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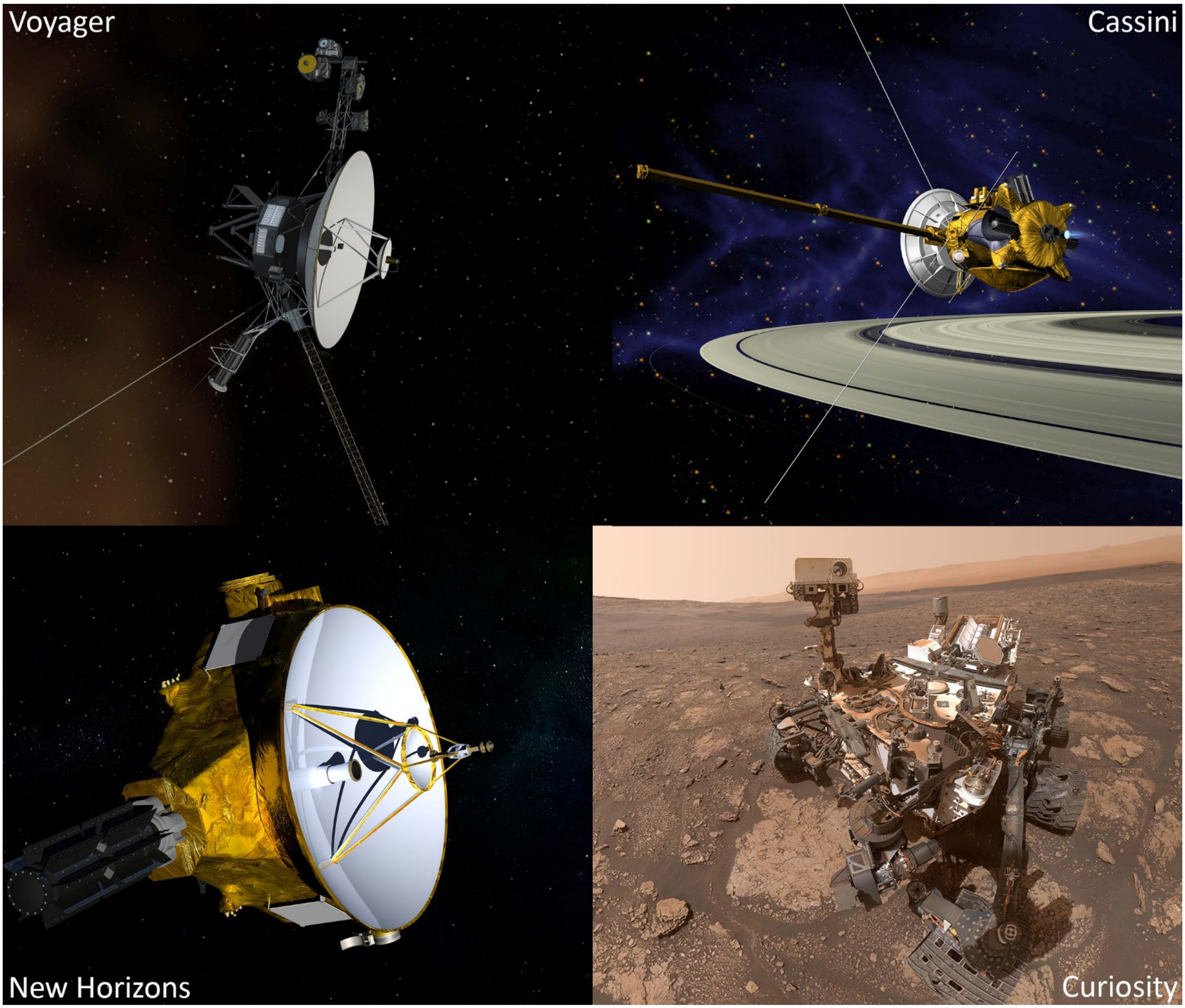
NASA's Management of Its Radioisotope Power Systems Program



March 20, 2023

IG-23-010

Office of Inspector General

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RESULTS IN BRIEF

NASA's Management of Its Radioisotope Power Systems Program

March 20, 2023 IG-23-010 (Assignment No. A-22-02-00-SAR)

WHY WE PERFORMED THIS AUDIT

All space exploration missions require a power source to enable the spacecraft to perform essential functions after launch such as operating scientific instruments, adjusting spacecraft position and trajectory, and sending data back to Earth. Solar and nuclear power are the two most effective options for providing long-term electrical power to missions that explore our Moon, the solar system, and destinations beyond. Solar power uses panels to harness the Sun's energy to generate electricity but is less effective over time in dusty environments—such as on the surface of Mars—and as the spacecraft's distance from the Sun increases. In contrast, nuclear power systems use the heat generated from the decay or fission of radioactive materials as their power source to generate electricity. Nuclear power enables missions in environments where solar panels are infeasible and can enhance mission capability by reducing spacecraft size and mass (because it does not rely on large external solar panels) while providing constant power output irrespective of its distance from the Sun. However, nuclear power systems for spacecraft are expensive, require rare nuclear materials, and entail new technologies that take a long time to develop.

