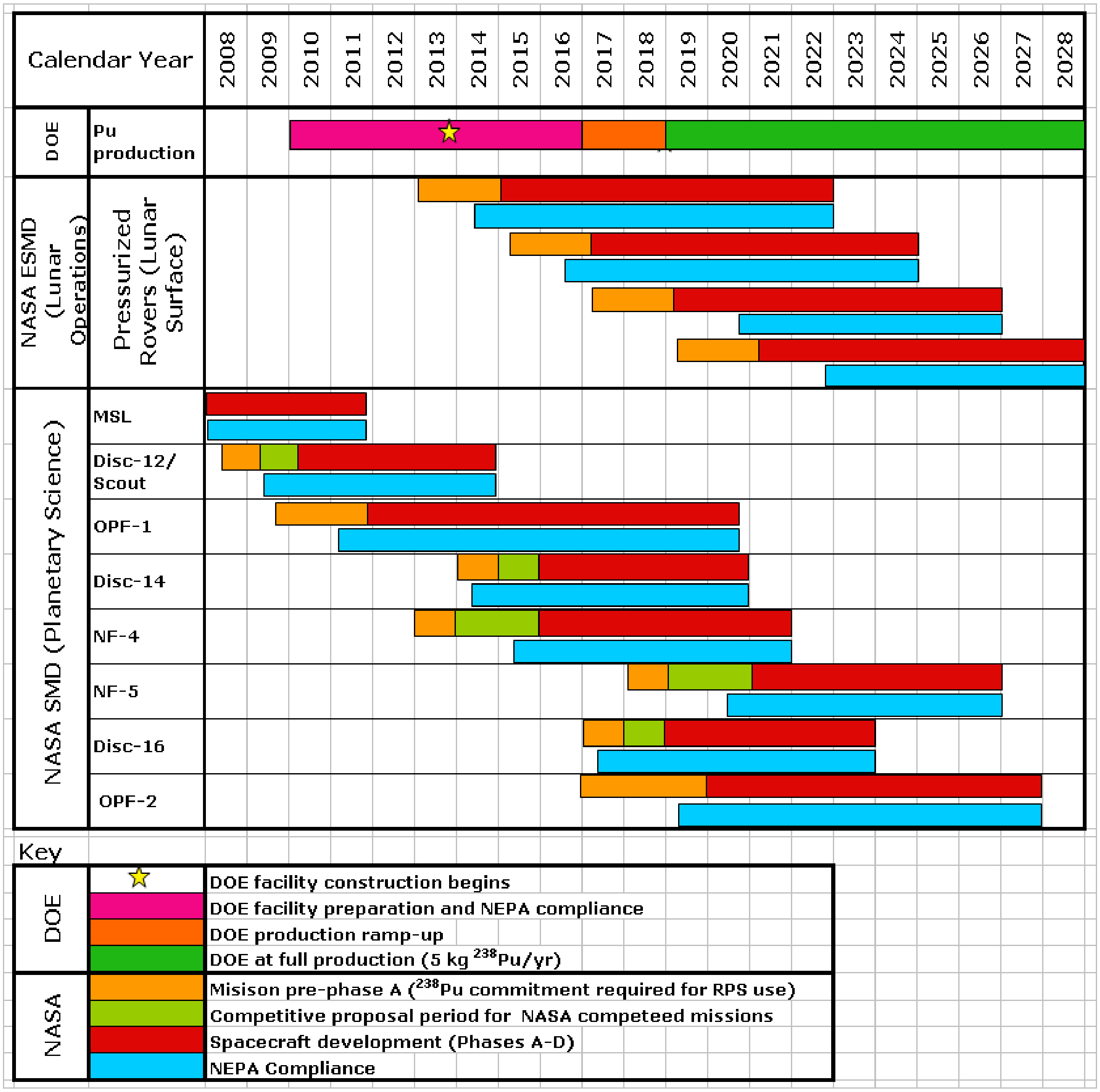

FIGURE 3-2 Timeline for reestablishing domestic ^{238}Pu production and NASA mission planning, 2010 through 2028, assuming the Department of Energy starts work in fiscal year 2010.

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4
RPS Research and Development

Assuming that there will be an ongoing supply of ^{238}Pu for NASA missions, NASA will also need an ongoing supply of RPSs to power those missions.

PROGRAM OVERVIEW

NASA's RPS Program Office operates as an extension of the Planetary Science Division of the Science Mission Directorate of NASA Headquarters. The program is a multi-center, multi-agency effort that supports strategic investments in RPS technologies; validation of flight systems; and production, certification, and delivery of flight hardware for NASA spacecraft. The program manages technology portfolio investments by determining priorities for future RPS mission needs in concert with NASA's Planetary Science Division and the larger science community. The program funds the development of mission-generic, engineering-model system hardware and, if warranted, prototype model hardware. This latter function is particularly critical for those missions that require RPS development activities to be started long before NASA determines what organization will manage a particular mission.

The RPS program consists of six major elements:

- Program Management is led by Glenn Research Center (GRC) and supported by the Jet Propulsion Laboratory (JPL) and the DOE. Primary responsibilities include management of program scope, budget, schedule, and risk; studies and long range planning; and education and public outreach.
- Advanced Stirling Radioisotope Generator (ASRG) flight system development is led by the DOE and supported by GRC. Lockheed Martin Space Company is the ASRG system integration contractor. The focus of this effort is on reliability improvement, risk reduction, and flight readiness.
- Advanced Stirling Converter (ASC) technology maturation is led by GRC and supported by JPL. An ASC developed by Sunpower, Inc., lies at the heart of the ASRG. The ASRG is projected to have a higher specific power and a higher system energy conversion efficiency than prior RPSs.
- Sustaining launch-approval-engineering (LAE) capabilities, as well as related capabilities necessary to comply with NEPA, is led by JPL and supported by the Kennedy Space Center.
- Small RPS development is intended to provide mission planners with more power options. The International Lunar Network has been suggested as an initial mission for a small RPS. The anticipated power level for the International Lunar Network is about 40 W,[1] with an initial launch date of 2013. This means that there is no time for technology development. In fact, it would be difficult for the DOE, NASA, and industry to design, assemble, test, and certify a new RPS and have it ready to go in time for a launch in 2013 even without technology development. Looking beyond the International Lunar Network, NASA is still in the process of setting specific goals for a small RPS. NASA anticipates that power requirements will be on the order of 10-60 W_e, mission length will be 3 to 10 years, system mass

[1]This is comparable to the initial requirements of the Surveyor program of the 1960s that were to be accommodated by the SNAP-11 project and for the same reason: to survive the 14-day-long lunar night. This requirement was abandoned on the Surveyor program and a SNAP-11 unit was never flown.

will be less than 15 kg, and the heat source will be a single GPHS module. This effort is to be led by the DOE. NASA has yet to decide which of its organizations will support this effort.

- The technology portfolio supports, at a low level, research and development for additional converter technologies with an eye toward future generations of RPSs, subsequent to the ASRG. This includes advanced thermoelectrics research, led by JPL with support from GRC, and thermophotovoltaics (TPV) research, led by GRC. The technology portfolio also includes funding for outside organizations through NASA Research Announcements.
  - The goal of advanced thermoelectric research is to develop thermoelectric materials that are much more efficient than traditional thermoelectric materials. Success in this area could ultimately lead to the development of an advanced thermoelectric converter, which could then be used in an advanced RTG (ARTG).
  - A TPV RPS would be a relatively simple device that uses an array of photovoltaic material adjacent to a GPHS to generate electricity. The basic device (without the cooling fins) is not much larger than the GPHS itself. The converter efficiency is expected to be at least 15 percent, so that a TPV RPS powered by a single GPHS module would produce at least $38W_e$ at beginning of life.

PROGRAM BALANCE

Figure 4-1 shows the relative magnitude (in terms of NASA's budget) of each element of the RPS program. Until 2007, the RPS program was a technology development effort. At that time, the focus shifted to development of a flight-ready ASRG, and that remains the current focus of the RPS program. The program received no additional funds to support this new tasking, so funding to develop a Brayton-cycle converter and a milliwatt-scale thermoelectric converter was eliminated. In addition, the budget for the remaining RPS technologies (advanced thermoelectrics and TPV) was cut. As a result, the development of new generations of RPSs that use these technologies has been delayed.

With the development of the MMRTG, the manufacture of GPHS RTGs was discontinued, and it would be very difficult and expensive to manufacture new GPHS RTGs (although it may be possible to build two or three GPHS RTGs using leftover thermocouples). The RPS program is now focused on development of ASRGs; the current budget has no funding set aside to retain the ability to produce MMRTGs, although NASA has asked the DOE to determine what it would take to keep MMRTG production capabilities active for two years.

The central issue that threatens the future of RPS-powered missions is the short supply of ^{238}Pu. Accordingly, RPS research and development should strive to meet NASA's mission requirements for RPSs while minimizing NASA's demand for ^{238}Pu. In addition, a balanced program would develop RPS technologies and systems suitable for various applications, and it would support development of RPS technology for near- and far-term use.

Because the RPS program is focused on advanced development of a single RPS design for near-term application, the RPS program (in FY 2009) is not well balanced. However, this imbalance is appropriate given that (1) the FY 2009 budget is insufficient to sustain a well-balanced program, and (2) the focus on ASRGs is well aligned with current programmatic priorities. The balance of the program would improve under the current out-year funding scenario (if enacted), as ASRG development is completed, the RPS budget is doubled, and funding for other RPS technologies is expanded. The planned development of a small RPS would be a good first step towards the goal of establishing a suite of RPSs with capabilities optimized for different mission scenarios.

