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Report to Congressional Requesters

September 2017

SPACE EXPLORATION

DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges

GAO-17-673

GAO Highlights

Highlights of GAO-17-673, a report to congressional requesters

September 2017

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Why GAO Did This Study

NASA uses RPS to generate electrical power in missions in which solar panels or batteries would be ineffective. RPS convert heat generated by the radioactive decay of Pu-238 into electricity. DOE maintains a capability to produce RPS for NASA missions, as well as a limited and aging supply of Pu-238 that will be depleted in the 2020s, according to NASA and DOE officials and documentation. With NASA funding, DOE initiated the Pu-238 Supply Project in 2011, with a goal of producing 1.5 kg of new Pu-238 per year by 2026. Without new Pu-238, future NASA missions requiring RPS are at risk.

GAO was asked to review planned RPS and Pu-238 production to support future NASA missions. This report (1) describes how NASA selects RPS for missions and what factors affect RPS and Pu-238 demand; and (2) evaluates DOE's progress and challenges in meeting NASA's RPS and Pu-238 demand. GAO reviewed NASA mission planning and DOE program documents, visited two DOE national laboratories involved in making new Pu-238 or RPS work, and interviewed agency officials.

What GAO Recommends

GAO is making three recommendations, including that DOE develop a plan with milestones and interim steps for its Pu-238 and RPS production approach, and that DOE assess the long-term effects of known production challenges and communicate these effects to NASA. DOE concurred with GAO's recommendations.

View GAO-17-673. For more information, contact Shelby S. Oakley at (202) 512-3841 or oakleys@gao.gov

What GAO Found

The National Aeronautics and Space Administration (NASA) selects radioisotope power systems (RPS) for missions primarily based on the agency's scientific objectives and mission destinations. Prior to the establishment of the Department of Energy's (DOE) Supply Project in fiscal year 2011 to produce new plutonium-238 (Pu-238), NASA officials said that Pu-238 supply was a limiting factor in selecting RPS-powered missions. After the initiation of the Supply Project, however, NASA officials GAO interviewed said that missions are selected independently of decisions on how to power them. Once a mission is selected, NASA considers power sources early in its mission review process. Multiple factors could affect NASA's demand for RPS and Pu-238. For example, high costs associated with RPS and missions can affect the demand for RPS because, according to officials, NASA's budget can only support one RPS mission about every 4 years. Expected technological advances in RPS efficiency could reduce NASA's demand for RPS and Pu-238.

DOE has made progress in reestablishing Pu-238 production to meet NASA's future demand to fuel RPS and has identified challenges to meeting its production goals. Specifically, since the start of the Supply Project, DOE has produced 100 grams of Pu-238 and expects to finalize production processes and produce interim quantities by 2019. However, DOE has also identified several challenges to meeting the Supply Project goal of producing 1.5 kilograms (kg) of new Pu-238 per year by 2026. DOE officials GAO interviewed said that DOE has not perfected the chemical processing required to extract new Pu-238 from irradiated targets to meet production goals. These officials also said that achieving the Pu-238 production goal is contingent on the use of two reactors, but only one reactor is currently qualified for Pu-238 production while the second reactor awaits scheduled maintenance. Moreover, while DOE has adopted a new approach for managing the Supply Project and RPS production—based on a constant production approach—the agency has not developed an implementation plan that identifies milestones and interim steps that can be used to demonstrate progress in meeting production goals and addressing previously identified challenges. GAO's prior work shows that plans that include milestones and interim steps help an agency to set priorities, use resources efficiently, and monitor progress in achieving agency goals. By developing a plan with milestones and interim steps for DOE's approach to managing Pu-238 and RPS production, DOE can show progress in implementing its approach and make adjustments when necessary. Lastly, DOE's new approach to managing the Supply Project does not improve its ability to assess the potential long-term effects of challenges DOE identified, such as chemical processing and reactor availability, or to communicate these effects to NASA. For example, DOE officials did not explain how the new approach would help assess the long-term effects of challenges, such as those related to chemical processing. Under *Standards for Internal Control in the Federal Government*, agencies should use quality information to achieve objectives and to communicate externally, so that external parties can help achieve agency objectives. Without the ability to assess the long-term effects of known challenges and communicate those effects to NASA, DOE may be jeopardizing NASA's ability to use RPS as a power source for future missions.

Contents

Abbreviations

ASRG	Advanced Stirling Radioisotope Generator
ATR	Advanced Test Reactor
DOE	Department of Energy
eMMRTG	enhanced Multi-Mission Radioisotope Thermoelectric Generator
GPHS	general purpose heat source
HEO	Human Exploration and Operations Mission Directorate
HFIR	High Flux Isotope Reactor
INL	Idaho National Laboratory
kg	kilogram
LANL	Los Alamos National Laboratory
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
NASA	National Aeronautics and Space Administration
ORNL	Oak Ridge National Laboratory
PSD	Planetary Science Division
Pu-238	plutonium-238
RPS	radioisotope power system
Supply Project	Pu-238 Supply Project

U.S. GOVERNMENT ACCOUNTABILITY OFFICE

441 G St. N.W.
Washington, DC 20548

September 8, 2017

The Honorable Lamar Smith
Chairman
Committee on Science, Space, and Technology
House of Representatives

The Honorable Brian Babin
Chairman
Subcommittee on Space
Committee on Science, Space, and Technology
House of Representatives

The National Aeronautics and Space Administration (NASA) has long used radioisotope power systems (RPS) to generate reliable electrical power and heat energy for long-duration space missions. RPS produce power by converting heat from the natural radioactive decay of plutonium-238 (Pu-238) into electricity and can operate where solar panels or batteries would be ineffective or impossible to use, such as in deep space or in shadowed craters.[1] RPS also have the advantage of being able to operate continuously and provide power for more than a decade. Currently, a single RPS unit is being used to power the Mars Science Laboratory, also known as Curiosity, NASA's unmanned robotic surface rover that has been exploring the planet Mars since 2012.

The Department of Energy (DOE) and its predecessor agencies have been providing Pu-238 and fabricating RPS for NASA and other federal agencies for more than 5 decades. Historically, Pu-238 was produced domestically or was purchased from Russia. Domestic Pu-238 production ended in 1988, and DOE has not purchased material from Russia since 2009.[2] As a result, supplies of available Pu-238 to support new missions have diminished. Because of a limited availability of Pu-238, the National

[1]For the purposes of this report, unless otherwise noted, Pu-238 is defined as Pu-238 oxide, also known as "heat-source" plutonium oxide or "bulk-oxide", and is the form used to power RPS. Pu-238 isotope is a precursor to Pu-238 oxide.

[2]Pu-238 was last produced at DOE's Savannah River Site in South Carolina in 1988, using nuclear reactors that have since been shut down. Pu-238 production at the site was facilitated from byproducts of nuclear weapons production. Chemical processing activities at the site were scheduled for shut-down following the completion of their mission to prepare Cold War legacy nuclear materials.

Academy of Sciences expressed concern about future missions in the *Vision and Voyages for Planetary Science in the Decade 2013-2022* survey report, which identifies the science community's highest priority space exploration interests,[3] because many of the highest priority missions identified in the report can only be enabled by RPS.

According to DOE documents and agency officials, DOE currently maintains about 35 kilograms (kg) of Pu-238 isotope designated for NASA missions,[4] about half of which meets power specifications for spaceflight.[5] This supply, however, could be exhausted within the next decade based on NASA's solar system exploration plans. Specifically, NASA plans to use about 3.5 kg of Pu-238 isotope for one RPS for the Mars 2020 mission. NASA could use an additional 10.5 kg of Pu-238 isotope for the New Frontiers #4 mission if it were to use three RPS, a decision that NASA officials said the agency expects to make in July 2019 to support a 2025 launch window. If DOE's existing Pu-238 supply is used for these two missions, according to DOE documentation, NASA will be forced to eliminate RPS as a power source for future missions, delaying future missions that require RPS until DOE produces or acquires more Pu-238. New Pu-238 can be blended with existing Pu-238 that does not meet power specifications so that the blended Pu-238 can be used for future NASA missions.

Under the authority of the Atomic Energy Act of 1954, DOE maintains the nation's capability to support the development, production, and safety of RPS used in NASA's space exploration missions.[6] Three DOE national laboratories—Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), and Los Alamos National Laboratory (LANL)—are currently involved in RPS production. In 2011, with funding provided by NASA, DOE initiated the Pu-238 Supply Project (Supply Project) in order to reestablish the capability to domestically produce Pu-238. Since 2011, DOE has produced approximately 100 grams of Pu-238 isotope under the

[3]National Research Council of the National Academies, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (Washington, D.C.: National Academy of Sciences, 2011).

[4]DOE manages a separate allocation of Pu-238 for national security purposes apart from the 35 kg set aside for NASA.

[5]Pu-238 must meet a minimum specification of 1,952 watts of heat, among other characteristics, to be used for spaceflight.

[6]Pub. L. No. 83-703, 68 Stat. 919 (codified as amended at 42. U.S.C. §§ 2011-2297-h13).

Supply Project.[7] DOE identified an interim goal of producing 300 to 500 grams of new Pu-238 per year by 2019, and in 2010, it established a goal of producing 1.5 kg of new Pu-238 per year—considered full production—by 2023, at the earliest.

In 2009, the National Academy of Sciences[8] reported that NASA has been making mission-limiting decisions for some time because of a limited supply of Pu-238 and that NASA has been eliminating RPS as an option for some missions and delaying other missions that require RPS until DOE can reestablish production of Pu-238. In the National Aeronautics and Space Administration Transition Authorization Act of 2017,[9] Congress required NASA and the Office of Science and Technology Policy to conduct an analysis of, among other things, the risks associated with NASA's ability to carry out planned, high-priority robotic missions in the solar system and other surface exploration activities beyond low-Earth orbit, resulting from a lack of adequate radioisotope power system material or Pu-238.

You asked us to examine NASA's process for considering and selecting power sources for missions, in particular the use of RPS, and to review DOE's ability to maintain the necessary infrastructure and workforce for RPS and Pu-238 production. This report (1) describes how NASA selects RPS for missions and what factors affect RPS and Pu-238 demand; and (2) evaluates DOE's progress in meeting NASA's RPS and Pu-238 demand and what challenges, if any, DOE faces in meeting the demand.

To describe how NASA selects RPS for missions and what factors affect RPS and Pu-238 demand, we reviewed documentation related to how NASA's mission procedural requirements were considered during planning for recent missions that considered or used RPS as a power source.[10] We also interviewed officials from the Planetary Science

[7]Initial samples of this newly produced Pu-238 did not meet space flight specifications because they contained impurities. These samples can, however, be blended and used with existing Pu-238, according to DOE officials.

[8]National Research Council of the National Academies, *Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration* (Washington, D.C.: National Academy of Sciences, 2009).

[9]Pub. L. No. 115-10, § 515(b)(2), 131 Stat. 18, 53.

[10]National Aeronautics and Space Administration, *NASA Space Flight Program and Project Management Requirements*, NPR 7120.5D (Sept. 28, 2011).

Division (PSD) of NASA's Science Mission Directorate and from the Human Exploration and Operations Mission Directorate (HEO).

To evaluate DOE's progress in meeting NASA's RPS and Pu-238 demand, and what challenges, if any, DOE faces in meeting the demand, we reviewed documentation related to DOE's efforts to develop the Supply Project and to DOE's RPS production process. We also interviewed officials from DOE's Office of Nuclear Energy and DOE's national laboratories involved in RPS work—INL, LANL, and ORNL—and conducted site visits to ORNL, the laboratory responsible for the Supply Project, and INL, the laboratory primarily responsible for overseeing RPS production. Finally, we compared DOE's efforts to collect and assess quality information about challenges associated with RPS and Pu-238 production and to communicate these challenges against criteria outlined in federal internal control standards.[11] We also evaluated DOE's management approach for RPS and Pu-238 production against key management practices established in prior GAO work.[12] For more detailed information on our methodology, see appendix I.

We conducted this performance audit from March 2016 to September 2017 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

This section provides information on the use of RPS in NASA space missions, NASA's PSD mission portfolio and mission classes, DOE's role in RPS production, DOE's Pu-238 Supply Project, RPS production across DOE's national laboratories, and NASA's funding for RPS production.

[11]GAO, *Standards for Internal Control in the Federal Government,* GAO-14-704G (Washington, D.C.: Sept. 10, 2014).