NASA has used various nuclear power systems for its spacecraft over the past 60 years and continues to develop the technology—generally using plutonium-238 (Pu-238)-based radioisotope power systems (RPS)—to expand solar system exploration where conventional solar or chemical powered space flight is impractical or impossible. To manage RPS investments and research, NASA established the RPS Program in 2010 to ensure the availability of nuclear power systems for space-based scientific mission exploration.

We conducted this audit to assess whether the RPS Program has adequate performance management practices and measurements in place to achieve its stated goals. Specifically, we evaluated the RPS Program's management of Pu-238 production rates, the status of current technology developments, and the Program's effectiveness in supporting NASA science missions. To gain an overall understanding of the Program, we interviewed RPS Program Office officials; RPS managers; leadership at NASA Headquarters, Space Technology Mission Directorate, the Langley and Glenn Research Centers, and Jet Propulsion Laboratory; and other subject matter experts. We also obtained additional information regarding nuclear fuel inventory, production, and development from the U.S. Department of Energy (DOE). Our primary criteria for assessing practices and procedures were federal and NASA directives.

WHAT WE FOUND

One of the RPS Program's primary objectives is to develop new technologies that advance NASA's capability to meet its science goals by developing more efficient RPS by reducing cost, reducing Pu-238 quantity requirements per RPS, reducing RPS mass and size, and increasing RPS power output and duration.

However, NASA has not produced a viable new RPS technology since the Program began in 2010 despite an average investment of $40 million per year. We also found that NASA lacks a clear resource allocation strategy to ensure completion of its new technology development projects. In addition, the Program's optimistic assumptions about the maturity of nuclear power technologies and its lack of formal assessments of technology readiness, coupled with associated technology maturation risks, contributed to the termination of two technology development projects—the Advanced Stirling Radioisotope Generator and Enhanced Multi-Mission Radioisotope Thermoelectric Generator—and portend cost and schedule challenges for current and future RPS developments. The cancellation of these technology development projects prior to substantive results disincentivizes the already limited number of contractors remaining in the RPS industry, leading to increased costs and risks to future space-based nuclear power systems developments. But despite these challenges, the Program has inappropriately tailored its management approach and elected not to implement required flight project management tools from NASA Procedural Requirements (NPR) 7120.5F, *NASA Space Flight Program and Project Management Requirements,* for its two current technology development efforts—the Next-Gen Radioisotope Thermoelectric Generator (Next-Gen RTG) and Dynamic Radioisotope Power System (DRPS).

The RPS Program's inability to bring new nuclear power technologies to fruition has negatively impacted its core objective of enabling space-based science outcomes. In turn, this creates strategic barriers to implementing new RPS flight systems because upcoming Science Mission Directorate (SMD) missions are less likely to propose projects incorporating unproven RPS technologies with known developmental challenges. Failing to integrate RPS investments into future space flight projects can also negatively impact the quantitative and qualitative science return of NASA missions.

Lastly, the RPS Program faces communication challenges with both DOE and internal stakeholders that negatively impact NASA's use of nuclear power system technologies for mission proposals. Restrictions on the level of detail DOE can share with the RPS Program due to national security concerns regarding Pu-238 production affect ongoing mission planning and new mission proposals. Internally, NASA needs to establish a more collaborative, strategic relationship between SMD and the Space Technology Mission Directorate to better enable Agency-wide decision making regarding nuclear power development activities, leveraging technical advancements, potential co-development cost efficiencies, and knowledge sharing.