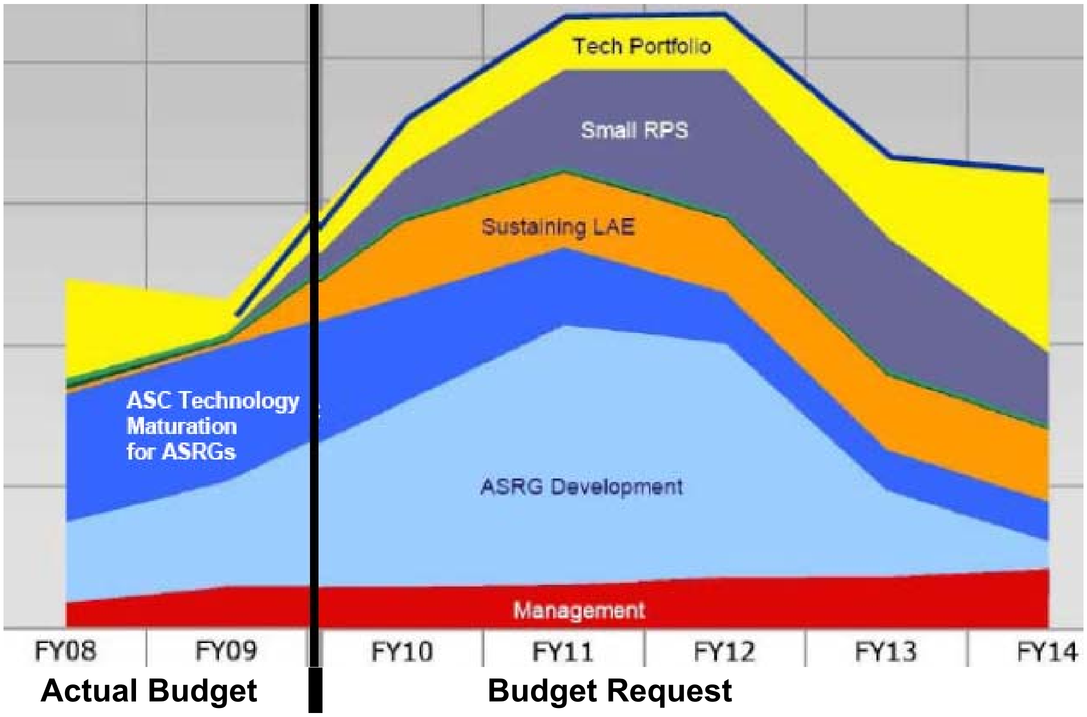
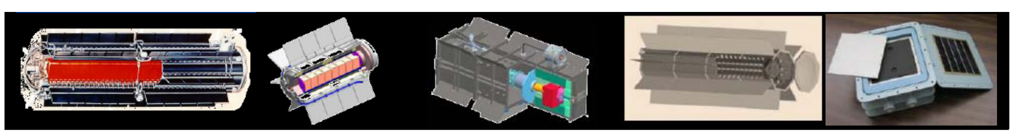


FIGURE 4-1 Relative magnitude of key elements of NASA's RPS program. (Actual budget shown for fiscal year (FY) 2008 and 2009. Budget shown for FY 2010 to 2014 not yet enacted.)
SOURCE: Leonard A. Dudzinski, NASA, "Radioisotope Power Systems. Power Systems Program. Historical Overview and Current Content," presentation to the Radioisotope Power Systems Committee, September 18, 2008, Washington, D.C.



	GPHS-RTG Past	MMRTG Present	ASRG In development	ARTG Future	TPV Future
Electric output, BOM, W_e	285	125	~140-150	~280 to 420	~38-50
Heat input, BOM, W_e	4500	2000	500	3000	250
RPS system efficiency, BOM, %	6.3	6.3	~28-30	~9-14	~15-20
Total system weight, kg	56	44.2	~19-21	~40	~7
Specific power, W_e/kg	5.1	2.8	~7-8	~7-10	~6-7
# GPHS modules	18	8	2	12	1
GPHS module weight, kg	25.7	12.9	3.2	19.3	1.6
^{238}Pu weight, kg	7.6	3.5	0.88	5.3	0.44

FIGURE 4-2 Performance of past, present, and future RPSs.
SOURCE: S. Surampudi, NASA, "Radioisotope Power Systems Technology Programs," presentation to the Radioisotope Power Systems Committee, November 18, 2008, Washington, D.C.

FINDING. Programmatic Balance. Balance within NASA's RPS program is impossible given the current (fiscal year 2009) budget and the focus on development of flight-ready ASRG technology. However, NASA is moving the ASRG project forward, albeit at the expense of other RPS technologies.

RPS SYSTEM CAPABILITIES

Figure 4-2 compares the performance of past, present, and future RPSs. The technology development cycle for new RPS technologies is typically 15 to 20 years long, and it is driven by perceived mission needs (rather than actual mission requirements) because, even for very large spacecraft and very important missions, it is impossible to predict with certainty what mission requirements will be 15 to 20 years in the future. Over such a long time span, space exploration priorities often change as changes occur in the leadership of the Administration and Congress.

POWER SYSTEM FOR THE OUTER PLANETS FLAGSHIP 1 MISSION

Studies of four possible OPF 1 mission concepts began in 2007. The last two mission concepts under consideration are the Titan Saturn System Mission (TSSM) and the Europa Jupiter System Mission (EJSM) (JPL, 2009). The EJSM would consist of two parts: NASA's Jupiter Europa Orbiter, which would be powered by RPSs, and the European Space Agency's Jupiter Ganymede Orbiter, which would be powered by solar arrays. Saturn is almost twice as far from the Sun as Jupiter, and the TSSM mission would last 13 years, somewhat longer than the EJSM mission (9 years).

In February 2009, NASA and European Space Agency officials determined that EJSM is more feasible technically, and it is now planned to go first as OPF 1 (NASA, 2009). NASA will ultimately decide whether OPF 1 will use MMRTGs, ASRGs, or a combination of both. (Mission studies indicate that all three options would work, assuming ASRGs are ready in time.)[2]

The ASRG is projected to have a specific power of 7 W_e/kg, compared to just 2.8 W_e/kg for the MMRTG and 5.1 W_e/kg for the best previous RPS. This improvement in specific power is a significant consideration for deep-space missions for which mass and launch-vehicle capability are typically significant system drivers. In addition, ASRGs are projected to have a system energy conversion efficiency more than four times higher than MMRTGs at beginning of life, and the projected power output of ASRGs decreases over time by only 0.8 percent per year, which is half the rate of decrease of MMRTGs.[3]

The electromagnetic interference produced by both systems is expected to be within tolerance levels for all OPF 1 instruments. Vibration measurements on the ASRG engineering unit are nearly an order of magnitude lower than the nominal vibration specification. Even so, vibration levels will require close attention and detailed analysis during spacecraft development. Regardless, the use of ASRGs on OPF 1 would not be driven by spacecraft design or operational factors. The primary motivation for using ASRGs on OPF 1 is to conserve ^{238}Pu for other missions. For NASA as a whole, this is an important consideration, given the large number of RPSs to be used on OPF 1. Using ASRGs on OPF 1 would save 16 to 19 kg of ^{238}Pu. That is enough to power RPSs for several other missions, and it is equivalent to more than 3 years of domestic production of ^{238}Pu at the highest anticipated rate of 5 kg/year.

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[2]TSSM would include an orbiter, a lander, and a Montgolfière balloon, which would be filled with the atmospheric gases present on Titan and then maintained aloft using the heat from an RPS to heat the gas inside the balloon. This balloon would use an MMRTG regardless of which RPS is chosen to power the orbiter, because an ASRG would not produce enough waste heat to keep the balloon aloft.

[3] Only part of the decay in power output in RPS systems flown to date is due to the half-life of the ^{238}Pu fuel; the rest is caused by degradation of the thermoelectric converters in the RTGs. Expectations are that ASRG power output would degrade at a lower rate than RTGs.

Nevertheless, as already noted, ASRGs are not yet ready for flight. NASA has yet to determine, for example, (1) what must be done to demonstrate that ASRGs are ready for use on OPF 1 and (2) if those requirements can be accomplished in time to meet the OPF 1 mission schedule. In general, project managers for long-life missions rely on proven technologies and redundant subsystems for mission-critical functions such as avionics and power. NASA's Science Mission Directorate generally expects new technology to advance to technology readiness level (TRL) 6 or beyond before the mission's preliminary design review.[4] With regard to ASRGs, NASA is responsible for defining (1) the specific criteria that ASRGs must satisfy prior to flight and (2) a strategy to satisfy those criteria. The problem is complex because accelerated life tests for the ASRG as a system are not possible, and the life-limiting failure modes and overall reliability of the ASRG as a system remain to be determined. Towards that end, a study team with members from JPL, GRC, and the DOE has been assessing what they believe would need to be done to qualify ASRG for the OPF 1 mission. As of February 2009, the results of this effort were not available.

The committee believes it is unlikely that NASA would baseline an ASRG for a major mission (such as an Outer Planets Flagship mission) until it first operates successfully on another mission to validate launch survivability and performance in space. The Discovery 12 mission is the earliest potential opportunity to fly an ASRG, and that mission is not scheduled for launch until 2014. NASA plans to make a final decision on whether to use MMRTGs or ASRGs for OPF 1 no later than 2012. Thus, it seems unlikely that NASA will decide to use ASRGs on OPF 1 unless (1) a flight-ready ASRG is developed in time for the Discovery 12 mission and (2) the current mission schedule for OPF 1 is delayed enough to allow NASA to postpone the selection of the OPF 1 power system until after Discovery 12 is launched and ASRGs demonstrate the ability to operate in space for some period of time.

DEVELOPMENT OF A FLIGHT-READY ASRG

Demonstrating the reliability of ASRGs for a long-life mission is critical—and it has yet to be achieved. RTGs and SRGs both begin to operate as soon as they are fueled, and they operate continuously thereafter. The design life of both MMRTGs and ASRGs is 17 years. This is intended to cover 3 years of storage (between the time they are fueled and mission launch) and 14 years of mission time after launch.