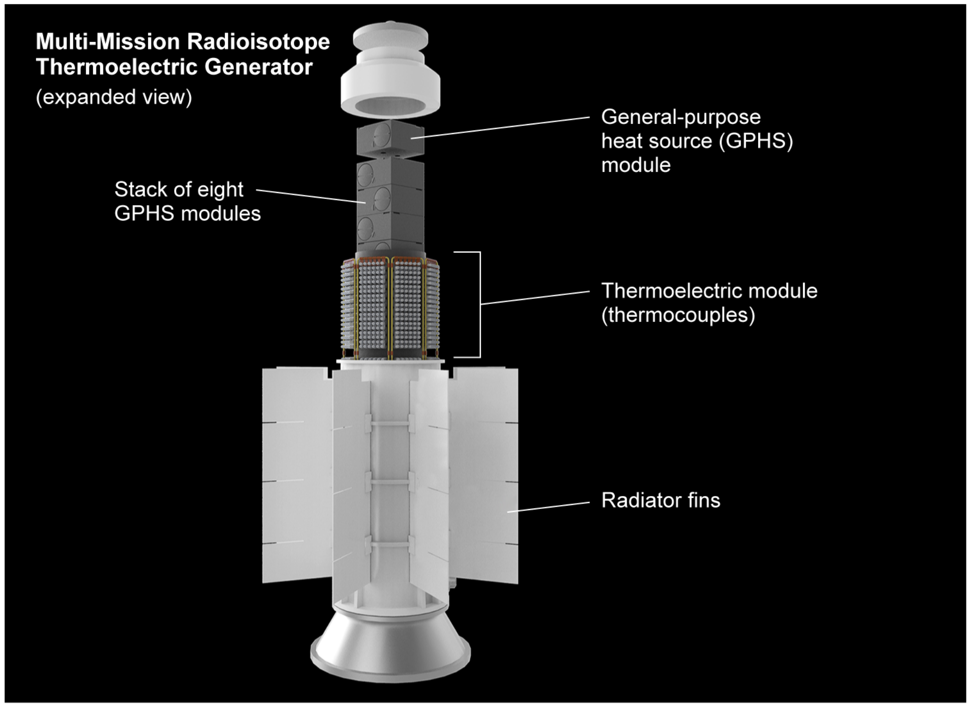
[12]GAO, *Defense Health Care Reform: Actions Needed to Help Ensure Defense Health Agency Maintains Implementation Progress*, GAO-15-759 (Washington, D.C.: Sept. 10, 2015), and *Biobased Products: Improved USDA Management Would Help Agencies Comply with Farm Bill Purchasing Requirements*, GAO-04-437 (Washington, D.C.: Apr. 7, 2004).

Use of RPS in NASA Space Missions

RPS are long-lived sources of spacecraft electrical power and heating that are rugged, compact, highly reliable, and relatively insensitive to radiation and other effects of the space environment, according to NASA documentation (see fig. 1). Such systems can provide spacecraft power for more than a decade and can do so billions of miles from the sun. In addition to providing electricity, heat generated by Pu-238 contained in the RPS is used to keep spacecraft instruments and components warm in the frigid environments of deep space. Waste heat is rejected into the environment via radiator fins that are attached to the RPS. Twenty-seven U.S. missions have used RPS over the past 5 decades. RPS produce electrical power by converting the heat generated by the natural radioactive decay of Pu-238. Pu-238 is the best possible fuel for RPS because it emits radiation that is easily shielded for the spacecraft, is producible in sufficient quantities from available material, and can be made into stable chemical forms that will not be taken up into the environment if accidentally released. The current RPS design, the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), converts heat given off by Pu-238 into about 120 watts of electrical power at the beginning of its life—a 6 percent power conversion efficiency.[13] One MMRTG contains 32 general purpose heat source (GPHS) fuel clads, which are pressed Pu-238 pellets encapsulated in iridium. Four fuel clads are encased in one GPHS module, and eight of these modules are used to fuel one RPS under the current MMRTG design.

[13]Over time, as Pu-238 degrades, it gives off less heat, and therefore the RPS produces fewer watts.

Figure 1: Expanded View of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)



Source: National Aeronautics and Space Administration. | GAO-17-673

NASA's PSD Mission Portfolio and Mission Classes

NASA's PSD science portfolio includes a wide array of missions that seek to address a variety of scientific objectives. PSD's scientific objectives aim to answer many questions about the solar system, from how life began to how the solar system is evolving, through the study of the planets and small bodies that inhabit the solar system. NASA's missions and associated mission objectives seek to address PSD's scientific objectives. Some potential mission objectives include returning samples from the surface of a comet, more intensive observations of the planets and previously unobserved small bodies, and planet surface exploration using unmanned robotic surface rovers. Scientific and mission objectives influence the types of equipment needed for the mission, including the mission's power source.

While NASA has used RPS in support of answering PSD's scientific objectives, NASA has not recently used RPS to pursue scientific objectives for other divisions or directorates, such as HEO, which oversees human spaceflight missions. The missions NASA conducts from

PSD's portfolio are of two types—directed and competed. Directed missions are planned and carried out by NASA or another project management organization to accomplish a specific set of priority objectives, while competed missions are competitively awarded and carried out by principal investigators under NASA oversight.[14] NASA offers competed missions through announcements of opportunity, which specify scientific objectives and mission requirements, including potential mission destinations and projected launch dates, and what equipment will be made available, such as RPS. According to NASA officials, missions in NASA's PSD portfolio are generally classified in three ways:

- **Flagship.** Flagship missions are the largest and most expensive of NASA's mission classes, costing $2 billion or more, and are given the highest priority for resources, including funding, infrastructure, and launch support. Flagship missions are directed by NASA to fulfill specific needs or gaps in scientific knowledge. Past Flagship missions that have used RPS include Galileo, Cassini, and Curiosity, and Mars 2020 is a planned Flagship mission using RPS.
- **New Frontiers.** Added to NASA's budget in 2003, New Frontiers missions are competed missions that focus on enhancing our understanding of the solar system and that have a development cost cap of $850 million.[15] New Frontiers missions are awarded to principal investigators. To date, there have been three New Frontiers missions—New Horizons, which is RPS-powered and is observing Pluto and the outer solar system; Juno, which uses solar power to observe Jupiter; and the Origins-Spectral Interpretation-Resource Identification Security-Regolith Explorer (OSIRIS-REx), which uses solar power and batteries and is to return samples from an asteroid back to Earth.
- **Discovery.** Missions in the Discovery program, which was started in 1992, are also competed, have a development cost cap of $450 million to $500 million according to NASA officials and documentation, and have the goal of enhancing our understanding of the solar system. The Discovery program utilizes many smaller missions with fewer resources and shorter development times. Discovery missions have never been powered by RPS.

[14]Principal investigators provide scientific and technical leadership for proposed research associated with competed missions.

[15]Mission cost caps are in fixed fiscal year 2015 dollars and do not include certain costs, such as those related to the launch vehicle and operations.

DOE's Role in RPS Production

The Atomic Energy Act of 1954 authorizes DOE to provide systems that meet the special nuclear material needs of other federal agencies, and under an agreement with NASA, DOE is responsible for maintaining our nation's capability to support the development, production, and safety of NASA's space exploration missions that use RPS.[16] According to DOE officials, DOE's Office of Nuclear Energy, Nuclear Infrastructure Programs, manages and oversees RPS production and the Supply Project and coordinates with NASA to ensure DOE can meet NASA's mission requirements.[17] This includes designing, developing, fabricating, testing, and delivering RPS to meet NASA's overall systems requirements, specifications, and schedules. DOE also maintains RPS production infrastructure to sustain capabilities between NASA missions and to support mission planning.

DOE's Pu-238 Supply Project

DOE restarted efforts to establish domestic Pu-238 production at the end of 2011, under its Supply Project, to provide fuel for RPS. DOE's goal is to reach a full Pu-238 production rate of 1.5 kg per year by 2023, at the earliest, with a late completion date of 2026. Before this full production rate is achieved, DOE established an interim production rate of 300 to 500 grams per year by 2019 in order to ensure an adequate supply of Pu-238 for NASA's near-term missions. Until March 2017, DOE divided work associated with the Supply Project into discrete segments. The segmented management approach associated with the Supply Project was a short-term, incremental approach to managing a program with uncertain funding levels, according to DOE officials. According to DOE officials, the segmented approach was intended to allow DOE to establish and reach near-term Supply Project goals while maintaining a base level of trained staff as the project developed from its early stages to its full production rate. In March 2017, DOE officials changed how they manage the Supply Project, discontinuing the segmented approach. The new management approach for the Supply Project is to align with how DOE expects to manage RPS production, according to DOE officials.

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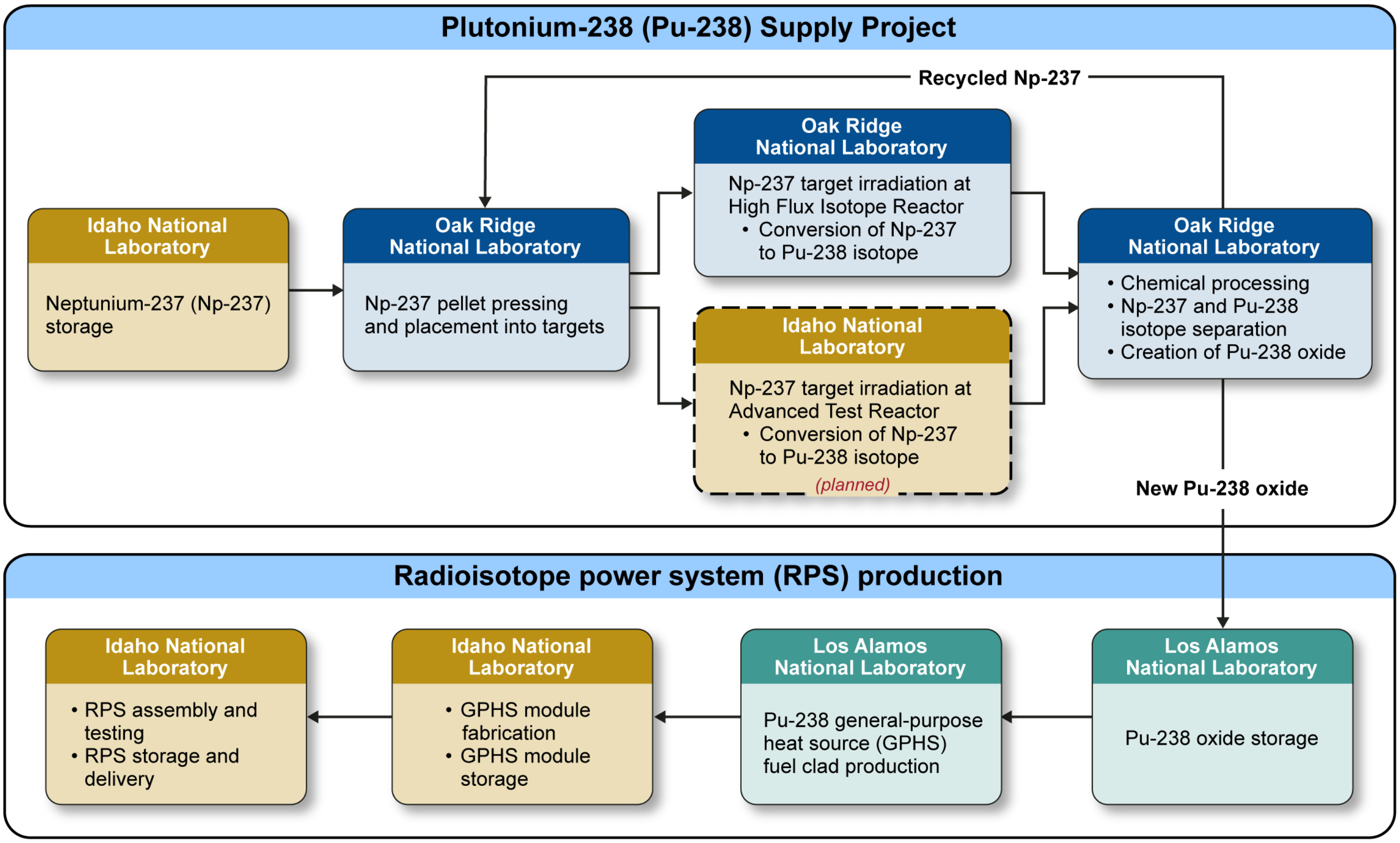
[16]DOE also manages a separate allocation of existing Pu-238 for national security applications.

[17]According to DOE officials, DOE conducted a reorganization effort in September 2016 that resulted in shifting RPS production responsibilities from what was the Office of Nuclear Energy's Office of Space and Defense Power Systems to its Nuclear Infrastructure Programs office.