What We Recommended

To ensure the RPS Program effectively and efficiently meets its goals, we recommended the Associate Administrator for Science Mission Directorate direct the Planetary Science Division Director to: (1) create an RPS resource allocation and technology development strategic plan; (2) conduct high quality, frequent, and routine self-assessment Technology Readiness Assessments; (3) per NPR 7120.5F, recalculate the life-cycle costs for the Next-Gen RTG and DRPS projects to include funding NASA provides to DOE; (4) institute an earned value management process for the Next-Gen RTG and DRPS projects that conforms with NASA policy, Federal Acquisition Regulation requirements, and industry best practices; (5) for Next-Gen RTG and DRPS development efforts that transition to a space flight project, execute a Joint Cost and Schedule Confidence Level analysis at the proper phases in accordance with NPR 7120.5F; (6) in coordination with DOE, develop a means for the RPS Program to obtain high-fidelity Pu-238 and fueled clad current and future inventory information; (7) develop a means to quantify risk of future Pu-238 and fueled clad availability that can be communicated to NASA mission managers and incorporated into mission development proposals and plans; and (8) leverage the RPS Program's existing business processes with its element structure to monitor fission technology development for SMD feasibility and educate stakeholders on the possibilities and differences. To enable an Agency-wide perspective for the efficient development of new nuclear technologies, we recommended the Associate Administrator for Space Technology Mission Directorate in coordination with the Associate Administrator for Science Mission Directorate: (9) Reevaluate the need and if appropriate reauthorize the organizational position of the Nuclear Power and Propulsion System Capability Leadership Team through the appropriate Mission Directorate and provide the Team responsibility for monitoring and advocating strategic nuclear power coordination across NASA.

We provided a draft of this report to NASA management who concurred or partially concurred with our recommendations and described planned actions to address them. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions.

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Acronyms

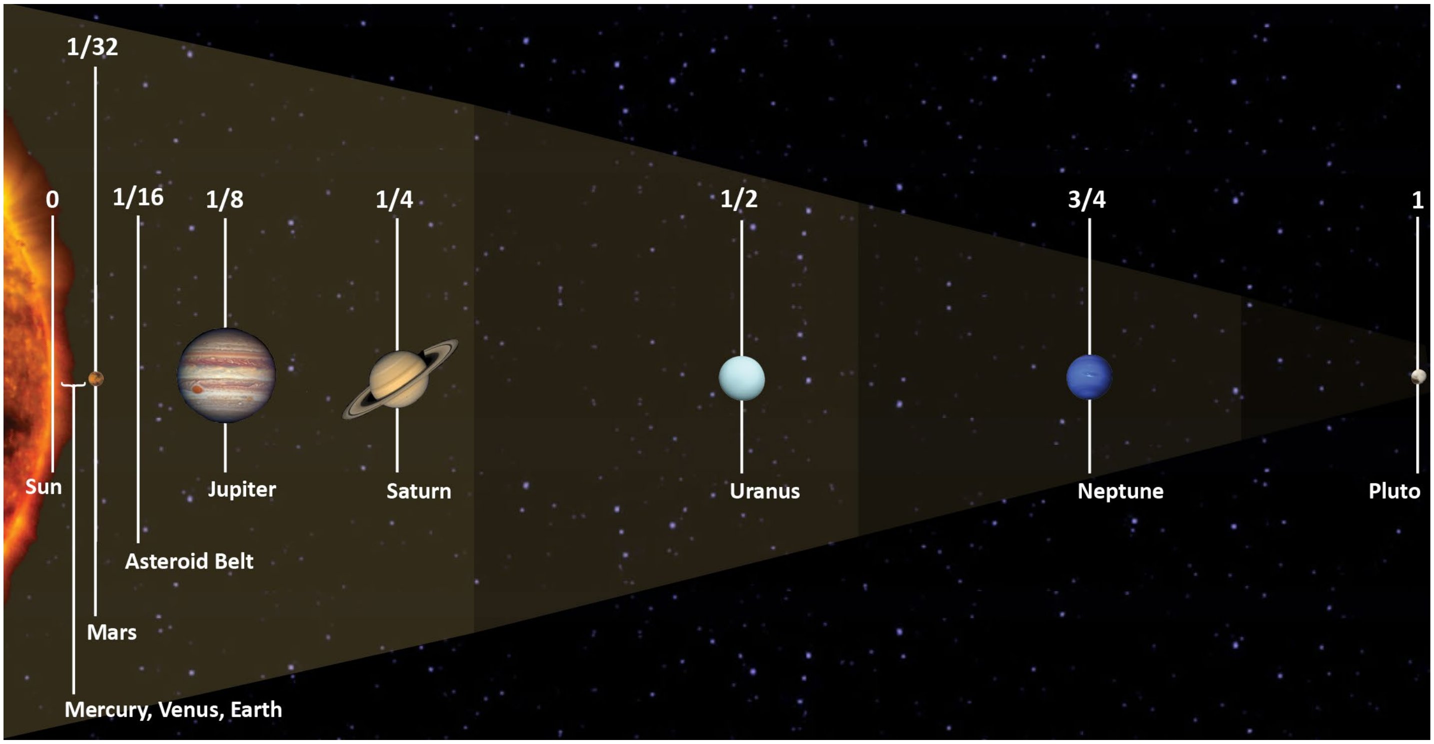
APMC	Agency Program Management Council
ASRG	Advanced Stirling Radioisotope Generator
CRP	continuous rate production
DOE	U.S. Department of Energy
DRPS	Dynamic Radioisotope Power System
eMMRTG	Enhanced Multi-Mission Radioisotope Thermoelectric Generator
EVM	earned value management
FAR	Federal Acquisition Regulation
FPS	fission power system
FY	fiscal year
GAO	Government Accountability Office
GPHS	General-Purpose Heat Source
JCL	Joint Cost and Schedule Confidence Level
kg	kilogram
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MPAR	Major Program Annual Report
NPR	NASA Procedural Requirements
OIG	Office of Inspector General
PSD	Planetary Science Division
Pu-238	plutonium-238
RPS	radioisotope power systems
RTG	Radioisotope Thermoelectric Generator
SiGe	silicon–germanium
SMD	Science Mission Directorate
STMD	Space Technology Mission Directorate
TRA	Technology Readiness Assessment
TRL	technology readiness level