NASA plans to freeze the system design specification for the ASRG in April 2009. This is a critical and necessary step for assessing ASRG reliability and technical risk and for producing a flight-qualified ASRG.

The RPS program's risk mitigation effort is using risk identification, characterization, and mitigation to reduce risk to a level that is acceptable for a flight mission. As part of its ongoing reliability improvement and risk reduction efforts, the RPS program has produced five ASC models. Two more development models are planned before the construction of ASRG operational flight units. The progression of models has featured improvements in many areas, including materials that allow higher operating temperatures, thereby increasing conversion efficiency and/or increasing reliability for a given operating temperature.

The primary life-limiting mechanisms for Stirling heat engines, in general, are wear, fatigue, creep, permeation of helium out through the containment vessel, radiation effects (when used in a high radiation environment), and contamination. The design of the ASC is intended to avoid each of these pitfalls. Wear is not generally considered an issue for Stirling engines used in ASCs because they use gas bearings in which the moving piston is centered by pumped gas. As a result, no moving parts are in contact with each other (unless the gas bearings fail for some reason).

The ASC materials testing program is assessing material fatigue and creep. In particular, an analytical model using accelerated life testing data for the ASC heater head (which is the component most

[4]NASA defines TRL 6 as "System/subsystem model or prototype demonstration in a relevant environment (ground or space)."

susceptible to creep) has predicted a reliability of 0.999 for the design lifetime of 17 years at 817°C. Testing of ASCs in vacuum and at temperature has shown that loss of helium via permeation is not a problem, and assessments of likely radiation environments have not forced a change in the selection of any materials.

The ASC risk mitigation effort also includes long-life tests of magnets; analyses of electromagnetic interference (EMI); and analysis and testing of organic materials used for electrical insulation and potting, structural bonding, and the surface finish of moving parts. Ongoing, long-term tests of magnets are scheduled to accumulate 2 years of test data. Current levels of EMI seem to be generally satisfactory. Options to reduce EMI have been identified and could be implemented, if required. All organics in the current ASC design have been identified, evaluated, and approved. Additional tests are planned, for example, to verify that the organics will perform as expected at operating temperatures and in a radiation environment.

ASRG development has included a great deal of component testing and analysis. ASC converters have cumulatively undergone more than 200,000 hours (23 years) of testing at GRC, but that testing has been accumulated by many different devices, manufactured to various different design specifications, and the testing has been conducted under various environmental conditions. Most importantly, the longest test time that any single ASC has to date experienced is still a relatively small fraction of the 17 year design life. It is encouraging that (1) no ASC failures have thus far been experienced and (2) space-qualified, Stirling engine cryocoolers have operated successfully in space for 12 years or more. Still, the reliability of ASCs and ASRGs over a 17-year design life remains unknown, in part because of design differences between ASCs and most cryocoolers with long-life experience in space.[5]

NASA intends to extensively test every pair of ASCs that have been built. In some cases, ASC units have been tested in the laboratory and then subjected to vibration testing to simulate a launch before being returned to testing. Even so, no individual ASC unit has accumulated more than 2 years of testing. Until (1) the ASRG design specification is frozen, (2) hardware manufactured according to that design is tested as a system, and (3) extensive testing is completed in conditions that simulate the operational environment, there will remain substantial uncertainty as to whether all failure modes of the flight design have been identified and how useful existing component tests will be in predicting the reliability of ASRG flight hardware, as a complete system, for a particular mission, and for the full design lifetime of 17 years. In particular, even if the ASRG design specification is frozen on schedule in April 2009, and even if subsequent testing detects no problems with the design, it remains to be seen if extended tests will be able to accumulate enough time to justify making a switch from MMRTGs to ASRGs as the baseline RPS for OPF 1.

The initial ASC testbed demonstrated 36 percent conversion efficiency. Subsequent devices have continued to meet or exceed performance expectations. The most advanced model (the ASC-E2) has demonstrated 38.4 percent efficiency (with a hot temperature of 850°C and a heat rejection temperature of 90°C). These high levels of efficiency will allow the ASRG, as a complete system, to meet or exceed its goal of 28 to 30 percent conversion efficiency. The high levels of demonstrated efficiency have also allowed the ASC and ASRG development efforts to focus on enhancing reliability and manufacturability rather than improving efficiency beyond that which has already been achieved.

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[5]Stirling-engine cryocoolers developed the technology that is the foundation for ASCs. Cryocoolers are used in instruments operating in the infrared, gamma-ray and x-ray spectrum. Long-life cryocoolers are widely accepted as a reliable spacecraft technology; more than 20 long-life Stirling cryocoolers have been used on spacecraft manufactured in the United States, Europe, and Japan. One cryocooler operating in space (the Rutherford Appleton Laboratory 80K Integral Stirling cryocooler in the Along Track Scanning Radiometer (ATSR-2) payload on the European Remote Sensing 2 spacecraft) accumulated 12.8 years of continuous operation with no degradation before the instrument was shut down. Six others have accumulated half that lifetime with no degradation that affected mission life. However, all but one of these non-wearing, long-life Stirling cryocoolers use flexure-supported gas bearings rather than the pumped gas bearings used by the ASRGs (Ross, 2008).

An ASRG quality assurance program plan has been formally implemented. This plan includes DOE requirements for nuclear systems as well as relevant NASA requirements. The quality assurance effort encompasses all of the organizations involved in developing the ASRG. In addition, the RPS program is continuing to work on a configuration management plan and other related plans and processes.

A failure mode, effects, and criticality assessment of the ASRG engineering unit identified 51 single-point failures (SPFs). By comparison, the design of the RTG-GPHS (the standard RPS used prior to the MMRTG) has only 17 SPFs. However, a numerical comparison of the number of SPFs does not provide a good understanding of the relative reliability of the two types of devices. The likelihood of the SPFs must also be understood. For example, about 80 percent of the SPFs on the ASRG engineering unit are structural in nature, and the designers believe that the likelihood of these failures has been reduced to very low levels through the use of conservative structural designs. In any case, the issue is not whether an ASRG will be as reliable as historic RTGs; the issue is whether mission managers can be convinced that an ASRG is sufficiently reliable to meet engineering and programmatic requirements for a given mission.

NASA has used fault tree and probabilistic analysis techniques to estimate that system-level reliability is 0.967 for an ASRG at full-power operation over the entire 17-year design life. System electronics (i.e., the electronics required to control and synchronize the ASCs and to convert the electrical output from ac to dc) have been identified as the major contributor to the estimated probability of failure. System-level reliability at half-power operation (that is, the probability that an ASRG will have at least one of its two converters functioning and producing power at the end of the 17-year design life) has been estimated to be 0.984. Extended life tests will provide additional data regarding reliability, but there is not enough time or money to build enough ASRGs and then test them for long enough to determine rigorously what level of reliability they will have over a 17-year lifetime. However, this has been the case for earlier RPSs—and for other critical spacecraft hardware, as well. There has never been a numeric reliability requirement specification for an RTG, and NASA does not intend to establish one for the ASRG.

RPS FACILITIES

NASA appears currently to be well positioned with regard to key RPS research and development facilities. These facilities are located at GRC and JPL.[6] The facilities at greatest immediate risk are those associated with advanced RPS research (e.g., advanced thermoelectric and TPV research facilities). NASA has not yet lost any critical RPS facilities, and the projected budget seems adequate to sustain necessary research and development facilities. However, there are concerns related to other facilities that are necessary for the production of flight systems.

The MMRTG will fly on the Mars Science Laboratory, but this is the only mission that is firmly committed to using the MMRTG. As this work is completed, the industry teams that developed and built the MMRTG are expected to disband and industry facilities reconfigured for other purposes. It remains to be seen if NASA will sustain work on MMRTGs to keep the MMRTG industrial teams and facilities intact and related infrastructure in place until a final decision is made on what system will power OPF 1. If the ability to manufacture MMRTGs is not sustained at least until (1) the ASRG is demonstrated to be flight ready and (2) NASA commits to using ASRGs (or another comparable RPS) for long-life, deep-space missions, then even with an adequate supply of ^{238}Pu, the United States could lose the ability to manufacture any RPSs, at least for a time.

[6]This section deals with facilities associated with development and fabrication of RPS technologies and RPS converters. DOE ^{238}Pu production and RPS assembly and testing facilities are addressed in Chapter 2.

FINDING. Multi-Mission Radioisotope Thermoelectric Generators. It is important to the national interest to maintain the capability to produce Multi-Mission Radioisotope Thermoelectric Generators, given that proven replacements do not now exist.

RECOMMENDATION. Multi-Mission Radioisotope Thermoelectric Generators. NASA and/or the Department of Energy should maintain the ability to produce Multi-Mission Radioisotope Thermoelectric Generators.

RPS RESEARCH AND DEVELOPMENT—SUMMARY

The next major milestones in the advancement of ASRGs are to freeze the design of the ASRG, to conduct system testing that verifies that all credible life-limiting mechanisms have been identified and assessed, and to demonstrate that ASRGs are ready for flight. However, neither the DOE or NASA have formal guidance or requirements concerning what constitutes flight readiness for RPSs. In general, RPSs (and other systems) on spacecraft for deep space missions are flight ready when the project manager for that mission says they are flight ready. Given this situation, ongoing efforts to advance ASRG technology and demonstrate that it is flight ready are being guided by experience with past programs and researchers' best guess about the needs and expectations of project managers for future missions. While this approach has enabled progress, the establishment of formal guidance and processes for flight certification of RPSs in general and ASRGs in particular would facilitate the acceptance of ASRGs as a viable option for a deep-space missions and reduce the impact that the limited supply of ^{238}Pu will have on the NASA's ability to complete important space missions.

FINDING. Flight Readiness. NASA does not have a broadly accepted set of requirements and processes for demonstrating that new technology is flight ready and for committing to its use.