DOE's Technical Integration Office, based at INL, coordinates with other DOE laboratories on Supply Project work. As shown in figure 2, the Supply Project involves a number of steps across several DOE national laboratories, including INL and ORNL. The production of new Pu-238 under the Supply Project begins with a shipment of neptunium-237 (neptunium) isotope from INL to ORNL.[18] The neptunium is blended with aluminum powder, pressed into pellets, and then placed into targets that are inserted into a reactor to be irradiated in order to convert neptunium into Pu-238 isotope. Under the Supply Project, DOE officials plan to use two DOE research reactors—the High Flux Isotope Reactor (HFIR) at ORNL, which is currently used, and the Advanced Test Reactor (ATR) at INL, which is planned for use to convert the neptunium to Pu-238 in the future. Targets for ATR will be shipped from ORNL to INL for irradiation and then shipped back to ORNL for chemical processing, a necessary step to separate the newly produced Pu-238 isotope from unconverted neptunium and other byproducts from the process. Chemical processing also involves converting Pu-238 isotope into its oxide form, which is the form of Pu-238 used as fuel for RPS. Unconverted neptunium is recycled to be reused in target fabrication, and other waste materials are disposed.

[18]Separated neptunium is a special nuclear material that, in specified forms and quantities, could be used to produce a nuclear explosive device.

Figure 2: Overview of the Plutonium-238 (Pu-238) Supply Project and Radioisotope Power System (RPS) Production Process



Source: GAO analysis of Department of Energy documents. | GAO-17-673

RPS Production across DOE's National Laboratories

RPS production occurs across three of DOE's national laboratories—ORNL, LANL, and INL. Until 2017, DOE officials managed RPS production across the national laboratories using a mission-specific approach. In March 2017, DOE officials, in consultation with NASA, moved from mission-specific production of GPHS fuel clads to a constant production rate. According to DOE officials, this change was made to provide stable staffing levels and maintain production capabilities across DOE's laboratories, among other things. Work at these laboratories requires specialized facilities, such as hot cells and glove boxes, and highly trained and qualified staff, because Pu-238 is highly radioactive.[19] These laboratories submit monthly reports to provide updates on RPS and Supply Project activities to DOE's Office of Nuclear Energy. Figure 2, above, provides an overview of DOE's RPS production process at ORNL, LANL, and INL. For example:

- ORNL is responsible for many of the processes related to DOE's efforts to reestablish a domestic supply of Pu-238. As such, Supply Project management is based at ORNL.[20] ORNL designs, tests, and qualifies neptunium targets for the Supply Project. Under the Supply Project, ORNL intends to ship newly produced Pu-238 to LANL for storage and use in new GPHS fuel clads.
- LANL maintains capability for Pu-238 processing and GPHS fuel clad production, among other mission support activities. This work is conducted at LANL's Plutonium Facility PF-4 and involves Pu-238 storage, chemical processing, analysis, fuel processing, and encapsulation of Pu-238 into GPHS fuel clads used in RPS.
- INL maintains capability for RPS assembly, testing, storage, and delivery of RPS for NASA. INL is also responsible for the transport equipment and logistics related to delivering RPS to NASA's Kennedy Space Center in Florida, as well as for supporting NASA at the launch site. Figure 3 shows an MMRTG being prepared for use in the Curiosity rover at Kennedy Space Center in 2011.

[19]According to DOE documents, a hot cell is a heavily shielded enclosure for handling and processing—by remote means or automatically—or storing highly radioactive materials. Remote operation refers to mechanical handling of irradiated nuclear materials by certain means, such as a robotic arm, to eliminate human contact with the materials. Gloveboxes are enclosures that enable operators to use their hands to manipulate hazardous materials through gloves without exposure to themselves or subsequent unfiltered release of the material to the environment.

[20]While ORNL manages the Supply Project, DOE's Technical Integration Office at INL aids in coordinating the Supply Project across the three laboratories.

Figure 3: Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for the Curiosity Rover at Kennedy Space Center

Source: National Aeronautics and Space Administration. | GAO-17-673

NASA Funding for RPS Production

In 2011, NASA began fully funding DOE's Supply Project, and since 2014, NASA has been responsible for funding all aspects of RPS production operations and analysis to support launch safety and approval, according to NASA documents.[21] NASA funds DOE's efforts to build, test, and fuel RPS, as well as to update equipment and sustain staffing levels associated with RPS production between missions. Specifically, NASA has provided, on average, approximately $50 million per year to support DOE's ongoing operations and maintenance of RPS production equipment. NASA provides additional funding related to specific missions that require RPS. According to NASA and DOE officials, DOE provides direct input during NASA's annual budgeting process, giving NASA officials information on DOE's capabilities and resource needs as they relate to the Supply Project and RPS production. See table 1 for NASA and DOE funding of RPS production activities, including the Supply Project.

[21]Prior to 2014, DOE provided funding for infrastructure related to RPS production at DOE facilities, and NASA provided funding for mission-specific RPS production.

Table 1: Radioisotope Power System (RPS) Funds, Fiscal Years 2011 to 2017

Dollars in thousands

	2011	2012	2013	2014[a]	2015	2016	2017
Department of Energy (DOE)							
DOE funds for RPS	46,906	64,524	60,707	$0	$0	$0	$0
National Aeronautics and Space Administration's (NASA) Planetary Science Division (PSD)							
Plutonium-238 Supply Project	3,450	10,000	10,000	14,500	17,000	17,700	20,000
Multi-Mission Radioisotope Thermoelectric Generator[b]	12,341	2,978	16	32	4,000	14,560	14,870
Advanced Stirling Radioisotope Generator[c]	40,908	69,924	31,976	3,000	300	0	0
Operations and maintenance of RPS production equipment	0	0	0	51,300	57,400	55,800	55,500
PSD funds for RPS	**56,699**	**82,902**	**41,992**	**68,832**	**78,700**	**88,060**	**90,370**
Total RPS funds	**103,605**	**147,426**	**102,699**	**68,832**	**78,700**	**88,060**	**90,370**

Source: NASA and DOE | GAO-17-673

[a]Beginning in fiscal year 2014, funding operations and maintenance of RPS equipment came from NASA funding.

[b]Multi-Mission Radioisotope Thermoelectric Generator funding includes funding for NASA's Mars 2020 and Mars Space Laboratory missions.

[c]The development of the Advanced Stirling Radioisotope Generator was discontinued in fiscal year 2014 for several reasons, including costs.

NASA's and DOE's general RPS production roles and responsibilities are established in a memorandum of understanding agreed to in 1991 and revised in October 2016. The 2016 memorandum of understanding delineates the authorities and responsibilities of each agency related to, among other things, research, development, design, and production with respect to RPS. Under the framework of the memorandum of understanding, NASA and DOE have set up interagency agreements to establish high-level milestones and funding profiles for specific RPS and Pu-238 related work. For example, an April 2014 interagency agreement was issued that included NASA's request that DOE maintain the unique program, facility, and safety capabilities required to produce RPS and RPS components and provide related services in support of NASA missions. The agreement also specified that DOE will coordinate with NASA at least annually on the short- and long-range planning of resources, including possible allocations of hardware, facilities, staff, and Pu-238 to potential NASA missions. Another interagency agreement from January 2015 identified commitments for the planned Mars 2020 mission that, among other things, specified the number of RPS required and their expected power requirements and described expected coordination responsibilities. In addition, according to DOE officials, DOE and NASA have established periodic reporting requirements and management meetings to report progress and challenges related to RPS production and the Supply Project.

NASA Selects RPS for Missions Based Primarily on the Agency's Scientific Objectives, and Additional Factors Could Affect Demand for RPS and Pu-238

NASA selects RPS to power missions based on the agency's scientific objectives and mission destinations. Multiple factors, including costs associated with RPS and missions, could affect demand for RPS and Pu-238.

NASA Selects RPS to Power Missions Based on the Agency's Scientific Objectives and Mission Destinations, and Power Source Selections are Made Early in NASA's Mission Review Process

According to the NASA officials we interviewed, NASA selects RPS to power its missions based on the agency's scientific objectives and mission destinations. Generally, the need for RPS is apparent based on the mission's scientific objectives and destination, according to NASA officials we interviewed. For instance, an RPS is more likely to be needed for a mission to a distant planet or permanently shadowed crater where there is minimal sunlight.

According to NASA officials we interviewed, NASA prioritizes missions identified in the National Academy of Sciences' decadal survey report, which include missions that respond to NASA's scientific objectives and may require the use of RPS.[22] In addition, the National Aeronautics and Space Administration Transition Authorization Act of 2017 states that the NASA Administrator should set science priorities by following guidance provided in this decadal survey report.[23] The most recent decadal survey

[22]The National Academy of Sciences' decadal survey report, which represents the highest priority space exploration interests of the scientific community, presents a 10-year program of science and exploration with the potential to yield revolutionary new discoveries.

[23]Pub. L. No. 115-10, § 501(a)(2), 131 Stat. 18, 48.

report identified 16 potential missions, as shown in appendix II.[24] Ten of these potential missions were suggested as options for the decade from 2013 to 2022, and RPS was the recommended power source for 7 of the 10 missions. The decadal survey report also identified 6 missions for the decade beginning in 2022 and recommended using RPS as the power source for 3 of these missions.

NASA officials said that in some cases it is not immediately clear whether RPS or a different power source would be appropriate for a mission's destination—e.g., Jupiter and its moons and, to a lesser extent, Saturn. In such cases, an independent review team would look at aspects of a proposed mission that are unique or require further evaluation. For example, NASA used an independent review team to further evaluate whether the Europa Clipper mission could be successfully accomplished using solar power because typically a mission to one of Jupiter's moons would require the use of RPS. From March 2012 to August 2014, NASA officials examined and assessed the baseline power requirements for the Europa Clipper mission and worked with an independent review team to determine whether solar power was a feasible power option and would not compromise the mission's scientific objectives.[25] NASA officials we interviewed said they were surprised that solar power was determined to be feasible for the Europa Clipper mission.

After NASA chooses a mission, the power source for that mission is typically considered and selected many years before a mission is launched.[26] Generally, NASA conducts mission concept studies to demonstrate why using RPS or another power source is most appropriate

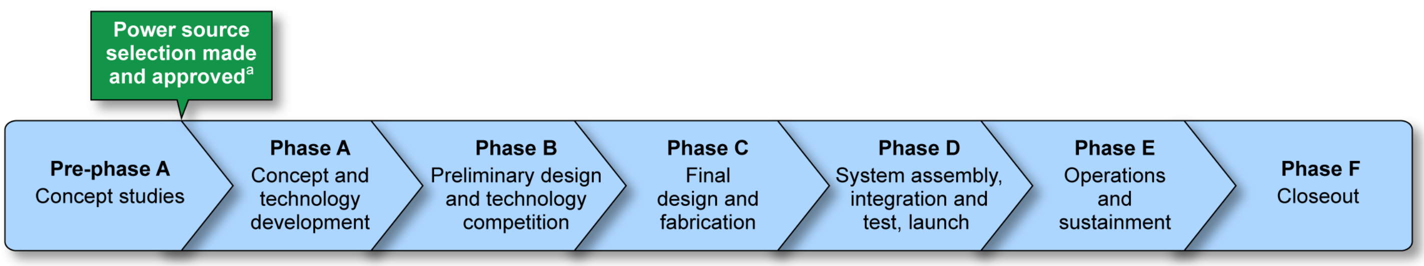
[24]The most recent report was published in 2011, before the Supply Project was started, and stated that some of its recommended missions cannot be accomplished without new Pu-238 production.

[25]Specifically, the independent review team performed a solar feasibility review examining potential radiation exposure on solar cells that would mimic conditions near Jupiter and one of its moons, Europa.

[26]For example, NASA conducted its Mars 2020 mission concept review in August 2013, about 7 years prior to its anticipated launch date. RPS production for Mars 2020 began in 2015, 5 years before its launch.

to meet a given mission's scientific objectives.[27] Subsequently, the power source for a mission is also considered early in NASA's formal mission review process—the lifecycle review process (see fig. 4). Specifically, NASA officials said that many aspects of a mission, including power sources, are considered during pre-Phase A, which is the first step of NASA's lifecycle review process.[28] At the conclusion of pre-Phase A, NASA's mission teams present the Mission Concept Review to a review board for consideration and to seek formal agency approval. A Mission Concept Review presentation outlines the preferred power source for a mission.[29]

Figure 4: Power Source Selection in NASA's Lifecycle Review Process



Source: GAO analysis of National Aeronautics and Space Administration guidance. | GAO-17-673

[a]Competed missions do not go through pre-Phase A and Phase A of NASA's lifecycle review because reviews of competed missions are conducted through the competitive review process.