INTRODUCTION

All space exploration missions require a power source to enable the spacecraft to perform essential functions after launch such as operating scientific instruments, adjusting spacecraft position and trajectory, and sending data back to Earth. Solar and nuclear power are the two most effective options for providing long-term electrical power to missions that explore our Moon, the solar system, and destinations beyond.[1]

Solar power uses panels to harness the Sun's energy to generate electricity but is less effective over time in dusty environments—such as on Mars—and as the distance from the Sun increases. Current solar power capabilities become less effective for missions at about the distance of Jupiter's orbit, approximately one-eighth of the way through the solar system (see Figure 1).

Figure 1: Solar System Distances Scale



Source: NASA Office of Inspector General (OIG) presentation of Agency information. Planet sources: NASA/Solar Dynamics Observatory (Sun); NASA/JPL (Mars, Saturn, Uranus, and Neptune); NASA/European Space Agency/Amy A. Simon (Jupiter); and NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (Pluto).

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[1] Chemical-based power systems such as lead-acid or nickel-cadmium batteries are another potential source of electrical power for spacecraft, but these systems are not viable options for missions needing a long-term power source because of their shorter lifetimes and limitations operating at extreme low temperatures often encountered in space.

Nuclear power systems use the heat generated from the decay or fission of radioactive materials as their power source to generate electricity. Nuclear power enables missions in environments where solar panels are infeasible and can enhance mission capability by reducing spacecraft size and mass (because it does not rely on large external sails or panels) and providing constant power output irrespective of the distance from the Sun. However, nuclear power systems for spacecraft are expensive, require rare nuclear materials, and involve new technologies that take a long time to develop.

Mission needs such as destination, duration, required power levels, mass, and cost constraints help determine which power source is the best fit. For example, the Mars rovers Spirit and Opportunity that launched in 2003 used solar power, while the more recent Curiosity and Perseverance rovers rely on nuclear power systems.[2]

NASA continues to develop nuclear power system technology—generally plutonium-238 (Pu-238)-based radioisotope power systems (RPS)—to expand solar system exploration where conventional solar or chemical power generation is impractical or impossible.[3] Accordingly, NASA established the RPS Program in 2010 to ensure the availability of these nuclear power systems for scientific missions that seek to achieve pioneering planetary exploration.

We conducted this audit to assess whether the RPS Program has adequate performance management practices and measurements in place to achieve its stated goals. Specifically, we evaluated the RPS Program's management of Pu-238 production rates, the status of current technology developments, and the Program's effectiveness in supporting NASA science missions. See Appendix A for a full explanation of our scope and methodology.

Background

The Science Mission Directorate's (SMD) Planetary Science Division (PSD) oversees NASA's RPS Program, which was created to manage the production of Pu-238, new RPS technology development, and RPS integration into NASA missions. The goal of NASA's RPS Program is to make RPS a low-risk, cost-effective option for SMD and other Mission Directorates' exploration needs. To meet this goal, the RPS Program manages investments in RPS technologies and RPS systems development while working closely with the U.S. Department of Energy (DOE), the federal agency responsible for plutonium production and its use in nuclear power systems.

RPS Program Organization

The RPS Program is structured to align with five program-level requirements:

- Procure RPS for NASA missions,
- Sustain the capability to conduct RPS missions,