RECOMMENDATION. **Flight Readiness.** The RPS program and mission planners should jointly develop a set of flight readiness requirements for RPSs in general and Advanced Stirling Radioisotope Generators in particular, as well as a plan and a timetable for meeting the requirements.

RECOMMENDATION: Technology Plan. NASA should develop and implement a comprehensive RPS technology plan that meets NASA's mission requirements for RPSs while minimizing NASA's demand for ^{238}Pu. This plan should include, for example:

- A prioritized set of program goals.
- A prioritized list of technologies.
- A list of critical facilities and skills.
- A plan for documenting and archiving the knowledge base.
- A plan for maturing technology in key areas, such as reliability, power, power degradation, electrical interfaces between the RPS and the spacecraft, thermal interfaces, and verification and validation.
- A plan for assessing and mitigating technical and schedule risk.

HIGH-PRIORITY RECOMMENDATION. ASRG Development. NASA and the Department of Energy should complete the development of the Advanced Stirling Radioisotope Generator (ASRG) with all deliberate speed, with the goal of demonstrating that ASRGs are a viable option for the Outer Planets Flagship 1 mission. As part of this effort, NASA and the Department of Energy should put final design ASRGs on life test as soon as possible (to demonstrate reliability on the ground) and pursue an early opportunity for operating an ASRG in space (e.g., on Discovery 12).

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List of Findings and Recommendations

Given below is a complete list of the committee's findings and recommendations, in the order in which they appear in the report.

FINDING. Production of ^{238}Pu. The United States has not produced ^{238}Pu since the Department of Energy shut down its nuclear weapons production reactors in the late 1980s.

FINDING. Importance of RPSs. RPSs have been, are now, and will continue to be essential to the U.S. space science and exploration program.

FINDING. Plutonium-238 Supply. Plutonium-238 is the only isotope suitable as an RPS fuel for long-duration missions because of its half-life, emissions, power density, specific power, fuel form, availability, and cost. An assured supply of ^{238}Pu is required to sustain the U.S. space science and exploration program.

FINDING. Roles and Responsibilities. Roles and responsibilities as currently allocated between NASA and the Department of Energy are appropriate, and it is possible to address outstanding issues related to the short supply of ^{238}Pu and advanced flight-qualified RPS technology under the existing organizational structures and allocation of roles and responsibilities.

FINDING. RPS Nuclear Safety. The U.S. flight safety review and launch approval process for nuclear systems comprehensively addresses public safety, but it introduces schedule requirements that must be considered early in the RPS system development and mission planning process.

FINDING. Foreign Sources of ^{238}Pu. No significant amounts of ^{238}Pu are available in Russia or elsewhere in the world, except for the remaining ^{238}Pu that Russia has already agreed to sell to the United States. Procuring ^{238}Pu from Russia or other foreign nations is not a viable option.

FINDING. Domestic Production of ^{238}Pu. There are two viable approaches for reestablishing production of ^{238}Pu, both of which would use facilities at Idaho National Laboratory and Oak Ridge National Laboratory. These are the best options, in terms of cost, schedule, and risk, for producing ^{238}Pu in time to minimize the disruption in NASA's space science and exploration missions powered by RPSs.

FINDING. Alternate Fuels and Innovative Concepts. Relying on fuels other than ^{238}Pu and/or innovative concepts for producing ^{238}Pu as the baseline for reestablishing domestic production of ^{238}Pu would increase technical risk and substantially delay the production schedule. Nevertheless, research into innovative concepts for producing ^{238}Pu, such as the use of a commercial light water reactor, may be a worthwhile investment in the long-term future of RPSs.

FINDING. Current Impact. NASA has already been making mission-limiting decisions based on the short supply of ^{238}Pu.

FINDING. Urgency. Even if the Department of Energy budget for fiscal year 2010 includes funds for reestablishing ^{238}Pu production, some of NASA's future demand for ^{238}Pu will not be met. Continued delays will increase the shortfall.

HIGH-PRIORITY RECOMMENDATION. Plutonium-238 Production. The fiscal year 2010 federal budget should fund the Department of Energy (DOE) to reestablish production of ^{238}Pu.

- As soon as possible, the DOE and the Office of Management and Budget should request—and Congress should provide—adequate funds to produce 5 kg of ^{238}Pu per year.
- NASA should issue annual letters to the DOE defining the future demand for ^{238}Pu.

FINDING. Programmatic Balance. Balance within NASA's RPS program is impossible given the current (fiscal year 2009) budget and the focus on development of flight-ready ASRG technology. However, NASA is moving the ASRG project forward, albeit at the expense of other RPS technologies.

FINDING. Multi-Mission Radioisotope Thermoelectric Generators. It is important to the national interest to maintain the capability to produce Multi-Mission Radioisotope Thermoelectric Generators, given that proven replacements do not now exist.

RECOMMENDATION. Multi-Mission Radioisotope Thermoelectric Generators. NASA and/or the Department of Energy should maintain the ability to produce Multi-Mission Radioisotope Thermoelectric Generators.

FINDING. Flight Readiness. NASA does not have a broadly accepted set of requirements and processes for demonstrating that new technology is flight ready and for committing to its use.

RECOMMENDATION. **Flight Readiness.** The RPS program and mission planners should jointly develop a set of flight readiness requirements for RPSs in general and Advanced Stirling Radioisotope Generators in particular, as well as a plan and a timetable for meeting the requirements.

RECOMMENDATION: Technology Plan. NASA should develop and implement a comprehensive RPS technology plan that meets NASA's mission requirements for RPSs while minimizing NASA's demand for ^{238}Pu. This plan should include, for example:

- A prioritized set of program goals.
- A prioritized list of technologies.
- A list of critical facilities and skills.
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- A plan for maturing technology in key areas, such as reliability, power, power degradation, electrical interfaces between the RPS and the spacecraft, thermal interfaces, and verification and validation.
- A plan for assessing and mitigating technical and schedule risk.

HIGH-PRIORITY RECOMMENDATION. ASRG Development. NASA and the Department of Energy (DOE) should complete the development of the Advanced Stirling Radioisotope Generator (ARSG) with all deliberate speed, with the goal of demonstrating that ASRGs are a viable option for the Outer Planets Flagship 1 mission. As part of this effort, NASA and the DOE should put final design ASRGs on life test as soon as possible (to demonstrate reliability on the ground) and pursue an early opportunity for operating an ASRG in space (e.g., on Discovery 12).

Appendixes

A
Statement of Task

The Space Studies Board, in conjunction with the Aeronautics and Space Engineering Board, will appoint a study committee to prepare a report that addresses the following issues regarding the development and use of radioisotope power systems (RPSs) for NASA space missions:

- Technical readiness and programmatic balance of NASA's RPS technology portfolio to support NASA near- and long-term mission plans;
- Effectiveness and ability of U.S. Government agency management structures, including participating organizations, roles and responsibilities, to meet stated goals and objectives of U.S. programs for RPS capabilities within the current statutory and policy framework;
- Importance to the national interest of maintaining and/or re-establishing needed infrastructure at field centers, laboratories, and the private sector R&D base, given the recent curtailment of RPS program content and ambitious national goals in space exploration;
- Strategies for re-establishment of ^{238}Pu domestic production versus the likelihood of continued procurement of Russian-produced material in view of potential competition for ^{238}Pu fuel from other space-faring nations and the critical shortage of U.S.-owned inventory; and
- Identification of any actions that could be taken in the context of the overall RPS program to meet stated science and exploration goals.

B
Biographies of Committee Members

WILLIAM HOOVER, *Co-Chair,* is a consultant for aviation, defense, and energy matters. He is a former Assistant Secretary, Defense Programs, U.S. Department of Energy, where he was responsible for the U.S. nuclear weapons development program, including production, research, testing, safety, and security. He is also a Major General, USAF (retired) and a former chair of the NRC's Aeronautics and Space Engineering Board.

RALPH L. McNUTT, JR., *Co-Chair,* is a senior space physicist at the Johns Hopkins University Applied Physics Laboratory. Dr. McNutt is currently the Project Scientist and a Co-Investigator on the MESSENGER Discovery mission to Mercury, a Co-Investigator on the New Horizons mission to Pluto, and a Co-Investigator on the Voyager Plasma Science (PLS) and Low-Energy Charged Particles (LECP) experiments. He is also a member of the Ion Neutral Mass Spectrometer Team for the Cassini Orbiter spacecraft. He has worked on the physics of the magnetospheres of the outer planets, the outer heliosphere (including solar wind dynamics and properties of VLF radiation), Pluto's atmosphere, pulsars, high current electron beams, the physics of active experiments in the mesosphere/thermosphere (artificial aurora), and the solar neutrino problem. Dr. McNutt previously served as a member of the NRC Committee for the Study of the Next Decadal Mars Architecture (2006), the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion: A Vision for Beyond 2015 (2004-2006), the Committee to Assess Solar System Exploration (2007-2008), and the Committee to Review New Opportunities in Solar System Exploration (2007-2008).

DOUGLAS M. ALLEN, the General Manager of Schafer Corporation's Dayton operations, has 28 years experience in aerospace technology, with an emphasis on space power technology. He formerly was the program manager of nuclear power system development for SDIO (now the Missile Defense Agency), including the SP-100 and Topaz programs. He served as a member of NASA's Lunar Surface Fission Power System Study in support of the Exploration Systems Architecture Study (ESAS) in 2005, as a member of NASA's Nuclear Strategic Roadmap committee in 2004-5, and as a member of an NRC thermionics study committee in 2000. He was awarded AIAA's Aerospace Power Systems Award for career achievements in space power in 2008.

SAMIM ANGHAIE is a professor of nuclear and radiological engineering at the University of Florida, where he also is director of the Innovative Nuclear Space Power and Propulsion Institute (INSPI). He has been a professor at Florida since 1986, before which he was an assistant professor at Oregon State University for two years. His research interests include thermal hydraulics, computational fluid dynamics and heat transfer; high temperature nuclear fuels and materials; inverse radiation transport methods; advanced reactor design, direct energy conversion; and space nuclear power and propulsion.