NASA officials we interviewed said that while power source decisions are reassessed throughout the lifecycle review process, once they are made,

[27]NASA officials said that mission concept studies are typically conducted for directed missions, and, for competed missions, it is the responsibility of the principal investigator to conduct the necessary studies to decide upon a power source. In addition, NASA gives principal investigators an estimate for expected RPS costs, and the principal investigator is responsible for fitting that cost into a given mission's budget. As was the case for New Frontiers #3, if NASA does not make RPS available for a mission, principal investigators cannot propose missions that can only be accomplished with RPS.

[28]NASA officials said that competed missions (Discovery and New Frontiers) do not go through pre-Phase A and Phase A of NASA's lifecycle review because reviews of competed missions are conducted through the competitive review process. The principal investigator produces a mission concept study report equivalent to directed missions' Mission Concept Review. When NASA evaluates competed mission proposals, power sources such as RPS are not an explicitly defined selection criterion. After selection, competed missions are subject to the same lifecycle review process as directed missions.

[29]For instance, the Mars 2020 Mission Concept Review presentation included the proposal to use an MMRTG, similar to the Curiosity mission.

changes to mission power source decisions are rare. In one instance, NASA officials said that the Solar Probe mission originally called for the use of RPS, but a decision was made to choose another power source due to cost constraints and mission objective downsizing. More specifically, following a narrowing of the scope of the Solar Probe mission, RPS is no longer required, and the mission will instead rely on solar power.[30]

NASA officials said they also use review boards to provide independent assessments of mission planning at the end of each phase of the lifecycle review, including an assessment of power sources and margins.[31] NASA conducts these assessments at the conclusion of Phases B through E. These assessments address questions about the electrical power system for the mission and consider whether the selected power source can provide sufficient electrical power margins, based on the current spacecraft design, for example.

While NASA officials generally decide on a mission's power source at the end of pre-Phase A of its lifecycle review process, NASA officials emphasized that the official decision to use RPS is contingent on a final environmental impact statement and record of decision, in accordance with National Environmental Policy Act of 1969 requirements.[32] In addition to its lifecycle review process, NASA officials added that, consistent with the National Space Policy, RPS are used when they enable or significantly enhance a mission, such as when a power alternative, such as solar power, significantly compromises mission objectives. The National Space Policy specifically states that RPS shall be developed and

[30]According to NASA officials, the new mission, called the Parker Solar Probe, is scheduled for launch in 2018, is intended to provide new data on solar activity, and will aid NASA's ability to forecast major space-weather events that impact life on Earth.

[31]In this context, margin is the spare amount of mass or power allowed or given for contingencies or special situations.

[32]Under the National Environmental Policy Act of 1969, agencies evaluate the likely environmental effects of projects they are proposing using an environmental assessment or, if the projects likely would significantly affect the environment, a more detailed environmental impact statement. 42 U.S.C. § 4332(2)(C), (E). According to NASA officials, before the official record of decision for the act, power source considerations are notional, where using an RPS is considered only as a proposal. NASA officials added that an environmental impact statement is typically done to coincide with Phase A of NASA's lifecycle review process. NASA may be working almost exclusively on one potential power source for a mission, but other power options must remain in consideration until the record of decision for the act has been finalized, according to NASA officials.

used only when it significantly enhances space exploration or operational capabilities.[33] Prior to the establishment of DOE's Supply Project in fiscal year 2011, mission selections were influenced by the limited amount of available Pu-238, NASA officials said. These same officials told us that missions are now selected independently from decisions about how they will be powered. However, projected availability of Pu-238 is factored into whether it is offered for a specific mission opportunity.

Multiple Factors Could Affect Demand for RPS and Pu-238

Costs Associated with RPS and Missions Can Affect RPS Demand

NASA officials we interviewed said that the demand for RPS is driven by a mission's cost.[34] Based on NASA's expected funding levels, these officials said, NASA can support no more than one mission using RPS about every 4 years—or two to three missions per decade. NASA's current plans for solar system exploration—one RPS on the Mars 2020 mission and up to three RPS to support the selected New Frontiers #4 mission—is consistent with this mission frequency over the next decade. NASA officials said that they try to work within their budget to pursue and complete the right number of missions to meet the needs of the scientific community and to be consistent with the agency's scientific objectives. According to NASA officials we interviewed, when NASA selects a mission that requires RPS, the cost of the RPS must be supported by the mission's budget.

According to NASA officials, RPS have typically been used on Flagship missions that cost $2 billion or more. Flagship missions are generally very challenging, require more power for scientific instruments, and have larger budgets that can accommodate the costs of RPS. NASA estimates that a single RPS costs about $77 million, which would account for less than 5 percent of a Flagship mission's overall cost.[35] Up to four RPS have

[33]U.S. Office of Science and Technology Policy, *National Space Policy of the United States of America* (Washington, D.C.: June 28, 2010).

[34]NASA's PSD conducts missions using RPS. Approximately $1.6 billion of NASA's $19.3 billion overall appropriation was allocated to PSD in fiscal year 2016.

[35]This estimate includes special services and other work associated with the launch of radioactive materials. However, this estimate does not include environmental reviews, which could cost $1 million or more to complete.

been used in past missions; however, planned missions are projected to use one to three RPS per mission. Flagship mission planning and development occurs over multiple years, and the costs, including those related to RPS, are spread across that time frame. NASA officials we interviewed said that they are currently in the development phase for one Flagship mission—Mars 2020—and the formulation phase for a second Flagship mission—Europa Clipper. NASA officials said that regardless of the availability of RPS, NASA cannot support additional Flagship missions until after the expected launch of Mars 2020 in July 2020, given their expense relative to NASA's overall budget. Mars 2020 has an estimated total cost of $2.44 billion and will use one RPS.[36]

According to NASA officials we interviewed, New Frontiers missions, which are selected through a competitive process, may be good candidates to use RPS given the types of instruments needed to address the scientific questions these missions seek to answer. However, New Frontiers missions have a development cost cap of $850 million, which could restrict the use of RPS. A single RPS would represent about 9 percent of the development cost of a New Frontiers mission. NASA documents indicate that the principal investigator chosen to develop a New Frontiers mission is responsible for fitting the cost of the RPS into the mission's budget. In December 2016, NASA issued an announcement of opportunity for the New Frontiers #4 mission, offering up to three RPS.[37]

RPS have not been used for previously completed Discovery-class missions because these missions had smaller budgets—about $450 million—and shorter mission planning cycles—no more than 36 months—according to the National Academy of Sciences' most recent decadal survey report and NASA officials we interviewed. According to NASA officials, Discovery-class missions are small, relatively quick missions that typically rely on solar panels and not RPS as a power source. The cost of

[36]NASA officials decided that another Flagship mission, the Europa Clipper mission that is expected to launch no earlier than May or June 2022, with a cost estimate range of $3.1 billion to $4 billion, will not use RPS.

[37]According to NASA documentation related to this announcement of opportunity, the use of one MMRTG—the current RPS design—would cost $77 million, two MMRTGs would cost $94 million, and three MMRTGs would cost $117 million. With an $850 million development cost cap, one MMRTG would account for 9 percent of the New Frontiers budget, two MMRTG would account for 11 percent, and three MMRTG would account for almost 14 percent of the mission's budget.

RPS would represent a large portion of a Discovery mission budget, according to NASA officials. A single RPS, at a cost of $77 million dollars, would represent more than 17 percent of a Discovery mission's $450 million development cap. Furthermore, the amount of time DOE takes to build an RPS generally exceeds Discovery-class mission development time frames of no more than 36 months and so it is unlikely that Discovery-class missions can use RPS unless limitations from cost and schedule can be reduced.

DOE's RPS Production Capability Can Limit RPS Use

In addition to budget factors, DOE's RPS production capability can limit NASA's ability to use RPS to power missions. According to DOE officials we interviewed, it can take up to 6 years to acquire, fuel, test, and deliver a new RPS for a NASA mission. According to both DOE and NASA officials we interviewed, DOE only has the capacity to produce three to four RPS at a time, given the current floor space dedicated to RPS development at INL and limits on staff exposure to radiation at LANL. NASA officials said that they would need to provide additional resources to scale up RPS production beyond its current levels. To accommodate DOE's current RPS production capability, NASA officials said they will not select two consecutive missions requiring RPS. For example, if NASA officials know that a Flagship mission will require RPS, they will not offer RPS for a competed mission that will launch around the same time. NASA officials we interviewed said that they provide DOE with a mission forecast, which provides prospective dates for missions offering RPS flight opportunities and gives DOE the associated power requirements for the missions.

Expected RPS and Solar Technological Advances Could Reduce NASA's Demand for RPS and Pu-238

NASA's Glenn Research Center is developing new RPS and solar power technology that may reduce NASA's demand for Pu-238 and thus RPS. NASA officials we interviewed said that they are working on technology advancements in order to preserve Pu-238, which they described as a scarce and expensive resource. Furthermore, the National Academy of Sciences' most recent decadal survey report advocates for RPS technology developments, stating that it is imperative that NASA invest in technology for likely future missions, with the goals of reducing costs and improving scientific capability and reliability.

According to a report to Congress, in 2010, NASA anticipated using a dynamic RPS design, such as the Advanced Stirling Radioisotope

Generator (ASRG), for future missions.[38] This design, according to NASA documentation, would have provided a more efficient power system than the MMRTG RPS design currently in use.[39] DOE's initial Pu-238 production goal of up to 5 kg per year from 2001 was reduced to 1.5 kg based on the assumption that a dynamic system like the ASRG would be available. The ASRG was projected to be more than four times as efficient as the MMRTG and would have required just one-fourth as much Pu-238. However, according to NASA officials, in 2013, the agency ceased ASRG development due to the cost to complete the project under reduced PSD funding (see table 1 for NASA's prior funding of RPS production activities, including ASRG). Although the 1.5 kg-per-year Pu-238 production goal was based on the improved efficiencies of the ASRG and a reduction in the amount of Pu-238 needed for missions, NASA officials said that the projected production from the Supply Project will nonetheless meet their demands using the MMRTG, based on PSD's current mission frequency. Furthermore, NASA's fiscal year 2018 budget estimate indicated that NASA will again invest in dynamic power conversion systems. Specifically, NASA's Glenn Research Center officials said that current work to advance RPS technology would reduce the amount of Pu-238 needed. Officials told us that they plan to invest $8 million in dynamic RPS technology beginning in fiscal year 2018 and increase funding to $10 million by fiscal year 2022.

In addition to dynamic RPS design, NASA's Glenn Research Center officials said that they are researching advancements in thermoelectric technologies that could also increase RPS efficiency. According to these officials, NASA is currently funding this effort in fiscal year 2017 at $8 million and plans to increase funding to $9 million per year by fiscal year 2022.[40] NASA officials said that new thermoelectric materials can lead to improved power conversion efficiency and reduce the degradation of

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[38]U.S. Department of Energy, *Start-up Plan for Plutonium-238 Production for Radioisotope Power Systems: Report to Congress* (Washington, D.C.: June 2010).

[39]The National Academy of Sciences' decadal survey report from 2011 advocated for the continued development of an ASRG, a dynamic RPS design that involves moving parts, as opposed to the MMRTG, which is a static system with no moving parts. The ASRG design is purported to have more efficient power conversion than the MMRTG currently in use.

[40]A portion of the funding—$5 million—will be used to look at the chemistry of thermoelectric elements, and once these are better understood, NASA intends to develop them into thermoelectric couples to be tested through NASA's advanced technology maturation project, according to NASA officials.

thermoelectric couples over time.[41] Specifically, NASA officials said NASA plans to update the current MMRTG design using a new thermoelectric couple material called skutterudite. NASA officials said that this enhanced MMRTG (eMMRTG) would have a 25 percent beginning-of-life efficiency improvement and a 50 percent increase of end-of-life power output. The power output for the MMRTG is about 120 watts, while the eMMRTG is expected to produce from 120 to 160 watts. According to NASA officials, for a mission requiring 300 watts of power, only two eMMRTGs would be needed instead of three MMRTGs. According to NASA officials, using one less RPS unit would save about 3.5 kg of Pu-238 isotope and reduce the mission's overall mass by 45 kg. A NASA official said that the thermoelectric couple technology for the eMMRTG is currently assessed to be at a technical readiness level 3 and will be assessed for technical readiness level 4 by the end of 2017.[42] NASA will determine at a later date if the technology is sufficiently advanced to use the new eMMRTG for the New Frontiers #4 mission.