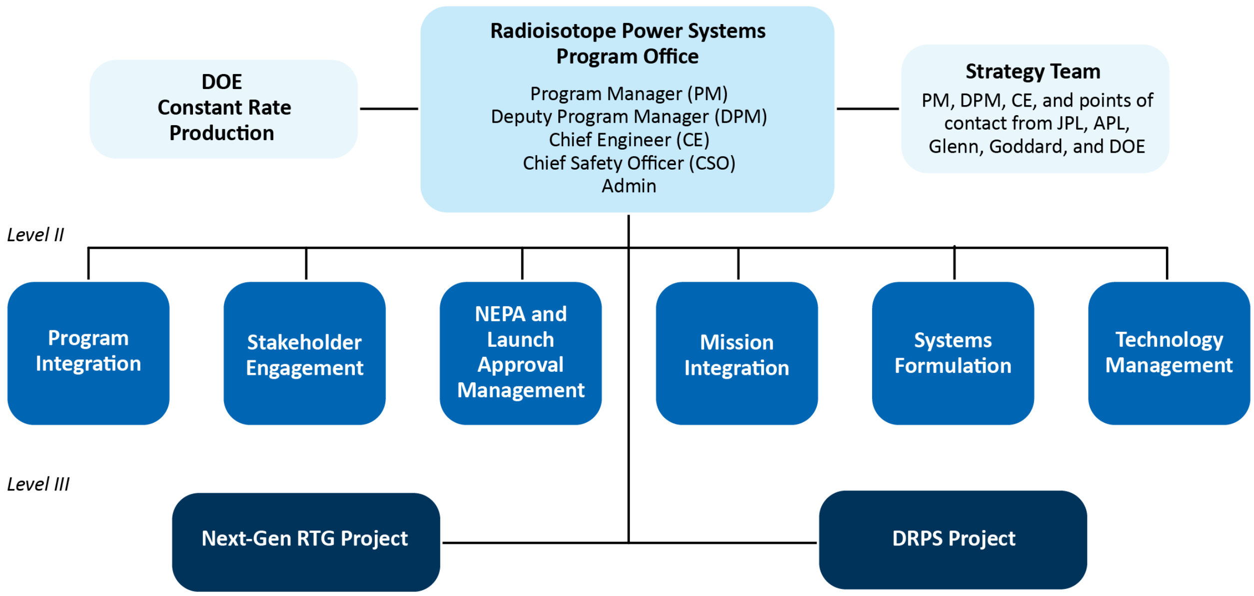
[2] The Mars Exploration Rover mission launched the Spirit and Opportunity rovers on June 10 and July 7, 2003, respectively, to search for water on Mars. Spirit's mission ended in 2011 and Opportunity last communicated with Earth in June 2018. The Mars Science Laboratory mission and its Curiosity rover launched in November 2011 to assess whether Mars ever had an environment capable of supporting life. The Mars 2020 mission and its Perseverance rover and Ingenuity helicopter launched in July 2020 to further key questions about the potential for life on Mars. As of March 2023, Curiosity, Perseverance, and Ingenuity were operating on the Martian surface.

[3] RPS use plutonium oxide—a ceramic form of Pu-238. For readability purposes, we use the term Pu-238 to include plutonium oxide in this report.

- Develop RPS technologies for inclusion in flight systems,
- Manage the nuclear launch safety approval process for RPS, and
- Develop and qualify a new vacuum-rated RPS by 2028.[4]

The RPS Program Office is organized into the six Level II groups shown in Figure 2. The figure also shows the Office's relationship with DOE and its role supporting Pu-238 production, the strategy team that coordinates initiatives with NASA Centers and DOE, and the projects the RPS Program is currently developing.

Figure 2: RPS Program Organizational Structure



Source: NASA OIG presentation of Agency information.

Note: Applied Physics Laboratory (APL), Dynamic Radioisotope Power System (DRPS), Glenn Research Center (Glenn), Goddard Space Flight Center (Goddard), Jet Propulsion Laboratory (JPL), National Environment Policy Act (NEPA), and Radioisotope Thermoelectric Generator (RTG).

DOE Role

NASA and DOE's relationship with respect to RPS activities is documented in a 2016 memorandum of understanding, Strategic Partnership Plans, and other topic-specific interagency agreements. Of prime importance, NASA relies on DOE to produce Pu-238 and integrate the material into RPS units for NASA-developed missions. Under a 2010 agreement between NASA and DOE, updated in 2018, DOE agreed to produce 1.5 kilograms (kg) of Pu-238 per year for NASA missions—about one-third the amount of plutonium aboard the Perseverance rover. The process of producing that amount of Pu-238 involves three DOE facilities in different parts of the country and takes several years to complete.[5] In addition, NASA and DOE are jointly responsible for evaluating RPS technology readiness, coordinating the acquisition approach, and exploring cost-savings opportunities.

[4] A vacuum-rated technology has been tested and proven to be operable in the vacuum of deep space.

[5] At the present time, only the United States produces Pu-238 although Russia may have the capability to produce it and the European Space Agency is considering implementing a production process over the coming decade.