RETA F. BEEBE is a professor in the Astronomy Department at New Mexico State University. She is a leading expert in the study of the atmospheres of Jupiter and Saturn, and in particular, studies of cloud motion and development in Jupiter's atmosphere. She undertakes her studies using a variety of techniques including ground- and space-based telescopic observations and remote-sensing studies using spacecraft. Most recently, she has served as an associate member of the Galileo imaging team and lead the team of astronomers using the Hubble Space Telescope to provide context images for the Galileo project. Dr. Beebe currently serves as the program scientist for the Planetary Data System (PDS). Dr. Beebe has also been extensively involved in the management and implementation of the R&A programs that provide basic research funding to planetary scientists.

WARREN W. BUCK, an internationally known theoretical physicist, is professor of Interdisciplinary Arts and Sciences and chancellor emeritus at the University of Washington, Bothell (UWB). He is also adjunct professor of physics at the Seattle campus of the University of Washington. Prior to joining UWB, Dr. Buck was professor of physics and director of the Nuclear/High Energy Physics Research Center of Excellence at Hampton University. He was also a member of the team that established the scientific program at the Department of Energy's Jefferson Laboratory in Newport News, Virginia.

BEVERLY A. COOK has over 30 years experience in nuclear safety, materials research, facilities operations and management. She is currently the Jet Propulsion Laboratory's Planning and Integration Manager for the Deep Space Network (DSN) Program. Prior to joining the DSN team, she supported the JPL development and use of space nuclear power systems in NASA missions. In her prior work for the Department of Energy, she was responsible for the fabrication and delivery of the radioisotope thermoelectric generators (RTGs) for the Cassini mission as well as delivery of RTGs to other DOE customers. She also interacted with Congress, OMB, and NASA on issues related to funding and support for continued development of nuclear power systems for space applications. Prior to joining JPL in 2004, Ms. Cook served as the Assistant Secretary of Energy for Environment, Safety, and Health. Other positions at the DOE included Manager of the Idaho Operations Office and Deputy Assistant Secretary of Nuclear Energy.

SERGIO B. GUARRO is a Distinguished Engineer in the Engineering and Technology Group (ETG), Systems Engineering Division (SED) of the Aerospace Corporation. He applies multi-decade expertise in systems engineering, risk assessment and risk management disciplines onto the development, coordination and implementation of mission assurance processes in National Security Space (NSS) and NASA programs. He provides leadership in the development and establishment of risk management and mission assurance best practices within Aerospace by assisting NSS programs in the setting and execution of their risk management and mission assurance goals and activities. He also supports the corporate Aerospace Corporation Chief Engineer and Systems Engineering organizations in the development of risk management and mission assurance guidance and implementation tools for use in all NSS programs supported by Aerospace. In the course of his career Dr. Guarro has developed risk assessment methodologies for both space and nuclear power systems, such as the one adopted for the launch approval of the NASA Cassini nuclear-powered mission, and the Dynamic Flowgraph Methodology (DFM) for the risk analysis of dynamic systems. He is the author of the chapters of the NASA Probabilistic Risk Assessment Procedures Guide that address the risk modeling of physical systems and the risk of software-intensive space systems, and he has served on National Research Council committees as an expert panelist for space systems risk assessment. He has authored and has been the co-editor of technical textbooks, and has published close to eighty papers in refereed journals and conference proceedings. His latest work in the area of mission assurance is documented in the Aerospace Corporation Mission Assurance Guide, which is currently being published and distributed across the Company. Dr. Guarro's direct nuclear power expertise was applied in jobs with the Nuclear Regulatory Commission's Advisory Committee on Reactor Safeguards (NRC/ACRS) and with the Lawrence Livermore National Laboratory, where he was a project leader in the nuclear systems safety program. He is still currently a consultant to the NRC/ACRS. At Aerospace, he started his career as an Engineering Specialist and then carried several ETG management positions, including that of Manager of the Reliability and Risk Assessment Section and then, before his current appointment, of Director of the Risk Planning and Assessment Office.

ROGER D. LAUNIUS is senior curator in the Division of Space History at the Smithsonian Institution's National Air and Space Museum in Washington, D.C. Between 1990 and 2002 he served as chief historian of the National Aeronautics and Space Administration. He has written or edited more than 20 books on aerospace history, including Critical Issues in the History of Spaceflight, Space Stations: Base Camps to the Stars, and Frontiers of Space Exploration. He has also completed a study of the history of radioisotope thermoelectric generators.

FRANK B. McDONALD (NAS) is a pioneer and leader in cosmic-ray astrophysics and high-energy astronomy in general. He is also well known in the areas of solar wind and planetary magnetospheres. He is currently a senior research scientist in the Institute for Physical Science and Technology at the University of Maryland and formerly served as NASA chief scientist. Dr. McDonald has been involved in the study of energetic particles in the heliosphere for many years. His energetic particle experiments on the Pioneer and Voyager spacecraft continue to be a resource for studying the dynamics of the outer heliosphere and the properties of low-energy galactic and anomalous cosmic rays. Dr. McDonald is a former NAS section 16 liaison and was chair of the NRC Panel on Space Sciences. He also served on the NRC Committee on Solar and Space Physics and Committee on NASA Astrophysics Performance Assessment.

ALAN R. NEWHOUSE is a consultant in the field of space nuclear power and related technologies. In 1995, he retired from the Department of Energy where he served as the Deputy Assistant Secretary of Energy for Space and Defense Power Systems. As such, he was responsible for the management and execution of programs to provide nuclear power systems for space and national security applications, for Cassini RTG production, for development of the SP100 space nuclear reactor; and for several classified programs. He initiated technical development of new energy conversion technologies for space and terrestrial applications. During 2002, Mr. Newhouse was a consultant to NASA's Office of Space Science on the Nuclear System Initiative (later Project Prometheus). In 2003 he joined NASA and was in charge of Project Prometheus. In late 2004 he was appointed as the Program Executive for Radioisotope Power Systems in the Science Mission Directorate and as a senior technical advisor to the Development Division of NASA's Exploration Systems Directorate. He retired again from government service at the end of 2004.

JOSEPH A. SHOLTIS, JR., Lt Col, USAF (Retired) is a nuclear and aerospace engineer with 38 years of experience with advanced nuclear systems and programs for a variety of applications. Areas of particular focus include space and advanced terrestrial nuclear systems and their safety, and risk assessment of space missions employing nuclear systems or materials, including preparation and delivery of formal studies and analyses to middle and top management in the Department of Defense (DoD), Department of Energy (DOE), NASA, the U.S. Nuclear Regulatory Commission NRC, the Environmental Protection Agency (EPA), the White House, and Congress. Mr. Sholtis is the owner and principal consultant of Sholtis Engineering & Safety Consulting. Current and prior customers include Sandia National Laboratories, Rocketdyne, the Jet Propulsion Laboratory, Los Alamos National Laboratory, the New Mexico Office of Space Commercialization, and the joint DoD, DOE, NASA, EPA, and Nuclear Regulatory Commission Interagency Nuclear Safety Review Panel. Areas currently being investigated include Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) safety, Mars Science Laboratory mission risk, as well as assessment and advancement of coated particle fuel for future radioisotope power systems. During his career, Mr. Sholtis has worked at Sandia National Laboratories (on advanced reactors), the Defense Nuclear Agency (on research and test reactors and radiation sources), and DOE Headquarters (on the joint DOE/DoD/NASA SP-100 Space Reactor Power System Development Program). He has been involved in the nuclear safety and risk assessment of every U.S. nuclear-powered space mission launched since 1974; i.e., Viking 1 & 2, Lincoln Experimental Satellites (LES) 8 & 9, Voyager 1 & 2, Galileo, Ulysses, Mars Pathfinder, Cassini, Mars Exploration Rover (MER) A & B, and Pluto-New Horizons.

SPENCER R. TITLEY (NAE) is a professor in the Department of Geosciences at the University of Arizona. He previously worked on NASA's Lunar Orbiter program and was also a member of the Apollo Field Geology Investigation Team, serving on Apollo missions 16 and 17. His current research involves the study of the origin of mineral deposits and the distribution and location of mineral and mineral fuel resources. His research has also included the study of chemical baselines of trace elements in rocks and ores for environmental purpose.

EMANUEL TWARD is a consultant to Northrop Grumman Space Technology, an organization from which he retired in 2006. At the time, he was the cryogenics business area manager and project manager for a number of flight cryocooler development projects (13 in orbit) and for development of a thermoacoustic Stirling power converter. Dr. Tward has also worked at the Jet Propulsion Laboratory's Low Temperature Physics Group, where he was active in the development of long-lived cryocoolers for spacecraft. Dr. Tward was previously an associate professor of physics at the University of Regina, where he was developing a gravitational wave detector.

EARL WAHLQUIST worked in the Radioisotope Power System program for the Department of Energy for more than 20 years, and he was the program director for the program for the last 8 years before he retired in 2006. In that role Mr. Wahlquist managed the development of the RTG for the Pluto spacecraft that was launched in 2006. This included responsibility for the contractors producing the RTG and the DOE facilities and infrastructure that processed the ^{238}Pu into heat sources and assembled the heat sources into the generators. It also included directing the review and assurance of the safety of the systems, including interfacing with the interagency review group that independently reviews the safety. Mr. Wahlquist also managed efforts to centralize all of the DOE RTG processing and assembling facilities at a single location. He also directed several studies looking at either purchasing ^{238}Pu from foreign sources or producing the material within the United States.

C
NASA's Projected Demand for ^{238}Pu

NASA's projected demand for ^{238}Pu are documented in a letter from NASA Administrator Michael D. Griffin to Secretary of Energy Samuel D. Bodman, dated April 29, 2008. A copy of this letter appears below.