In addition, NASA officials we interviewed said that they are investigating the next generation of RPS beyond the MMRTG and eMMRTG designs. For example, these officials said that they are reviewing a modular RPS device. A modular RPS would provide a smaller power output, but the modular units could be bundled together to provide a specific power output that meets mission requirements. This would allow NASA to use smaller power increments for missions, thus requiring less Pu-238 to provide that power. More specifically, NASA officials said that this type of power system could have a reduced mass and use a more precise amount of Pu-238 than is required for a mission, depending on the mission's power needs. According to NASA officials, the next generation RPS would ideally achieve up to 600 watts if using two next-generation

[41]Thermoelectric couples are pairs of electrically conductive materials joined in a closed circuit with each side of the pair kept at different temperatures. The thermoelectric couples in the MMRTG use the heat from the decay of Pu-238 to heat the hot side, and the cold of space or planetary atmosphere on the cold side of each pair. However, the MMRTG experiences a power drop-off over time due to the natural decay of Pu-238 as well as the decreased performance of the thermoelectric elements due to high heat deterioration and sublimation of materials.

[42]Technical readiness levels are a scale used to measure the maturity of a given technology. Technology readiness level 3 represents analytical studies and demonstration of nonscale pieces of a subsystem in the laboratory environment. Technology readiness level 4 is representative of a technically feasible approach, though not fully functional. It has been validated in the laboratory environment. See GAO, *Technical Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects.* GAO-16-410G (Washington, D.C.: August 2016).

systems for New Frontiers missions and about 300 watts for Discovery-class missions. Although NASA officials said that they anticipate the Supply Project's Pu-238 production rate goals to be sufficient to meet their mission demands using the existing MMRTG, if advances in conversion efficiency of future RPS designs come to fruition, NASA's future demand for Pu-238 may decrease. Table 2 compares the current MMRTG with other potential RPS technologies.

Table 2: Radioisotope Power Systems for Space Exploration

	Current	Potential Performance	
	Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)	**Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG)[a]**	**Advanced Stirling Radioisotope Generator (ASRG)[b]**
Power	120 Watts (W)	120-160 W	120-160 W
Lifetime	17 years	17 years	17 years
Efficiency (in percent)	6	8-12	12-30
Pu-238 Oxide	4.8 kilograms (kg)	4.8 kg	1.2 kg
General purpose heat source fuel clads	32	32	8

Source: GAO analysis of National Aeronautics and Space Administration documents. | GAO-17-673

[a]The eMMRTG is still in development. The eMMRTG would use the same platform and components as the MMRTG with the exception of the materials used in thermoelectric couples.

[b]In 2013, NASA stopped funding ASRG because of costs, among other things. However, funding for dynamic power conversion development is included in NASA's fiscal year 2018 budget estimate.

According to NASA officials, advances in solar technology could increase the distance from the sun at which missions can operate, making it possible for missions that would otherwise require RPS to be powered, instead, by solar panels. NASA officials said they are working with contractors to focus on overcoming two of the main challenges with using solar panels that are specific to deep space missions—low-intensity, low-temperature conditions and high-radiation environments. These officials said that there have been advances in solar technology regarding how much energy can be captured and converted into electricity, and these advances could help address low levels of light intensity. NASA officials said that because low temperatures can degrade some solar cells, the agency is pursuing solar cells that are better suited for cold environments. NASA officials said that advances in solar power technology have realistically expanded the ability to use solar power for missions for which it would not have been considered before. For example, these officials noted that NASA's current Juno mission and its planned Europa Clipper mission—both with destinations being at Jupiter and its moons and which would typically have used RPS—have demonstrated that solar power is a viable power option.[43]

NASA Does Not Anticipate RPS and Pu-238 Demand from Other Users

NASA does not anticipate other potential users to affect demand for RPS or Pu-238. According to DOE planning documents and NASA officials, expected RPS and Pu-238 production from the Supply Project is intended to only meet PSD's demand. The Supply Project goal of 1.5 kg of Pu-238 per year was established to support two to three PSD missions using RPS each decade. NASA officials said that they did not account for demand from other potential users within NASA or national security and commercial sectors when establishing production goals for Pu-238. While NASA does not expect other users to affect demand for Pu-238, there are other potential uses for Pu-238 outside PSD, including precursor missions in support of human exploration missions or to provide RPS for national security uses.

Specifically, NASA Human Exploration and Operations (HEO) officials we interviewed said that RPS could be used to power precursor missions to Mars in advance of human exploration missions. As of now, HEO officials have identified only one potential precursor mission—a prospecting rover that would test equipment needed to convert atmospheric gas on Mars into fuel—but the baseline power option for this mission would likely be solar. In addition, NASA officials said that they do not anticipate using RPS for primary power on missions involving manned surface rovers or human inhabitants because, even with extreme production projections, there cannot be enough Pu-238 to provide sufficient power. According to NASA officials, however, they are in the early stages of planning for potential future human exploration and precursor missions, and through this planning process, they will determine whether RPS have a potential role in these missions.[44] Because such potential HEO missions are not factored into the current production goal of 1.5 kg of Pu-238 per year, if HEO officials determine that RPS are needed, such as for providing heat or auxiliary power, HEO would need to coordinate with the PSD to make mission prioritization decisions.

[43]According to NASA officials, advances in solar technology have been able to concentrate light intensity at Jupiter to near Earth levels. Light intensity at Jupiter is 1/50th of the light intensity at Earth.

[44]According to PSD officials, NASA's early demand estimate for 5 kg of Pu-238 per year included both PSD and HEO mission needs; however, since then, HEO has moved away from the use of RPS. According to HEO officials, RPS do not provide sufficient power to support human exploration missions.

NASA officials said they have been approached in the past about RPS availability for privately funded space missions, though not in several years. If commercial entities were to require RPS for their missions, they would need to develop a partnership with NASA and DOE to acquire RPS. Additionally, despite being approached in the past, NASA officials said they currently have no plans to offer RPS for privately funded space missions. Similarly, DOE officials view the use of Pu-238 in these contexts as unlikely. As a result, NASA officials did not account for this potential use of RPS when establishing production goals for the Supply Project. These officials said that if any significant quantity of Pu-238 was to be offered to private industry, NASA planetary exploration would be affected.

While DOE maintains a separate inventory of Pu-238 for national security purposes, if that inventory degrades below usable levels or more quantity is needed, according to NASA and DOE officials, NASA's expected Pu-238 from the Supply Project could be reallocated for national security purposes. NASA officials said that DOE has the authority to govern the allocations of the Pu-238 inventory, and that any reallocation for national security purposes would be addressed by the executive branch and its agencies. In such circumstances, NASA officials said that they would work with the administration to address those priorities.

DOE Has Made Progress Reestablishing Pu-238 Production but Faces Challenges that Could Affect Its Ability to Meet RPS and Pu-238 Demand

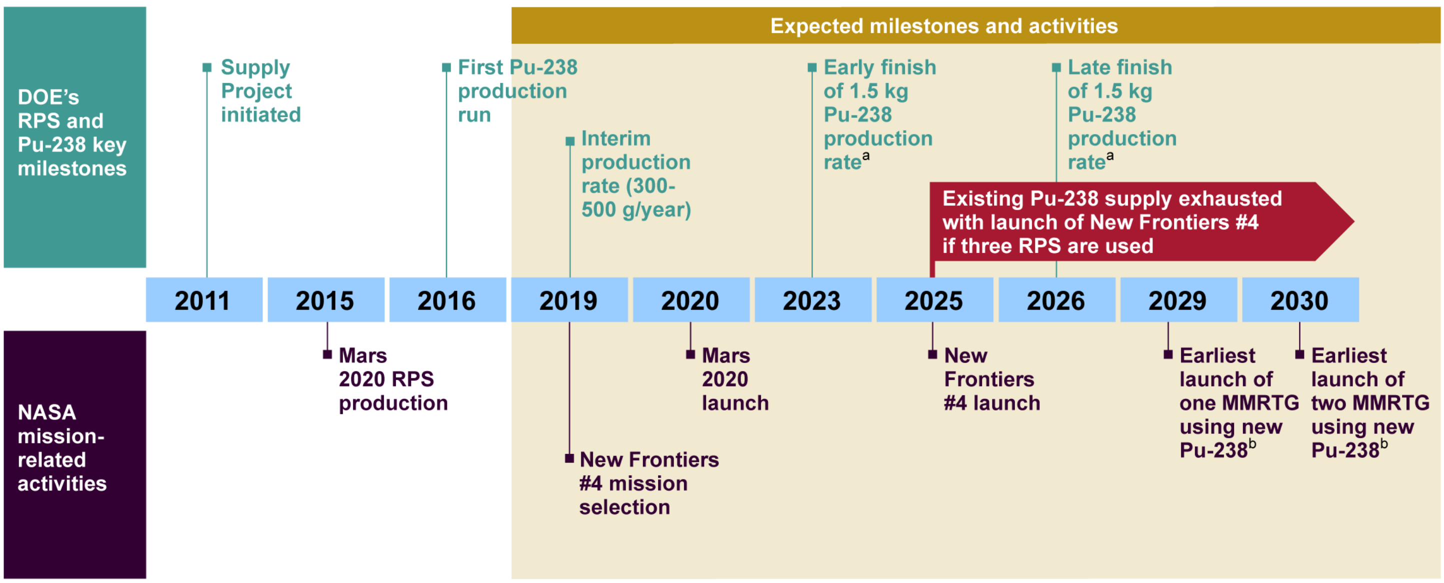
DOE has made progress reestablishing Pu-238 production to meet NASA's RPS demand, is in position to support NASA's current plans for solar system exploration, and anticipates being able to support two to three RPS-powered missions per decade using new Pu-238 expected from the Supply Project. However, DOE faces challenges with key aspects of RPS and Pu-238 production that could put production goals at risk.

DOE Has Made Progress Reestablishing Pu-238 Production to Meet NASA's RPS Demand

DOE has made progress reestablishing Pu-238 production to meet NASA's future demand for Pu-238 to fuel RPS. DOE officials said that they will be able to support NASA's current plans for solar system exploration and expect to be able to support two to three RPS-powered missions per decade for the foreseeable future using new Pu-238 expected from the Supply Project. A selected chronology of key planned

DOE RPS and Pu-238 production activities, with NASA's mission-related activities, are shown in figure 5.

Figure 5: Selected Chronology of Department of Energy and National Aeronautics and Space Administration Radioisotope Power Systems and Plutonium-238 Production Activities



DOE	Department of Energy
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
NASA	National Aeronautics and Space Administration
Pu-238	plutonium-238
RPS	radioisotope power system

Source: GAO analysis of DOE and NASA information. | GAO-17-673

[a]DOE has established a date range of 2023 to 2026 to achieve full production of 1.5 kg of Pu-238 per year; however, as of June 2017, DOE officials said they expect to reach full production no earlier than 2025.

[b]Earliest launch dates assume delivery of 1.5 kg of Pu-238 by the start of fiscal year 2026.

A critical component of meeting NASA's expected RPS-related mission requirements is the production of new Pu-238. NASA officials said that they are confident that DOE will meet its Pu-238 production goals. DOE demonstrated a proof of concept for new Pu-238 production and has made approximately 100 grams of new Pu-238 isotope under its Supply Project since its inception in 2011. As a result of the newly produced Pu-238 isotope quality, it can be blended with Pu-238 that does not meet NASA's spaceflight power specifications in order to extend the usefulness of NASA's existing Pu-238 supply. Both DOE and NASA officials said that they expect to develop and finalize a blending strategy after the quality of Pu-238 produced under the Supply Project is fully assessed. Given DOE's current Supply Project and RPS production schedule, and NASA's space exploration plans, the existing Pu-238 supply will be exhausted by 2025 if four total RPS are used for NASA's Mars 2020 and New Frontiers #4 missions. Furthermore, until DOE and NASA develop and finalize a blending strategy, the earliest RPS-powered mission using new Pu-238 would be in 2029, assuming delivery of 1.5 kg of Pu-238 to LANL for GPHS fuel clad production at the start of fiscal year 2026, as shown in figure 4, above. DOE's progress in meeting NASA's future Pu-238 and RPS demand are illustrated in the following examples.