Policy Governance

The RPS Program follows NASA Procedural Requirements (NPR) that establish program and project management requirements. RPS technologies and projects are managed under one of the following two NPRs:

- NPR 7120.5F, *NASA Space Flight Program and Project Management Requirements,* establishes the requirements by which NASA formulates and implements space flight programs and projects.[6] This NPR outlines a comprehensive set of requirements for space flight that can be tailored based on mission size and objective and is the more stringent of the two NPRs used by the RPS Program.
- NPR 7120.8A, *NASA Research and Technology Program and Project Management Requirements*, is used by NASA to formulate and execute research and technology programs and projects.[7] The NPR contains a minimum set of essential requirements designed to give maximum flexibility to support research and technology programs and projects. Projects managed under NPR 7120.8A will sometimes need to adopt additional requirements from NPR 7120.5F's more robust and structured program management processes, especially if the project transitions to flight.

The RPS Program initially manages its acquisition and development efforts according to NPR 7120.8A until technologies have sufficiently matured, at which point the technologies are managed via NPR 7120.5F requirements.

NASA's Current Nuclear Power Development Activities: Radioisotope and Fission Power Systems

NASA considers two primary nuclear power technologies for its space exploration missions: RPS and fission power systems (FPS). Both convert the heat generated by nuclear material into electrical power but through different mechanisms. In addition, substantial differences exist in power output, development progress, and possible mission uses between RPS and FPS.

- RPS use heat from the natural decay of Pu-238 to generate electric power at levels up to about 1 kilowatt. NASA has spent decades developing RPS for use in a variety of mission types such as flight systems and rovers.
- FPS rely on a sustained fission reaction of uranium-235 and generate electric power of several kilowatts to megawatts—thousands of times more powerful than RPS, but at the cost of increased mass from the shielding and additional generator structures. NASA's Space Technology Mission Directorate (STMD) is researching FPS as a potential energy source for spacecraft propulsion and electric power for exploration in NASA's Moon to Mars initiative.[8] FPS is in the early stages of technology development.

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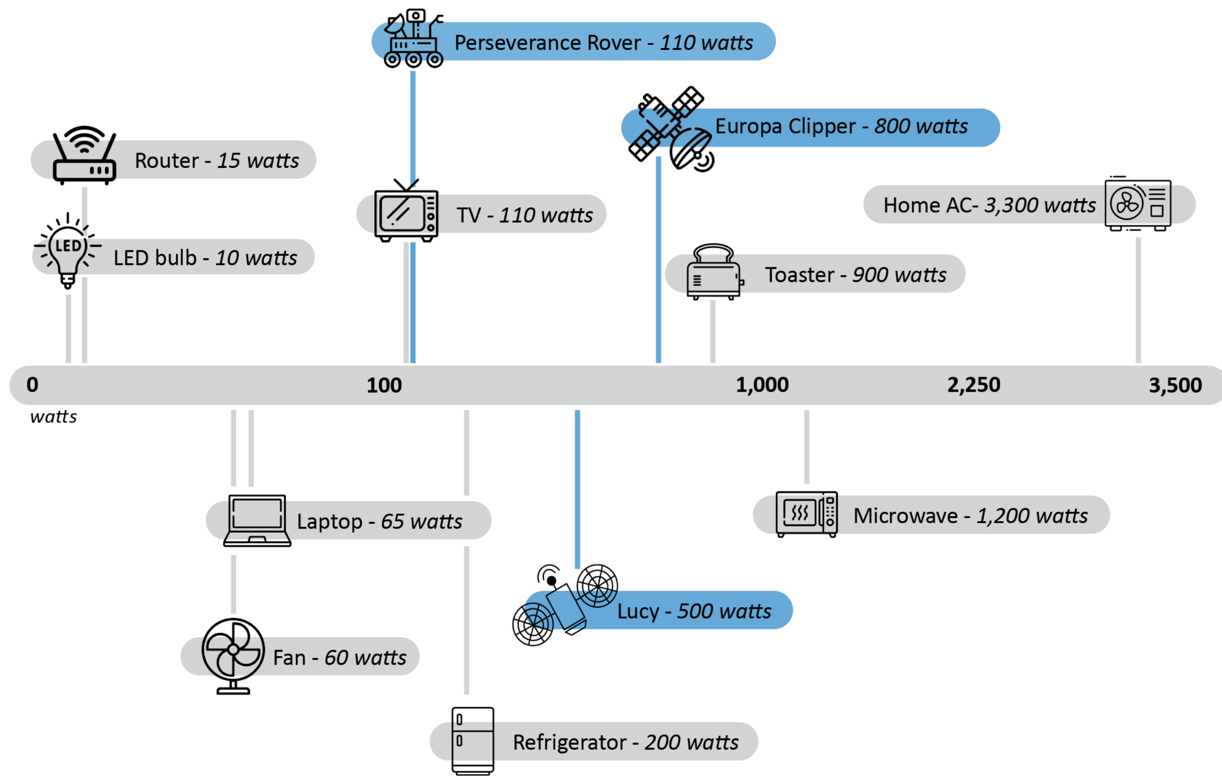
[6] NPR 7120.5F, *NASA Space Flight Program and Project Management Requirements* (August 3, 2021).