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

April 29, 2008

The Honorable Samuel W. Bodman
Secretary of Energy
Washington, DC 20585

Dear Mr. Secretary:

NASA requires the Department of Energy (DOE) to maintain the Radioisotope Power System (RPS) related facilities in an operational readiness status with the capability to provide NASA with current and future fueled RPS assemblies. As required by the National Space Policy of 2006 and the Atomic Energy Act of 1954 (as amended), the Atomic Energy Commission is "… the exclusive owner of all production facilities …" for special nuclear materials and as such we must emphasize that DOE must "… maintain the capability and infrastructure to develop and furnish nuclear power systems for use in United States Government Space systems …." NASA will pay for the special nuclear material used for our missions, but we are prohibited from directly funding production facilities or infrastructure required when the DOE has an appropriation for the same.

All NASA missions are subject to budget authority and Agency priorities. Likewise, NASA missions considering RPS must go through the National Environmental Policy Act review. However, for DOE planning purposes, NASA provides the following projected mission requirements:

Projected NASA Science Missions

Approved Missions	Projected Launch Year	Power Req'm (We)	Pu238 Usage (kg)[1]
Mars Science Lab	2009	100	3.5
Outer Planets Flagship 1	2017	700-850	24.6

[1] The Mars Science Lab and the Outer Planet Flagship 1 are designed to use the Multi Mission Radioisotope Thermoelectric Generator technology. The rest of the missions assume the use of Advanced Stirling Radioisotope Generator technology, significantly reducing the quantity of Pu238 required to meet the power requirement.

Envisioned (Not yet approved)

Discovery 12	2014	250	1.8
Discovery 14	2020	500	3.5
New Frontiers 4	2021	800	5.3
New Frontiers 5	2026	250-800	1.8-5.3
Discovery 16	2026	500	3.5
Outer Planets Flagship 2	2027	600-1000	5.3-6.2

Projected NASA Exploration Missions

	Projected Launch Year	Power Req'm (We)	Pu238 Usage (kg)
Pressurized Rover #1	2022	2000	14
ATHLETE Rover	2024	2000	14
Pressurized Rover #2	2026	2000	14
Pressurized Rover #3	2028	2000	14

The contract that DOE has now renegotiated to allow NASA to purchase the remaining available supply of Russian Pu238 clearly signifies DOE's commitment to meeting the requirements of NASA's space systems. NASA is committed to working in partnership with DOE to support the budget process for maintaining capability to supply Pu238 RPS, including establishment of new domestic Pu238 production capability as soon as possible.

If you have any questions, please contact Mr. Christopher Scolese, the Associate Administrator, at 202-358-1808.

Sincerely,

Michael D. Griffin
Administrator

cc:
NASA HQ/Associate Administrator/Mr. Scolese

D
Comparison of ^{238}Pu to Alternatives

Numerous studies have been conducted over many years to determine the optimum isotope for use in radioisotope power systems (RPSs). After reviewing many of these studies, it is clear that ^{238}Pu is the only technically credible isotope for powering RPSs.

Selection of a suitable RPS fuel focuses mainly on three areas: radioactive decay half-life, radiation emissions, and power density/specific power. Secondary considerations include fuel form and availability/cost.

HALF-LIFE CONSIDERATIONS

Radioisotopes decay in a predictable and unalterable process that emits particles and/or photons, including alpha, beta, and gamma radiation. When this radiation is absorbed by the fuel or the fuel container, it is transformed into useful heat. The half-life of the fuel should be at least as long or longer than the mission lifetime. If the half-life is too short, the fuel decays too quickly, and a large amount of excess fuel is required at the beginning of life to provide adequate power at the end of life and to provide mission scheduling flexibility. However, if the half-life is too long, radioactive decay occurs so slowly that a large amount of fuel is required to provide adequate power throughout the mission. For projected NASA missions with lifetimes of 15 to 25 years, a half-life over 100 years is not required, and it would substantially reduce power density and specific power. Of more than 2,900 known radioisotopes, only the 22 listed in Table D-1 have half-lives in the range of 15 to 100 years.

RADIATION EMISSION CONSIDERATIONS

An RPS fuel should produce radiation that can easily be shielded to minimize shielding weight, to reduce worker exposure, to minimize risk of exposure to the general population in the event of a launch accident, and to avoid interference with sensitive particle and photon detectors used on the spacecraft.

The first seven isotopes listed in Table D-1 decay purely by gamma radiation emissions. This is a highly penetrating form of radiation, and therefore these isotopes can be eliminated from consideration as an RPS fuel source.

Although beta particles emissions are easily shielded, some of the beta particle energy is converted to bremsstrahlung radiation (x rays), which is difficult to shield. Beta decay also produces less heat energy that decay by highly energetic alpha emissions. This eliminates the nine beta emitting radioisotopes listed in Table D-1.

The five remaining radioisotopes are alpha emitters. Gadolinium-148 (^{148}Gd) is ideal in terms of emissions, because it decays directly to a stable nuclide (^{144}Sm) and emits no secondary radiation. However, ^{148}Gd can only be produced using a proton accelerator, rather than a reactor. Even if an accelerator were devoted full-time to the production of ^{148}Gd, the output would only be a few grams per year. There is no known or projected method for making kg quantities of this isotope in a year's time. Curium-243 (^{243}Cm) and the daughter products of ^{232}U (especially ^{228}Th) emit a significant level of gamma radiation, resulting in dose rates that are higher than either ^{244}Cm or ^{238}Pu heat sources of comparable size. This leaves ^{238}Pu and ^{244}Cm as the only isotopes worthy of further consideration.[1]

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[1]Four additional alpha-emitters have half lives between 100 and 500 years (Polonium-209, Americium-242m, Californium-249, and Americium-241). In addition to the problem of low specific power (caused by their long half life), all four also emit significant amounts of gamma rays.

TABLE D-1 Primary Emissions Produced by Radioisotopes with Half-lives of 15 to 100 Years

Isotope	Half-Life (years)	Type of Primary Emissions
Promethium-145 (Pm-145)	18	gamma
Halfnium-178m (Hf-178m)	31	gamma
Bismuth-207 (Bi-207)	33	gamma
Europium-150 (Eu-150)	37	gamma
Titanium-44 (Ti-44)	47	gamma
Platinum-193 (Pt-193)	50	gamma
Terbium-157 (Tb-157)	99	gamma
Actinium-227 (Ac-227)	22	beta, some alpha
Niobium-93m (Nb-93m)	16	beta, gamma
Lead-210 (Pb-210)	22	beta, some alpha
Strontium-90 (Sr-90)	29	beta
Cesium-137 (Cs-137)	30	beta, gamma
Argon-42 (Ar-42)	33	beta
Tin-121m (Sn-121m)	55	beta
Samarium-151 (Sm-151)	90	beta
Nickel-63 (Ni-63)	100	beta
Curium-244 (Cm-244)	18	alpha, spontaneous fission
Curium-243 (Cm-243)	29	alpha, gamma
Uranium-232 (U-232)	72	alpha, spontaneous fission
Gadolinium-148 (Gd-148)	75	alpha
Plutonium-238 (Pu-238)	88	alpha, spontaneous fission

Table D-2 compares the characteristics of ^{238}Pu and ^{244}Cm. Both produce gamma radiation (although the amount produced is much smaller than the amount from isotopes that produce gamma radiation as a primary emission.) As shown, ^{244}Cm produces much more gamma radiation than ^{238}Pu. Also, the fast neutron radiation level from ^{244}Cm is nearly 450 times that of ^{238}Pu. These high gamma and neutron radiation levels would require shielding during handling and use of the ^{244}Cm heat sources to protect personnel and sensitive components. The shield weights would most likely be too heavy for deep space applications.

Nearly all of the gamma dose from ^{238}Pu is attributable to the decay chain of the ^{236}Pu isotope impurity in the fuel, which is limited to very small amounts by ^{238}Pu fuel quality specifications.

POWER DENSITY/SPECIFIC POWER CONSIDERATIONS

The power density (watts/cubic centimeter) and specific power (watts/gram) of radioisotope fuel is directly proportional to the energy absorbed per disintegration and is inversely proportional to half-life. (As shown in Table D-2, ^{244}Cm has a higher specific power and power density than ^{238}Pu, because the former has a shorter half-life, but the selection of RPSs powered by ^{238}Pu to power many important missions has demonstrated that its specific power and power density are acceptable.) Higher power density leads to smaller volume heat sources for comparable power levels and higher specific power leads to lighter weight heat sources. Both characteristics are highly significant for space power heat sources. For radioisotope fuels with comparable half-lives, a beta emitting heat source will be larger and heavier than an alpha emitter.

TABLE D-2 Characteristics of ^{238}Pu and ^{244}Cm Isotope Fuels

Isotope	Pu-238	Cm-244
Half-life	87	18.1
Type of emission	Alpha	Alpha
Activity (curies/watt)	30.73	29.12
Fuel form	PuO_2	Cm_2O_3
Melting point (°C)	2,150	1,950
Specific power (watt/g)	0.40	2.42
Power density (watt/cc)	4.0	26.1
Radiation levels		
Gamma dose rate (mR/hr@ 1m)	~5	~900
Gamma shield thickness* (cm of uranium)	0	5.6
Fast neutron flux @ 1m (n/cm^{2}sec)	260	116,000

Note: mR, milliroentgen.
*Gamma shielding to reduce dose rates to ~5mR/hr@1m (equivalent to Pu-238)

FUEL FORM CONSIDERATIONS

The radioisotope fuel must be used in a fuel form that has a high melting point and remains stable during credible launch accidents and accidental reentries into Earth's atmosphere. The fuel form must also be non-corrosive and chemically compatible with its containment material (metallic cladding) over the operating lifetime of the power system. It is desirable that the fuel form have a low solubility rate in the human body and the natural environment. Daughter products and the decay process must not affect the integrity of the fuel form. All of the alpha emitting isotopes listed in Table D-1 form very stable, high-melting-temperature oxides which are acceptable for space applications.