Using Existing Facilities and Automating Supply Project Steps at ORNL

For the Supply Project, as well as for RPS production, DOE officials said that they are primarily leveraging existing facilities, equipment, and previously proven processes. DOE officials said that it would be prohibitively expensive to build new facilities for the Supply Project's chemical processing work. For example, DOE officials are using hot cells at ORNL that are also used for other isotope work.[45] In addition, according to DOE officials we interviewed, new equipment is being acquired at ORNL to modernize and automate some steps of the Supply Project.[46] For example, DOE has acquired equipment to automate neptunium target production, which DOE officials said they expect will increase Supply Project efficiency as well as reduce staff radiation exposure. Preparing and pressing neptunium into pellets for use in targets is currently a manual process done in gloveboxes, with a press that was formerly used for iridium processing and that was built in the 1920s. DOE officials said that they are able to make about 40 neptunium targets per year, equivalent to pressing one neptunium pellet about every 35 minutes. To achieve DOE's interim goal of 300 to 500 grams of new Pu-238 per year by 2019 and to build up an inventory of targets for full production, DOE will need to make about 128 targets per year, or one neptunium pellet about every 6 minutes. DOE officials said that the automated system will help provide the necessary throughput to meet interim production goals. Without automation, DOE officials determined that they could produce from 120 to 150 grams of new Pu-238 per year. DOE officials said that they intend to have neptunium pellet automation implemented in 2017. The officials added that neptunium pellet automation is expected to increase efficiencies with respect to meeting

[45]Existing hot cells at ORNL are used for other isotope production work, such as californium.

[46]According to DOE documentation, facility and infrastructure improvements at ORNL for the first segment of the Supply Project were estimated to cost $450,000. Beginning at the start of this segment in October 2015, through the planned end of the Supply Project in 2026, these improvements are estimated to cost a total of $1.74 million.

documentation and quality control requirements prior to target irradiation in a reactor.

Upgrading RPS Fuel Production Equipment at LANL

DOE officials said that investments and equipment upgrades are also being undertaken at LANL in support of RPS production. Specifically, LANL officials said that from 2010 through 2012, they carried out a comprehensive programmatic equipment plan to maintain and upgrade equipment related to RPS production work. The plan is now being updated since major work has been completed, according to LANL officials. As part of this plan, LANL officials said they are undertaking efforts to revitalize and extend the life of gloveboxes and other equipment at PF-4 in support of Pu-238 activities. For instance, LANL monthly reports indicate that windows on a fuel production line have been changed out—a necessary improvement because of degradation caused by oxidation in the processing environment. According to LANL reports and officials, they are installing a new Pu-238 fuel pellet hot press that will be used after the current production run of Pu-238 fuel clads for NASA's Mars 2020 mission is complete. The Pu-238 fuel pellet hot press currently in use is about 50 years old and needs frequent maintenance in order to keep it operational. The hot press currently in use will serve as a backup once installation of the new press is completed in 2019.

Testing and Fabricating RPS at INL

DOE officials told us that their main objective for RPS production at INL is to maintain core capabilities to fabricate RPS units. DOE officials said they maintain 30 pieces of equipment, totaling about $30 million in value, that are replaced or refurbished on a rolling basis. For example, INL maintains equipment to support RPS acceptance tests—vibration testing, mass properties testing, magnetics testing, and thermal vacuum testing—to ensure that RPS are suitable for space flight.[47] INL officials said that they do not have backups for most of the equipment so it is imperative that they enhance the equipment's reliability through repair or replacement. INL funding data show that INL sets aside about 5 percent of its annual operations funding provided by NASA for RPS production work to update equipment at INL. These officials said that over the last 12 years they have nearly completed updates to existing equipment related to RPS production.

[47]Vibration testing, for example, is conducted to ensure that the RPS can withstand forces during a launch that could destroy the RPS.

Stabilizing Staff Levels with a Constant GPHS Production Rate

DOE officials we interviewed said that staff retention between missions has been a challenge and that hiring and training new staff to support new missions can take up to 2 years because of the highly technical nature of the job. According to DOE officials and documents, under the previous management approach, DOE retained some staff to support ongoing Pu-238 and RPS work at INL, ORNL, and LANL but would need to hire more staff to support mission-specific work. Specifically, according to INL documentation, there are 40 staff members who support ongoing maintenance and operation of RPS equipment during off-peak times. INL officials said that they would need to hire 15 to 20 people, to reach 55 to 60 staff members, to support mission-related activities under the mission-specific production rate at their laboratory.

DOE officials said that the constant GPHS fuel clad production rate will provide stable staffing levels, removing the need to ramp up hiring and training of qualified staff for mission-specific RPS production. However, according to DOE officials, there are limits on how much DOE can increase GPHS fuel clad production. DOE may only be able to produce 10 to 15 GPHS fuel clads per year—consistent with DOE's current production rate when preparing for a NASA mission and a sufficient quantity to meet currently planned NASA missions. According to DOE officials, if NASA were to require additional GPHS fuel clads for RPS—for example, from 15 to 20 per year—DOE would face challenges in increasing production due to risks to staff from potential radiation exposure at LANL. Additionally, LANL officials said that if NASA requires an increase in the GPHS fuel clad production rate, the current Pu-238 supply would be depleted by 2022, before the Supply Project is fully operational.[48] DOE has instructed its facilities to develop plans to carry out constant rate production and to begin transitioning to the constant production rate model by June 2017.[49] DOE anticipates that NASA will sign new interagency agreements and will provide funding to implement constant GPHS fuel clad production in fiscal year 2017.

[48]The Supply Project is expected to be fully operational in 2023 at the earliest and in 2026 at the latest.

[49]The Office of Nuclear Energy issued a memo on March 7, 2017, to its facilities, INL, LANL, and ORNL, to develop a plan within 45 days and to begin operating under the constant production rate model within 90 days.

DOE Faces Challenges with Key Aspects of Pu-238 and RPS Production

DOE officials from INL, LANL, and ORNL identified several challenges that need to be overcome for DOE to be able to meet its projected Supply Project goal of 1.5 kg per year of Pu-238 by 2026, at the latest. Otherwise, DOE may not able to reach its full production rate or may need to delay its delivery of 1.5 kg of Pu-238 per year. Specifically, these officials identified perfecting and scaling up chemical processing, the availability of reactors, and the qualification of targets for irradiation as challenges that need to be overcome.

Perfecting and Scaling Up Chemical Processing

DOE faces challenges perfecting and scaling up chemical processing that, if not overcome, could result in delays in producing Pu-238 to support future NASA missions. According to DOE officials, DOE is still in the experimental stage and has not perfected the chemical processing required to extract new Pu-238 isotope from the irradiated targets, which creates a bottleneck in the Supply Project and puts production goals at risk. ORNL monthly reports and DOE officials state they are continuing to develop the process to chemically separate newly produced Pu-238 isotope from unconverted neptunium and other materials resulting from irradiation in the reactor. According to officials, DOE is exploring chemical processing methods to effectively recycle neptunium for reuse in the process, convert Pu-238 isotope into its oxide form for use in RPS, and improve methods to reduce radioactive liquid waste.[50]

According to ORNL monthly reports and officials we interviewed, two 5-gram samples of Pu-238 taken from the first 50 grams of new Pu-238 from the Supply Project were shipped to LANL and tested in January and February 2016. These initial samples, however, did not meet space flight specifications.[51] Office of Nuclear Energy officials said that samples from a second 50-gram batch were tested at both ORNL and LANL in October 2016 and met flight specifications. According to DOE officials, chemical processing cannot be done in a linear fashion—that is, the chemicals used in the process are not all increased in the same quantities when making increasing amounts of new Pu-238. As a result, DOE officials said that they need to develop a chemical processing model that will help identify bottlenecks and provide information to help DOE officials improve

[50]Office of Nuclear Energy officials said that improving the neptunium recycling process associated with chemical processing is not a necessary step to meet its production goals.

[51]LANL officials said that a specific chemical composition for Pu-238 is required in order to meet flight specifications. For example, the irradiation of neptunium-237 to create Pu-238 creates unwanted byproducts, such as thorium, that must be removed during the chemical processing phase, according to LANL officials and an ORNL report.

the Pu-238 production process. However, ORNL officials said that chemical processing needs to be scaled up to meet interim and final production goals for Pu-238. For example, ORNL officials said they have sufficient staff to process one batch of irradiated targets at a time to extract new Pu-238 isotope, though multiple batches would need to be run simultaneously to achieve production goals.

According to ORNL documents and officials, to reduce the risk of failing to achieve Pu-238 production goals, additional resources for staff and equipment are needed to increase chemical processing operations. Specifically, to achieve interim production of 300 to 500 grams of Pu-238 per year by 2019, ORNL officials said they would require additional funding of $3 million to 4 million per year for staff and other process improvements. In addition, to reach full-scale operation of 1.5 kg of Pu-238 per year by the end of fiscal year 2023, even more staff and funding are needed. However, these officials did not specify how many new hires would be needed to meet interim and full-scale operations. ORNL officials said that because of the highly technical nature of the job, it can take 2 years to train staff to use specialized equipment. Furthermore, DOE officials we interviewed at ORNL said that the laboratory needs infrastructure improvements for chemical processing, including additional storage tanks, transfer lines, and glove boxes, in order to increase Pu-238 production beyond current sample-sized levels. DOE's ability to meet its production goal and support future NASA missions is at risk if the chemical processing steps in the Pu-238 production process are not improved and scaled up.

Availability of Reactor Positions for Target Irradiation

Officials we interviewed at INL and ORNL also said that achieving 1.5 kg of Pu-238 per year is contingent on the availability of positions within both the High Flux Isotope Reactor (HFIR) and the Advanced Test Reactor (ATR) to irradiate neptunium targets for conversion to Pu-238 isotope.[52] DOE officials stated that ATR must be used, as projected in DOE's initial plans, to reach the production goal of 1.5 kg of Pu-238 per year. However, ATR has not been qualified for Supply Project work because NASA has decided to wait until the reactor returns to service in 2021,

[52]Positions are locations within the reactors where targets are bundled and placed for the irradiation process. Only certain positions are suitable for Pu-238 production. According to DOE documentation, HFIR has 22 positions within the reactor, of which 20 are suitable for Pu-238 isotope production. According to INL documentation and officials, ATR has 75 positions within the reactor, of which 9 are suitable for Pu-238 isotope production.

after a yearlong scheduled maintenance shutdown beginning in 2020.[53] Until ATR is qualified, it is not available for new Pu-238 production. DOE officials responsible for the Supply Project have utilized HFIR at ORNL to irradiate targets, but the forecasted Pu-238 production from this reactor is anticipated to be less than initially planned because target positions within HFIR are limited so as to not interfere with other reactor activities. DOE's 2013 analysis of Pu-238 production projected that HFIR could produce 2 kg of Pu-238 per year, but according to DOE officials, to avoid interference with HFIR's other missions, they subsequently determined that HFIR would produce approximately 600 grams of Pu-238 isotope with the current target design. According to DOE officials, they plan to use positions within ATR to achieve full production goals.

In addition, deferring ATR's use could put achieving production goals at risk because accessing positions within ATR is highly competitive. DOE officials at INL have said that ATR's availability for the Supply Project may be limited due to competition from other users, such as the U.S. Navy, universities, medical researchers, and other DOE programs. Specifically, DOE officials at INL said that the positions most useful for irradiating neptunium targets to create Pu-238 isotope are over-utilized, and of the nine available positions for target irradiation, six are dedicated for Navy use.[54] Despite this, Office of Nuclear Energy officials said that they do not foresee an impact on meeting Pu-238 production goals from deferring the use of ATR. These officials said that DOE conducted a trade study to identify positions within ATR that are not currently being used by the Navy or other ATR users, in order to determine whether they are suitable for Pu-238 isotope production. According to the study, several such positions could be suitable for Pu-238 production, but DOE officials said that additional verification testing would be conducted in fiscal year 2017 to confirm such findings. However, DOE officials said that if positions in ATR are not available for Pu-238 isotope production, they do not have a plan to address this longer-term challenge and will be unable to meet full Pu-238 production goals.

Target Design and Qualification

While DOE officials said that they expect to meet Pu-238 production goals with the existing target design, they have not qualified the existing

[53]DOE officials said that reactors require periodic shutdowns to replace necessary shielding for safety purposes, among other things.