[7] NPR 7120.8A, *NASA Research and Technology Program and Project Management Requirements (Updated w/Change 2)* (September 14, 2018).

[8] The Moon to Mars initiative is NASA's plan for eventual human exploration of Mars. Building on elements of the current Artemis lunar campaign, NASA will test systems and concepts for the follow-on Mars campaign.

NASA's science missions generally do not need power systems exceeding 600 watts and have not required nuclear propulsion in the past, so RPS has proven more efficient than FPS for those missions. See Figure 3 for context of wattage per hour usage for common household items.

Figure 3: Household Item and NASA Mission Wattage Usage



Source: NASA OIG presentation of Agency information; Freepik (router, LED bulb, laptop, tv, Clipper, microwave, and Perseverance Rover icons); photo3idea_studio (fan icon); Iconic Panda (refrigerator icon); Good Ware (toaster icon); and Icon Home (home AC icon).

Note: Lucy launched in October 2021 and will be the first space mission to explore a population of small bodies known as the Trojan asteroids that orbit the Sun in front and behind Jupiter. NASA plans to launch Europa Clipper in October 2024 to arrive at Jupiter in April 2030 where it will perform dozens of close flybys of Jupiter's moon Europa to investigate whether the moon could have conditions suitable for life.

SMD has one current RPS technology for generating electricity. It is developing two new RPS capabilities—one static and the other dynamic.[9] The current RPS technology is:

- **Multi-Mission Radioisotope Thermoelectric Generator (MMRTG).** MMRTG was first developed for the Mars Curiosity rover prior to formation of the RPS Program. Since then, MMRTG has been the only flight-qualified RPS option available to SMD missions. The MMRTG has limitations that make it less suitable: its efficiency is low at the beginning of missions and it degrades faster compared to the General-Purpose Heat Source-Radioisotope Thermoelectric Generator (GPHS-

[9] The Program is also responsible for Radioisotope Heater Units that use small amounts of Pu-238 to heat spacecraft components. RPS are generally categorized as "static" or "dynamic" by their power conversion method. Static RPS use thermoelectric power conversion that converts heat into electricity through the difference in temperature between two or more materials. Dynamic RPS convert power using a thermodynamic engine that requires moving parts (e.g., a piston).

RTG). NASA has used various RTG systems for over 60 years, starting in 1961 with the Transit IV-A mission, which was the first satellite to carry one of these systems into space.[10]

Developing RPS capabilities include:

- **Next Generation (Next-Gen) Radioisotope Thermoelectric Generator (RTG).** Next-Gen RTG technology uses thermocouples—a device that produces an electric voltage when two dissimilar, electrically conductive materials are joined in a closed circuit and the two materials are kept at different temperatures.[11] The Next-Gen RTG project is expected to ensure the availability of high-power, vacuum-rated RTGs to enable future deep space missions. This technology leverages the heritage GPHS-RTG design and allows for future upgrades using new technology developed under the Technology Management Element of the RPS Program. Three successive system variants or "Mods" are planned:
    - **Mod-0** seeks to refurbish a previously constructed GPHS-RTG flight unit and verify compliance with project requirements. This system variant provides mitigation against Mod-1 encountering schedule or technical issues.
    - **Mod-1** seeks to reestablish the capability to manufacture silicon-germanium (SiGe) thermoelectric converters (which change heat into power) and hardware with minimal changes to the heritage GPHS-RTG design.[12] The project's objective is to deliver the first unfueled Mod-1 flight unit system as "flight-ready once fueled" or upgradable when advanced thermoelectric technology (i.e., Mod-2) is available.
    - **Mod-2** seeks to upgrade the Mod-1 system with a significantly higher performing thermoelectric convertor technology and other possible hardware changes.

  Currently, the most likely scenario for initial Next-Gen Mod-1 generator deployment is a mission to the outer planets launching in the 2030 timeframe. Consequently, the Next-Gen RTG project's schedule-based requirements are aimed at supporting this rough timetable.

- **Dynamic Radioisotope Power System (DRPS).** DRPS uses heat to move gas that in turn moves a piston to generate electric current. NASA selected two designs to begin a technology maturity review in fiscal year (FY) 2022 and has proposed a DRPS lunar surface demonstration in 2031 as part of NASA's Artemis campaign.