AVAILABILITY AND COST CONSIDERATIONS:

Any radioisotope fuel selected for space power applications must be producible in sufficient quantities and on a schedule to meet mission power needs. As a practical matter, this means that it must be possible to produce the radioisotope of interest by irradiation of target materials in a nuclear reactor, rather than using a particle accelerator. In addition, appropriate types and amounts of target materials and facilities for processing them are needed. Chemical processing technology to produce the power fuel compound is required, as well as fuel form fabrication processes and facilities.

The proposed fuel form must be extensively tested to support launch safety approvals. The fueled heat source and power system must undergo an extensive analysis and test program to qualify them for use in space applications. Development of a fuel production and fuel form fabrication capability for a new fuel is very costly and time consuming. To qualify a new fuel form and heat source for flight use is also a large effort in terms of cost and time. Over $40 million has been spent on safety qualification of the ^{238}Pu-fueled General Purpose Heat Source. Similar work has not been done for ^{244}Cm oxide fuel form, heat source, or power system.

Also, ^{244}Cm is more difficult to produce than ^{238}Pu because the former requires extended irradiation of ^{239}Pu or ^{241}Am, with more neutron captures per gram than is required to produce ^{238}Pu from ^{237}Np.[2] Ultimately, ^{244}Cm would cost more and be less beneficial to NASA for long duration, deep space missions.

[2]The availability of target materials is not a key discriminating factor. The Department of Energy already has a large supply of Np-237 on hand, and Am-241, which is commonly used in smoke detectors, can be produced in kilogram quantities.

SUMMARY

In the final analysis, no other radioisotope is available that meets or exceeds the safety and performance characteristics of ^{238}Pu, particularly for long-duration, deep-space exploration missions. Pu-238 stands alone in terms of its half-life, emissions, power density, specific power, fuel form, availability, and cost.

E
History of Space Nuclear Power Systems

INTRODUCTION

Through an investment of considerable resources—engineering and scientific knowledge, human capital, and public funds—the United States has gained undisputed leadership in the exploration of the outer solar system, that part of the system beyond the orbit of Mars. This has been made possible since the 1950s by harnessing several core technologies that have enabled the nation's scientific spacecraft to travel for years on end, engage in extended scientific observations, and relay critical data back to Earth. Radioisotope power systems (RPSs) are one such technology.

Radioisotope power systems generate heat from the natural decay of a radioactive isotope, or radionuclide. This heat is transformed into electricity with some level of efficiency, depending upon the converter design. A variety of converter approaches have been, and continue to be, investigated. In all flight systems used to date, the heat flows from a radioactive heat source, through an array of thermocouples, and to a heat sink, generating electricity in the process.[1] These systems are called radioisotope thermoelectric generators (RTGs). RTGs are the preferred method for supplying the power needs of U.S. deep space probes to the outer solar system and beyond, and they have also been used for some Earth-orbiting spacecraft and to support missions to the Moon and Mars. All U.S. RPSs launched into space have been powered by ^{238}Pu. They have provided power ranging from 2.7 Watts on the very early systems to 500 Watts on more recent flights (Lee, 1994).[2] RPSs have powered many types of spacecraft, including orbiters and landers. They allow spacecraft operations in extreme environments that rule out the use of other power systems (e.g., solar arrays).

ORIGINS OF NUCLEAR POWER SYSTEMS FOR SPACEFLIGHT

Beginning in the late 1940s several threads converged to make it possible to develop and use RPSs. In particular, the Atomic Energy Commission (AEC) began to investigate production and use of radioisotopes in connection with nuclear weapons. This prompted scientific research to understand the radioactive decay and chemistry of various isotopes that are not found in nature. Second, scientists and engineers began to experiment with the development of small nuclear power generators for a variety of uses on Earth, especially in extreme locations and environments (e.g., at the poles and under the seas), where scientific instruments could be placed and left alone for months at a time. Third, advances in thermoelectricity and semiconductors made RTGs feasible.

In 1946 the newly-established RAND Corporation explored the viability of orbital satellites and outlined the technologies necessary for their success (RAND, 1946). By 1949 a full-scale analysis by RAND had sketched out the large-scale use of nuclear power sources for satellites in Earth orbit (Gender and Kock, 1949. Beginning in 1951, at the Department of Defense's (DoD) request, the AEC sponsored research into nuclear power for spacecraft to support the development of a reconnaissance satellite. The AEC pursued two related avenues: a small nuclear reactor and an RTG. These Systems for Nuclear Auxiliary Power (SNAP) were numbered such that the odd numbers designated RTGs and the even numbers designated reactor power systems.

By June 1952, an early, classified study of the effort reported there were no insurmountable technical hurdles, and a year later, in May 1953, U.S. Air Force Headquarters authorized development of a nuclear power source for satellites. The first bench-test RTGs emerged from the Mound Laboratory (operated for the AEC by the Monsanto Research Corp.) in 1953 and quickly found application in

[1] The Seebeck effect.
[2] Cassini had over 800 W of electrical power at launch using this approach.

Antarctica to power scientific research stations (Jordan and Birden, 1954, and Morse, 1963). SNAP-1 (an RTG) was built at the Mound Laboratory under AEC supervision in 1954 (Anderson and Featherstone, 1960). This was followed by the use of nuclear power systems on spacecraft in the early 1960s.

The possibilities of space nuclear power first entered the public sphere in January 1959 when President Dwight D. Eisenhower posed with a SNAP-3 RTG in the Oval Office of the White House. Ultimately, the Transit 4A and 4B navigation satellites were provided with SNAP-3B power sources from the AEC. They were the first satellites to operate in space with RPSs. Both satellites were also equipped with solar panels that supplied 35 W of power (Dassoulas and McNutt, 2007). These and subsequent missions proved the feasibility of using RPSs for space missions.

SPACE NUCLEAR REACTOR SYSTEMS

Space nuclear power reactors are another potential option for missions where solar power is not practical. However, the United States has launched only one space nuclear power reactor (SNAP-10A), and that took place in 1965. That early system was designed to produce 40 kW of thermal power and 500 W of electricity for an operating life of just 1 year, and the failure of a voltage regulator caused the system to shut down after 43 days (Wilson et al., 1965).

Beginning in 1983, NASA, the Department of Defense, and the Department of Energy invested approximately $500 million in the SP-100 space nuclear power reactor. This system was intended to generated 2 MW of thermal power and 100 kW of electricity, but because of high costs, schedule delays, and changing national space mission priorities, the SP-100 program was suspended in the early 1990s and later canceled. The Soviet Union launched dozens of short-lived space nuclear power reactors during the 1970s and 1980s, and several unfueled Soviet systems were purchased by the United States in the early 1990s. These systems were extensively ground tested by a joint team of U.S., British, French, and Russian engineers using electrical heaters in place of the nuclear cores. Although the test program was successful, the United States did not use the Soviet equipment or technology in a flight program (NRC, 2006).

Project Prometheus was the most recent U.S. attempt to develop space nuclear power reactors. This project began in 2002, and it’s initial focus was on the Jupiter Icy Moons Orbiter mission. The project selected a nuclear electric propulsion reactor concept that was scalable from 20 kW_e to 300 kW_e. A nuclear electric propulsion system for a deep space mission would need to be validated for reliable operation for a mission lifetime of 10 to 20 years, with no maintenance or repair. However, as with the SP-100 program, Project Prometheus did not proceed to the point of demonstrating the ability of system designs or available technology to meet required performance or lifetime specifications. Instead, it was terminated in 2005, after it became clear that it would have cost at least $4 billion to complete development of a spacecraft reactor module, and a total of at least $16 billion to develop the entire spacecraft and complete the mission, not counting the cost of the launch vehicle or any financial reserves to cover unexpected cost growth (JPL, 2005).

The performance and reliability of space nuclear power reactor systems using current technology remains unproven, especially for missions with long lifetimes. In addition, the committee is not aware of any substantive effort currently underway anywhere in the world to develop space nuclear power reactor systems. The history of space nuclear power reactors suggests that space nuclear reactors, if successfully developed, could meet the needs of some missions and could enable other missions that are not now under consideration because of power limitations. However, history also shows that the development of high-power, long-life space nuclear power reactors would be very time-consuming and expensive.

VEHICLE ACCIDENTS AND MALFUNCTIONS

Three U.S. spacecraft with RPSs on board have inadvertently returned to Earth. In all cases, the RPSs performed as designed; the cause of the mission failure lay with other, non-nuclear systems.

The Transit 5BN-3 spacecraft with one SNAP-9A RPS on board broke up and burned up on reentry after a launch-vehicle upper stage failure. The design philosophy at that time was to require that the ^{238}Pu oxide fuel totally burn-up during reentry into Earth's atmosphere, which it did.

As a result of that accident, the RPS design philosophy was changed to require full containment of the fuel (i.e., no fuel burn-up) during an inadvertent reentry from or to Earth orbit. This design philosophy is still in effect.

The Nimbus B-1 weather satellite, the first NASA satellite to use an RPS, was intentionally destroyed during launch due to the erratic ascent of the launch vehicle. The launch vehicle, upper stage, and payload were totally destroyed by the explosion initiated by the destruct action, and the debris fell into the Santa Barbara Channel off Vandenberg Air Force Base. The two SNAP-19B2 RPSs were recovered intact (i.e., no ^{238}Pu oxide fuel release occurred), and the fuel was used on a later mission.