[54]DOE officials at INL said that the U.S. Navy uses ATR for work related to extending the life of fuel on naval ships.

target for use in ATR, which is needed to reach 1.5 kg of Pu-238 per year. In addition, DOE is pursuing a new target design with a higher expected Pu-238 yield. However, the new target design has not been developed and qualified for either HFIR or ATR. Furthermore, because the target has not been fully developed, its expected yield—double the amount of Pu-238 as the current target in certain reactor positions—remains theoretical. According to Office of Nuclear Energy officials, DOE and NASA have agreed to complete research and development efforts to support a decision on the new neptunium target by 2019 that can be used in both HFIR and ATR. ORNL documentation from July 2016 indicated that the laboratory's initial task is to test and assess the new target design on a small scale. According to DOE officials at ORNL, upon successful small-scale testing, they will scale up a prototype target for further testing.

DOE officials said that the higher yield from the new target design could allow DOE to meet or exceed interim and final production time frames and goals because they were calculated using the current target design as the baseline. Officials from the Office of Nuclear Energy said that the established Pu-238 production goals used the existing neptunium target design as their baseline and that any increased Pu-238 production expected with the new target design represents an opportunity. However, officials we interviewed at ORNL and INL said that the anticipated production from the new neptunium target design may be necessary in order to mitigate the effects of other challenges, such as limited reactor space, as discussed above. Office of Nuclear Energy officials said that the existing Pu-238 inventory and planned NASA missions will allow them time to finalize the target design and begin using ATR to provide irradiation capability starting in 2021. According to DOE estimates, it would take from 1 to 2 years to begin irradiating targets at ATR for new Pu-238 isotope production.

Prioritizing Pu-238 for NASA at Plutonium Facility 4

Another challenge DOE must overcome to achieve its RPS and Pu-238 production goals relates to potential competition for space between Pu-238 and nuclear weapons pit production activities at LANL, which could significantly affect a key step in the RPS production process within the next decade, and thus delay the delivery of RPS for NASA missions. Specifically, LANL officials said that Pu-238 work must compete with other priorities for facility space at LANL's Plutonium Facility PF-4. As we stated in an August 2016 report, the National Nuclear Security Administration—a semiautonomous agency within DOE that is responsible for the management and security of the nation's nuclear weapons, nuclear nonproliferation, and naval reactor programs—through its plutonium strategy is focused primarily on the fabrication of plutonium pits for nuclear weapons and has not coordinated with the Pu-238 program about potential modifications planned for PF-4.[55] A May 2015 Congressional Research Service report suggested that moving Pu-238 operations outside of the current LANL PF-4 facility could free up floor space for pit production operations, and also reduce the amount of nuclear material at risk in the facility due to the very high radioactivity of Pu-238.[56] However, LANL officials told us that such a move would be unlikely because of cleanup costs and difficulties in transporting contaminated equipment. In addition, DOE's Office of Nuclear Energy officials said that they do not anticipate pit production to impact RPS production. However, LANL officials told us that they have begun preliminary discussions on this issue but are awaiting the results of a National Nuclear Security Administration plutonium strategy study that is focused on nuclear weapons needs. DOE officials added that they have discussed moving Pu-238 capabilities out of PF-4, where they would seek to move the capability to another DOE site. According to DOE officials, a move of this nature would likely be an expensive, disruptive, and time-consuming effort.

Challenges May Put RPS and Pu-238 Production Goals at Risk

The challenges noted above—chemical processing, availability of reactor positions, target design and qualification, and prioritizing Pu-238 at PF-4—may put DOE's RPS and Pu-238 production goals at risk, in part because of the short-term and incremental segmented management approach DOE has used to manage the Supply Project through early 2017. In this approach, DOE established short-term segments of Supply Project work to be connected to time frames over which DOE could more reliably predict funding from NASA. While DOE officials have known the general tasks required to achieve full production goals for the Supply Project, they have been relying on the developments of each segment to inform specific tasks and activities of subsequent segments. For example, up until March 2017, when DOE changed its management approach for the Supply Project, if challenges, such as delays in scaling up chemical processing, were to be realized, DOE officials said that they would have shifted Supply Project activities from one segment to the next. DOE's own work, however, demonstrates the risks in this approach. For example, an

[55]GAO, *DOE Project Management: NNSA Needs to Clarify Requirements for Its Plutonium Analysis Project at Los Alamos,* GAO-16-585 (Washington, D.C.: Aug. 9, 2016).

[56]Congressional Research Service, *Nuclear Weapon "Pit" Production: Options to Help Meet a Congressional Requirement*, R44033 (Washington, D.C.: May 14, 2015).

October 2016 DOE independent cost estimate for another DOE program showed that deferring activities to later stages in that program may result in program delays or, if delays are undesirable, future activities may be compressed and would likely be less technically mature. Delays in the Supply Project, or the use of less technically mature processes, could put DOE's ability to meet NASA's Pu-238 demands at risk. DOE officials said in June 2017 that the Supply Project's early completion of full Pu-238 production was initially planned for 2023. However, DOE officials said they now expect to reach full production no earlier than 2025 with a late completion date remaining in 2026.

DOE officials, acknowledging that some long-term challenges to the Supply Project exist, said that they recognized that the segmented management approach was not well suited to dealing with those challenges. As previously noted, in March 2017, DOE officials said that the change to a constant GPHS production rate approach was expected to help provide funding flexibility and stabilize RPS production staffing levels between NASA missions. In June 2017, DOE officials said that the constant GPHS production rate approach would also address other identified challenges associated with RPS production and the Supply Project and decided to discontinue the segmented management approach. According to DOE officials, the constant GPHS production rate approach is designed to ensure stable and predictable funding levels and allow DOE more flexibility in how these funds are to be used. This approach, according to DOE officials, will allow the agency to address high-priority challenges by providing flexibility to use NASA funding throughout the RPS supply chain, including for the Supply Project, and will better enable them to sequence work. For example, DOE officials described how a constant GPHS production rate approach allowed DOE to prioritize funding for shipping containers to transport Pu-238 between laboratories.[57] DOE officials did not describe, however, how this new approach would help address some of the other longer-term challenges identified, such as scaling up and perfecting chemical processing. Furthermore, DOE officials provided basic details about the new approach as well as a memorandum dated March 7, 2017, with deliverables that DOE states that the new approach will achieve.

[57]For example, in response to Congress' proposed fiscal year 2017 omnibus appropriation bill, DOE recommended accelerating the procurement of equipment necessary to increase Pu-238 load-out capability at ORNL—including the development, design, and procurement of inner and outer shipping containers—rather than conducting this work in fiscal year 2019, according to a DOE document.

However, DOE does not yet have an implementation plan under the new constant GPHS production rate approach with milestones and interim steps for the Supply Project or for RPS production that can be used to show progress toward implementing efforts, show how risk is being addressed or mitigated, or make adjustments to those efforts when necessary. Our body of work has shown that without defined tasks and milestones, it is difficult for an agency to set priorities, use resources efficiently, measure progress, and provide management a means to monitor this progress.[58] By developing an implementation plan with milestones and interim steps for the department's management approach for Pu-238 and RPS production, DOE can show progress toward implementation, show how risk is being addressed or mitigated, or make adjustments to its efforts when necessary.

In addition, DOE's new approach still does not improve the agency's ability to assess the long-term effects of the challenges associated with Pu-238 and RPS production, such as chemical processing, availability of reactor positions, target design and qualification, and prioritizing Pu-238 at PF-4. DOE's previous segmented management approach did not require that DOE officials assess the potential long-term effects of these challenges, and it allowed them to defer addressing challenges to later segments of the Supply Project. The new approach also does not allow for DOE to adequately communicate long-term challenges to NASA, and it is unclear how DOE will use this approach to communicate these challenges. According to DOE officials we interviewed, DOE and NASA are to develop reports and hold management meetings to communicate identified challenges. In addition, *Standards for Internal Control in the Federal Government* states that agency management should use quality information to achieve the entity's objectives and communicate quality information externally through reporting lines so that external parties can help the entity achieve its objectives and address related risks.[59] DOE officials said they believe the new constant GPHS production rate approach will aid DOE in identifying and addressing challenges associated with RPS production and the Supply Project, as well as

[58]GAO, *Defense Health Care Reform: Actions Needed to Help Ensure Defense Health Agency Maintains Implementation Progress*, GAO-15-759 (Washington, D.C.: Sept. 10, 2015), and *Biobased Products: Improved USDA Management Would Help Agencies Comply with Farm Bill Purchasing Requirements*, GAO-04-437 (Washington, D.C.: Apr. 7, 2004).

[59]GAO, *Standards for Internal Control in the Federal Government,* GAO-14-704G (Washington, D.C.: September 2014).

communicating such challenges to NASA. DOE officials we interviewed, however, provided few details on how they would address identified challenges. Without adequately assessing the long-term effects of existing challenges identified by DOE officials, DOE cannot develop the quality information it needs to understand the effects of these challenges, and this may affect its ability to achieve its Pu-238 production goal or to communicate that information to NASA.

Moreover, because DOE does not maintain a comprehensive risk tracking system for RPS production and, instead, defers to its individual laboratories to track and manage their specific risks, DOE officials may not have the necessary information needed to inform NASA about the effects of these challenges. These potential effects may result in DOE not meeting its Pu-238 production goal, which could cause NASA to delay future RPS-powered missions. DOE officials said that they do not maintain a risk tracking system for the RPS program and that this is maintained by NASA. However, according to NASA officials we interviewed, NASA only tracks high-level risks that could directly affect NASA. *Standards for Internal Control in the Federal Government* states that agency management should identify, analyze, and respond to risks related to achieving defined objectives. Management is to identify risk throughout the agency to provide a basis for analyzing risks. With a more comprehensive risk tracking system that allows DOE to identify more systemic risks beyond the specific technical risks identified by individual laboratories, DOE will be better positioned to adequately assess the long-term effects of all of the identified challenges associated with Pu-238 and RPS production objectives.

Conclusions

NASA is entirely dependent on DOE to supply Pu-238 and RPS for space missions, and future missions requiring RPS are at risk if DOE is unable to fuel and provide these RPS. To meet NASA's demand for new Pu-238, DOE's Supply Project goal of 1.5 kg per year was initially established assuming the use of a more efficient RPS design, which has yet to be realized. While NASA officials subsequently said that the full production rate under DOE's Supply Project would be sufficient using existing RPS designs, any Pu-238 production shortage, coupled with the use of less efficient RPS technology, could present a challenge to carrying out NASA's future RPS-powered missions. In addition, if any of NASA's Pu-238 supply is needed for national security or other applications, NASA may not have sufficient Pu-238 to support future missions or will have to delay such missions until more Pu-238 is provided under the Supply Project. Finally, if NASA intends to launch an additional RPS-powered mission before the end of the 2020s, NASA officials would have to make such a decision by 2023, before full-scale Pu-238 production under the Supply Project is achieved, because it takes multiple years between the time a mission and its power source are selected to the time of launch.

DOE has taken steps to reestablish domestic production of Pu-238 under its Supply Project, and has produced small quantities of new Pu-238. In addition, DOE has identified key challenges to the Supply Project—such as scaling up chemical processing and qualifying targets—that put achieving Supply Project production goals at risk. However, DOE has not fully assessed the potential long-term effects of these challenges on production goals. While DOE officials anticipate that their new approach to managing RPS and Pu-238 production will better help address these challenges, DOE is in the very early stages of implementing this approach and has not identified details, including milestones and interim steps, for how it would address them. In addition, DOE's plans for nuclear weapons pit production activities have not taken into account their potential effects on RPS production and the Supply Project. Federal standards for internal control state that agency management should use and communicate quality information externally to help the entity achieve its objectives and address related risks. While DOE and its laboratories have identified existing challenges to RPS and Pu-238 production, the effect of these challenges on expected Pu-238 production goals have not been fully assessed and thus not fully communicated with NASA. Moreover, DOE's risk tracking system for RPS does not track systemic risks, but rather relies on individual laboratories to track and manage specific risks. Better information about risks would allow DOE officials to inform NASA about the effects of these challenges. Supply Project challenges, if not addressed, may result in DOE not meeting, or being delayed in meeting, the Supply Project goals, and DOE may not be able to fully support NASA missions to deep space using RPS after New Frontiers #4 in 2025.

Recommendations for Executive Action

To help ensure the availability of Pu-238 and RPS for space exploration, we recommend that the Secretary of Energy take the following three actions:

- develop an implementation plan with milestones and interim steps for the department's management approach for Pu-238 and RPS production;

- assess the long-term effects that known challenges may have on production quantities, time frames, or required funding, and communicate these potential effects to NASA; and
- develop a more comprehensive system to track more systemic risks, beyond the specific technical risks identified by individual laboratories.

Agency Comments and Our Evaluation

We provided a draft of this report to DOE and NASA for review and comment. In response, we received written comments from DOE, which are summarized below and reprinted in appendix III. NASA did not provide a formal response because the report made no recommendations to NASA; instead, NASA provided technical comments, which we incorporated as appropriate.

DOE concurred with our three recommendations, stating that it is in the process of implementing a new approach, termed Constant Rate Production, for the RPS supply chain that is more responsive to NASA's needs, among other things. In response to our first recommendation, DOE said that the agency is developing an integrated program plan to implement the Constant Rate Production strategy that will document the management approach for Pu-238 and RPS production. DOE expects to complete this plan in September 2018. We believe that the development of an integrated program plan is an important step, and reiterate that any such plan documenting DOE's management approach should include milestones and interim steps so DOE can show progress toward implementation, among other things. In response to our second recommendation, DOE said that the agency will work with NASA to identify, assess, and develop plans to address known challenges to the RPS program and expects to complete this effort in September 2019. In response to our third recommendation, DOE said that as part of the integrated program plan it intends to develop in response to our first recommendation, the agency will include steps to ensure the current risk system includes comprehensive programmatic risks to support NASA's risk management activities. We believe that implementing these actions will help DOE better ensure the availability of Pu-238 and RPS in support of NASA's space exploration missions.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report date. At that time, we will send copies to the appropriate congressional committees, the Secretary of Energy, the Administrator of the National Aeronautics and Space Administration, and other interested parties. In addition, the report will be available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact me at (202) 512-3841 or oakleys@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix IV.

Shelby S. Oakley
Director
Acquisition and Sourcing Management

Appendix I: Objectives, Scope, and Methodology

This report examines the National Aeronautics and Space Administration's (NASA) process for considering and selecting power sources for missions, in particular the use of radioisotope power systems (RPS), and the Department of Energy's (DOE) ability to maintain the necessary infrastructure and workforce for RPS and plutonium-238 (Pu-238) production. Our objectives were to (1) describe how NASA selects RPS for missions and what factors affect RPS and Pu-238 demand; and (2) evaluate DOE's progress in meeting NASA's RPS and Pu-238 demand and what challenges, if any, DOE faces in meeting the demand.

To describe how NASA selects RPS for missions and what factors affect RPS and Pu-238 demand, we reviewed NASA documents, including procedural requirements, key decision documentation for specific missions, and agreements between NASA and DOE. Specifically, we reviewed NASA's procedural requirements, including the *NASA Space Flight Program and Project Management Handbook*, and reviewed how those requirements were applied to recent missions that used or considered RPS as a power source.[1] We also reviewed documentation related to NASA's key decisions for specific missions—including Mars Space Laboratory, Mars 2020, and the Europa Clipper—to identify NASA's power source decisions and when they were made under NASA's review process. To determine how NASA and DOE collaborate on RPS and Pu-238 development, we reviewed interagency agreements and memoranda of understanding between these two agencies. We also met with NASA officials to discuss how mission decisions related to power sources are made and the impact of technological advances on NASA's demand for RPS. In addition, we conducted interviews with officials from the Planetary Science Division (PSD) of NASA's Science Mission Directorate to determine how NASA selects its missions and how, if at all, the availability of Pu-238 has affected mission selection. In addition, we asked PSD officials about the process NASA uses when making decisions on how to power missions, including the timing of when such decisions are made. We also met with officials from NASA's Human Exploration and Operations Mission Directorate to learn whether NASA expects future human exploration missions to use RPS. We interviewed officials at NASA's Glenn Research Center to discuss how, if at all, advancements in RPS and solar technology could affect future demand for Pu-238-fueled missions. We also interviewed members of the

[1]National Aeronautics and Space Administration, *NASA Space Flight Program and Project Management Requirements*, NPR 7120.5D (Sept. 28, 2011).

scientific community and representatives from a commercial entity to obtain their perspectives on the use of RPS for future NASA missions.

To evaluate DOE's progress in meeting NASA's RPS and Pu-238 demand and what challenges, if any, DOE faces in meeting the demand, we reviewed DOE documentation, including DOE's program management guidelines, Pu-238 Supply Project (Supply Project) plans, monthly reports, and RPS and Supply Project management presentations. We reviewed DOE Order 413.3B to evaluate its applicability to the Supply Project.[2] In addition, we reviewed the *Plutonium-238 Production Program Management Plan*[3] *and the Pu-238 Supply Project - Project Execution Plan*[4] to gain an understanding of the planning, management, and execution of the Supply Project. We obtained and reviewed additional documents associated with the Supply Project, such as DOE's risk management plan and risk register, to determine how DOE is managing new Pu-238 production and the extent to which DOE identifies and mitigates risks. In addition, we reviewed Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), and Oak Ridge National Laboratory (ORNL) monthly reports to assess periodic updates from each laboratory on the Supply Project and RPS production. We also reviewed presentations from DOE officials who oversee RPS production and the Supply Project. In addition, we interviewed officials from DOE's Office of Nuclear Energy to determine the extent to which DOE is prepared to meet NASA's demand for RPS using Pu-238 for planned and future missions. We also discussed with these officials how DOE prioritizes Pu-238 work within its plutonium strategy and how DOE integrates RPS production with other DOE activities. We interviewed officials at DOE's national laboratories involved in RPS production—INL, LANL, and ORNL—to discuss the Supply Project and RPS production. We conducted site visits to ORNL, the laboratory responsible for the Supply Project, and INL, the laboratory primarily responsible for overseeing RPS production, to meet with officials and examine facilities involved in the Supply Project and RPS production. Finally, we compared DOE's efforts to collect and assess quality information about challenges associated with RPS and Pu-

[2]U.S. Department of Energy, *Program and Project Management for the Acquisition of Capital Assets*, DOE Order 413.3B (Washington, D.C.: November 2010).

[3]U.S. Department of Energy, Office of Nuclear Energy, *Plutonium-238 Production Program Management Plan* (Washington, D.C.: September 2015).

[4]U.S. Department of Energy, Oak Ridge National Laboratory Site Office, *Pu-238 Supply Project - Project Execution Plan* (April 2016).

238 production and to communicate these challenges against criteria outlined in federal internal control standards.[5] We also evaluated DOE's management approach for RPS and Pu-238 production against key management practices established in prior GAO work.[6]

We conducted this performance audit from March 2016 to September 2017 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[5]GAO, *Standards for Internal Control in the Federal Government,* GAO-14-704G (Washington, D.C.: September 2014).

[6]GAO, *Defense Health Care Reform: Actions Needed to Help Ensure Defense Health Agency Maintains Implementation Progress*, GAO-15-759 (Washington, D.C.: Sept. 10, 2015), and *Biobased Products: Improved USDA Management Would Help Agencies Comply with Farm Bill Purchasing Requirements*, GAO-04-437 (Washington, D.C.: Apr. 7, 2004).

Appendix II: National Academy of Sciences Decadal Survey Recommended Missions and Power Sources, 2013-2022

Table 3: National Academy of Sciences' (NAS) 2013-2022 Decadal Survey Recommended Missions and Power Sources

Mission	Mission Type (mission number)	Power Source	Power Source Type (number of units proposed)
Mars Astrobiology Explorer-Cacher (MAX-C)[a]	Flagship	Solar	Ultraflex (2)
Jupiter Europa Orbiter[b]	Flagship	RPS	MMRTG (5)
Uranus Orbiter and Probe	Flagship	RPS	ASRG (1)
Comet Surface Sample Return	New Frontiers (4 or 5)	Solar	Ultraflex (1)
Lunar South Pole-Aitken Basin Sample Return[c]	New Frontiers (4 or 5)	RPS	Not specified
Saturn Probe	New Frontiers (4 or 5)	RPS	ASRG (2)
Trojan Tour and Rendezvous	New Frontiers (4 or 5)	RPS	ASRG (2)
Venus In Situ Explorer[d]	New Frontiers (4 or 5)	Solar	Advanced solar-electric propulsion
Io Observer	New Frontiers (5)	RPS	ASRG (2)
Lunar Geophysical Network	New Frontiers (5)	RPS	ASRG (1)
Venus Climate Mission	Beyond the current decade	Solar	Gimbaled (1)
Enceladus Orbiter	Beyond the current decade	RPS	ASRG (3)
Mars Sample Return Lander and Mars Ascent Vehicle	Beyond the current decade	Solar	Ultraflex (1) + Fetch Rover (1)
Mars Sample Return Orbiter and Earth Entry Vehicle	Beyond the current decade	Solar	Ultraflex (1)
Titan Saturn System Mission	Beyond the current decade	RPS	ASRG (5) + MMRTG (1)
Neptune System Orbiter and Probe	Beyond the current decade	RPS	ASRG (3 to 6)

Legend: RPS = radioisotope power system; MMRTG = Multi-Mission Radioisotope Thermoelectric Generator; ASRG = Advanced Stirling Radioisotope Generator

Source: NAS Decadal Survey | GAO-17-673

Notes: The NAS decadal survey report, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, proposes an array of missions to be considered by the National Aeronautics and Space Administration (NASA). The decadal survey report acknowledges that NASA cannot carry out all of these missions. The decadal survey lists Flagship missions in priority order. The New Frontiers missions are not prioritized, and Discovery missions are not listed in the survey report. The survey report also suggests technological investments for some missions beyond the current decade.

[a]NASA has chosen to pursue the Mars 2020 Flagship mission in this decade as an alternative to the MAX-C mission. Mars 2020 is in the planning and development phase and will use one RPS, rather than solar power, which is proposed for the MAX-C mission in the decadal survey report.

[b]NASA is pursuing the Europa Clipper mission, originally called the Jupiter Europa Orbiter (JEO) mission, which is in the planning and development phase. Although originally proposed as an RPS-powered mission, NASA determined that solar power is a feasible power source for the Europa Clipper.

[c]The Lunar South Pole-Aitken Basin Sample Return was originally proposed in the 2003-2013 decadal survey report.

[d]The Venus In Situ Explorer mission was originally proposed in the 2003-2013 decadal survey report.

Appendix III: Comments from the Department of Energy

Department of Energy
Washington, DC 20585
August 14, 2017

Ms. Shelby S. Oakley
Director, Natural Resources
and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, D.C. 20548

Dear Ms. Oakley:

Thank you for providing a draft copy of the Government Accountability Office (GAO) Report "Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges" (GAO-17-673). We appreciate GAO's efforts in this review.

The Office of Nuclear Energy (NE) is in the process of implementing a new approach for the Radioisotope Power Systems (RPS) supply chain that is more responsive to the National Aeronautics and Space Administration's (NASA) needs. This new strategy, termed Constant Rate Production (CRP), will position the RPS infrastructure to support a sustained level of production in line with production goals of NASA. The CRP strategy includes an approach to identifying and assessing issues that could have long term effects to program success as well as communication of issues to NASA. This strategy will be executed through an integrated program plan that prioritizes activities across the program laboratories while linking to risks identified by both Agencies.

The draft report recommendations are:

Recommendation 1: Develop an implementation plan with milestones and interim steps for the department's management approach for Pu-238 and RPS production.

We concur with the recommendation. The Department is developing an integrated program plan to implement the Constant Rate Production strategy that will document the management approach for Pu-238 and RPS production. Estimated completion date: September 2018.

Recommendation 2: Assess the long-term effects that known challenges may have on production quantities, time frames, or required funding, and communicate these potential effects to NASA.

We concur with the recommendation. The Department will work with NASA to identify, assess, and develop plans to address known challenges to the RPS program. Estimated completion date: September 2019.

2

Recommendation 3: Develop a more comprehensive system to track more systemic risks, beyond the specific technical risks identified by individual laboratories.

We concur with the recommendation. As part of the integrated program plan, DOE will include steps to ensure the current risk system includes comprehensive programmatic risks to support NASA's risk management activities. Estimated completion date: September 2018.

If you have any questions, please contact Kelly Scott at kelly.scott@nuclear.energy.gov or 202-586-4288.

Sincerely,

Ed McGinnis,
Acting Assistant Secretary
for Nuclear Energy

Enclosure

Appendix IV: GAO Contact and Staff Acknowledgments

GAO Contact

Shelby S. Oakley, (202) 512-3841, or OakleyS@gao.gov

Staff Acknowledgments

In addition to the contact named above, Jonathan Gill (Assistant Director), Samuel Blake, Kevin Bray, John Delicath, Jennifer Echard, Cindy Gilbert, Timothy Guinane, John Hocker, Michael Kaeser, Jason Lee, Danny Royer, Aaron Shiffrin, Kiki Theodoropoulos, Kristin VanWychen, and John Warren made key contributions to the work.

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