The last accident involving a U.S. RPS was the Apollo-13 mission, which has been well documented. The SNAP-27 heat source assembly was stowed in the Lunar Excursion Module, which returned to Earth after the mission was aborted. It reentered over the South Pacific Ocean. Air and water sampling detected no ^{238}Pu oxide fuel, indicating that the SNAP-27 heat source assembly survived reentry intact (as designed) and came to rest at the bottom of the Tonga Trench under more than 7,000 feet of water, where it still remains.

SPACE NUCLEAR POWER AND OUTER-PLANET MISSIONS

A major shift in the use of RPSs came with the NASA's decision to pursue outer-planet exploration. This initiative was driven by the discovery of "grand tour" trajectories that could enable relatively short missions to the planets of the outer solar system by using multiple planetary gravity assists.[3] This planetary configuration is rare, occurring only about every 176 years, but it was due to occur in the late 1970s and led to one of the most significant space exploration efforts undertaken by the United States (Dethloff and Schorn, 2003).

The nearly identical Pioneer 10 and 11 spacecraft were launched in 1972 and 1973, respectively, to make the first trips through the asteroid belt to Jupiter and beyond. Both relied on RPSs to provide power far from the Sun. Pioneer 10 flew past Jupiter in late 1973. It transmitted data about the planet and continued on its way out of the solar system. Pioneer 11 provided scientists with an even closer view of Jupiter, whose gravity was used to send Pioneer 11 to Saturn before it, too, departed the solar system. Pioneer 11 ended its mission in 1995, when the last transmission from the spacecraft was received. NASA continued to receive signals from Pioneer 10 until 2003, when the spacecraft was 7.6 billion miles from Earth. The success of the Pioneer missions would not have been possible without the four SNAP-19 RTGs that each spacecraft carried as their sole source of power. Each Pioneer spacecraft also had a dozen radioisotope heater units (RHUs), each generating 1 W of thermal energy, to heat selected components (Wolverton, 2004). A third spacecraft, the flight spare Pioneer H, is displayed in the National Air and Space Museum.

After the success of the Pioneer missions, two Voyager spacecraft were built to conduct intensive flyby studies of Jupiter and Saturn, in effect repeating on a more elaborate scale the flights of the two Pioneers. These spacecraft were scaled back versions of the proposed Grand-Tour spacecraft, which was

[3]A gravity assist is used to speed up or slow down the speed of a spacecraft by a close flyby of a planet that exchanges momentum between the spacecraft and the planet. Prograde approaches to planets in the outer solar system increase spacecraft speed, enabling them to reach planets further from the Sun faster than they could otherwise.

rejected at the time for budgetary reasons. Voyager 1 and 2 were launched in 1977, each with three MHW RTGs. With the successful flyby of Saturn's moon Titan by Voyager 1 in November 1980, Voyager 2 was targeted for one of the grand-tour trajectories.[4] Voyager 2 subsequently had close flybys of Saturn (August 1981), Uranus (January 1986), and Neptune (August 1989), providing the bulk of all human knowledge about the latter two "ice giant" planets (Dethloff and Schorn, 2003).

Voyager 1, which is travelling faster than Voyager 2, is now farther from Earth than any other human-made object. Now traveling out of the solar system, both Voyager 1 and Voyager 2 have passed the "termination shock" of the solar wind and continue to send back the first information ever received from the outer boundary of our solar neighborhood. The Voyagers are expected to return scientific data until the RPSs can no longer supply enough electrical energy to power critical systems. With the adoption of power sharing among the still-operating instruments, the final transmission is expected to occur in about 2020. Whether Voyager 1 will reach the heliopause, the "boundary" between the shocked solar wind and interstellar plasma, by then is unknown

NASA has continued to use RPSs on missions to the outer planets, and on selected long-term missions closer to the Sun when necessary to enable the mission. In 1989, NASA deployed the Galileo spacecraft from a space shuttle and sent it on a 6-year, gravity-assisted journey to Jupiter, where it became the first spacecraft to orbit the giant planet (Launius and Johnston, 2009). The flight team for Galileo ceased operations in 2003 and the spacecraft was deorbited by command into Jupiter's atmosphere to guard against any potential future contamination of Jupiter's moon Europa by an uncontrolled spacecraft impact.

Galileo carried two, newly developed General Purpose Heat Source (GPHS) RTGs. These units produced 300 W of electricity at beginning of life and had a total mass of 55.9 kg, giving these devices the highest specific power of any RPS the United States had ever flown.

The Ulysses spacecraft was also launched from a Space Shuttle in 1990 with one GPHS RTG to undertake a sustained exploration of the Sun. To enable a trajectory nearly over the Sun's poles, the spacecraft was sent to Jupiter, to use a gravity assist to rotate the heliocentric orbital plane of the spacecraft by almost 90°. Ulysses made the first and only observations of fields and particles in interplanetary space out of the ecliptic plane. It recently fell silent because of problems with its telecommunications system.

Cassini became the mission to orbit Saturn. It is an international program involving the United States, the Italian Space Agency, and the European Space Agency. Conceived in 1982, Cassini was launched in October 1997 with three modified GPHS RTGs and multiple RHUs. Cassini arrived at Saturn and began orbiting the planet in July 2004. It also sent a probe (Huygens) to the surface of Saturn's moon Titan early in 2005. Huygens is the first outer-planet mission built by the European Space Agency. Now in extended mission, Cassini continues to make fundamental discoveries in the Saturn system (Launius and Johnston, 2009).

New Horizons is the most recent mission to employ RPS generators. It will be the first spacecraft to visit Pluto and the Kuiper Belt. Launched in January 2006, New Horizons conducted a Jupiter flyby 13 months later to increase speed. New Horizons will make its closest approach to Pluto on July 14, 2015. The half-ton spacecraft contains scientific instruments to map the surface geology and composition of Pluto and its three moons, investigate Pluto's atmosphere, measure the solar wind, and assess interplanetary dust and energetic particles. After it passes Pluto, NASA plans to fly the spacecraft by one or two Kuiper Belt objects. Since sunlight at the Kuiper Belt is more than 1,000 times less intense than at Earth, New Horizons relies on a GPHS-RTG for power (Ottman and Hersman, 2006).

Table E-1 lists key parameters for U.S. RPSs that have been used in space, the missions on which they were used, and the fuel, mass, and output. All have been fueled by ^{238}Pu.

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[4]As the backup for Voyager 1, Voyager 2 would have been targeted to Titan if Voyager 1 had failed.

TABLE E-1 Radioisotope Power Systems for Space Exploration

Name and Model	Used on (Number of RTGs per User)	Maximum Output: Electrical (W)	Maximum Output: Heat (W)	Maximum Fuel Used (kg)	RPS Mass (kg)
SNAP-3B	Transit-4A/B (1)	2.7	52.5	~0.2	2
SNAP-9A	Transit 5BN-1/2/3 (1)	25	525	~1	12
SNAP-19	Nimbus B1 (2) Nimbus III (2) Pioneer 10/11 (4)	40.3	525	~1	14
modified SNAP-19	Viking 1/2 (2)	42.7	525	~1	15
SNAP-27	Apollo 12-17 ALSEP (1)	73	1480	3.8	20
MHW-RTG	LES-8/9 (2) Voyager 1/2 (3)	470	2400	~4.5	38
GPHS-RTG	Galileo (2) Ulysses (1) Cassini (3) New Horizons (1)	285	4500	7.6	56

NOTE: ALSEP, Apollo Lunar Surface Experiments Package; GPHS, General Purpose Heat Source; LES, Lincoln Experimental Satellite; MHW, Multi-hundred Watt; SNAP, Systems for Nuclear Auxiliary Power.
SOURCES: Data from G.L. Bennett, "Space Nuclear Power: Opening the Final Frontier," AIAA 2006-4191, pp. 12-13, presentation at 4th International Energy Conversion Engineering Conference and Exhibit (IECEC), San Diego, Calif., June 26-29, 2006; G.K. Ottman and C.B. Hersman, "The Pluto-New Horizons RTG and Power System Early Mission Performance," AIAA-2006-4029, 4th International Energy Conversion Engineering Conference, San Diego, Calif., June 26-29, 2006; R.D. Cockfield, "Preparation of RTG F8 for the Pluto New Horizons Mission", AIAA-2006-4031, 4th International Energy Conversion Engineering Conference, San Diego, CA, June 26-29, 2006; R.R. Furlong and E.J. Wahlquist, "U.S. Space Missions Using Radioisotope Power Systems," *Nuclear News*, April 1999, p. 29.

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Acronyms

ac	alternating current
ASC	Advanced Stirling Converter
ASRG	Advanced Stirling Radioisotope Generator
ATHLETE	All-Terrain Hex-Legged Extra-Terrestrial Explorer (as in ATHLETE rover)
ATR	Advanced Test Reactor (at Idaho National Laboratory)
CLWR	commercial light water reactor
dc	direct current
DOE	Department of Energy
EIS	Environmental Impact Statement
EJSM	Europa Jupiter System Mission
EMI	electromagnetic interference
GPHS	general purpose heat source
GRC	Glenn Research Center
HFIR	High Flux Isotope Reactor (at Oak Ridge National Laboratory)
INL	Idaho National Laboratory
INSRP	Interagency Nuclear Safety Review Panel
JPL	Jet Propulsion Laboratory
LAE	launch approval engineering
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NI	Nuclear Infrastructure (as in NI PEIS)
Np	neptunium
OPF	Outer Planets Flagship
ORNL	Oak Ridge National Laboratory
PEIS	Programmatic Environmental Impact Statement
Pu	plutonium
RHU	radioisotope heater unit
RPS	radioisotope power system
RTG	radioisotope thermoelectric generator
SNAP	Systems for Nuclear Auxiliary Power
SPF	single-point failure
SRG	Stirling radioisotope generator

TPV	thermophotovoltaic
TRIGA	Training, Research, Isotopes, General Atomics (as in, a TRIGA reactor)
TRL	technology readiness level
TSSM	Titan Saturn System Mission (one of two options for the OPF 1 mission)
W_e	watts of electrical power