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[10] Among the goals of the Transit IV-A mission was to conduct navigation trials and demonstrations and increase knowledge of the Earth's shape and gravitational field. Other RTGs have been used in various configurations including the 160-watt Multi-hundred Watt RTG on NASA's Voyager mission operating since 1977. The first GPHS-RTG was used on the Galileo spacecraft that launched in 1989 on a mission to Jupiter and later 300-watt GPHS-RTGs were used on NASA's Cassini mission launched in 1997 and Pluto New Horizons mission launched in 2006.

[11] The thermocouples in RTGs use the natural radioactive decay of Pu-238 to heat the hot junction of the thermocouple in opposition to the cold of outer space.

[12] SiGe thermocouples have been used for converting heat into power in spacecraft designed for deep space NASA missions since 1976. This material was used in the RTGs that power Voyager 1, Voyager 2, Galileo, Ulysses, Cassini, and New Horizons spacecraft.

See Table 1 for performance factors and capability of MMRTG, each Next-Gen RTG iteration, and DRPS.

Table 1: Current SMD RPS Technology Developments and MMRTG

Acronym	Name	Pu-238 Required (kg)	Fueled Clads[a]	BODL Watts[b]	EODL Watts[c]	System Mass (kg)
MMRTG	Multi-Mission RTG	4.8	32	110	63	44
Next-Gen Mod-0	Next-Generation RTG—Mod-0	10.8	72	293	208	57
Next-Gen Mod-1	Next-Generation RTG—Mod-1	9.6	64	245	177	56
Next-Gen Mod-2	Next-Generation RTG—Mod-2	9.6	64	400	290	56
DRPS	Dynamic Radioisotope Power System	3.6	24	300-400	241-321	150-200

Source: NASA and OIG analysis of NASA data.

[a] Pu-238 is fabricated into ceramic pellets of Pu-238 dioxide and encapsulated in a protective casing of iridium, forming a fueled clad containing 150 grams of Pu-238. There are four fueled clads in every GPHS module. See Appendix B for greater detail.
[b] Beginning-of-Design-Life (BODL).
[c] End-of-Design-Life (EODL).

History of RPS Development Efforts

Before its current efforts to develop the Next-Gen RTGs and DRPS, SMD attempted to develop two other RPS technologies that were never fully developed into flight systems. However, aspects of these projects continue to be incorporated into ongoing RPS projects.

- **Advanced Stirling Radioisotope Generator (ASRG).** This dynamic RPS was intended to produce power at an increased efficiency of up to four times greater than the MMRTG. The ASRG concept would have used the heat from Pu-238 to drive a moving piston. After approximately 10 years of effort that saw development costs increase from $150 million to $446 million, flight development for this system was terminated in November 2013.
- **Enhanced MMRTG (eMMRTG)**. The eMMRTG upgrade of the MMRTG would have used existing GPHS technology but upgraded the thermocouple material to provide a significantly longer-lasting power supply while using the same number of heat source modules (see Appendix B for a description of GPHS modules). In 2019, the classification of eMMRTG was downgraded from a "project" to a "technology maturation effort" because its technology readiness level (TRL) had been overestimated.[13]

[13] TRL is a widely used metric for measuring the readiness of new technologies or applications of existing technologies. NASA categorizes its technologies between TRL 1 and TRL 9. At TRL 1, preliminary research of a basic concept is in the earliest stages. At TRL 9, the technology is integrated into a product and successfully operated in its intended environment. NASA guidelines state that critical technologies should be at least at a TRL 6—a fully integrated prototype demonstration in a relevant environment—at the time a project completes its Preliminary Design Review.

RPS Program Annual Budget

The RPS Program's requested annual budget for the next 5 years averages $187.7 million per year—about 6 percent of the PSD's annual budget. For those 5 years, slightly more than half or $102.8 million (54.8 percent) of the RPS budget is allocated to DOE for Pu-238 production and related activities. Since the RPS Program's first budget in 2010, an average of $40 million has been allocated to new technology development each year.

Pertinent Laws and Regulations

Two recent federal policy documents have significantly affected the RPS Program's operations and strategic planning:

- Space Policy Directive-6, *National Strategy for Space Nuclear Power and Propulsion*, issued in 2020 provides a strategy for advancing the United States' dominance and strategic leadership in space using space nuclear propulsion and power systems.[14] The directive, intended to serve as a roadmap to pursue coordinated, federally supported space nuclear propulsion and power activities, establishes goals and principles for affected agencies.
- Presidential Memorandum, *Launch of Spacecraft Containing Space Nuclear Systems,* issued in 2019 updated the process for launches of spacecraft containing space nuclear systems and provided clarity for the nuclear safety analysis and review process and documents superseding the National Space Policy of 2010.[15]

See Appendix C for a complete listing of recent reviews and publications that provided stakeholder input relevant to our assessment of the development and application of RPS capabilities.

[14] Space Policy Directive-6, *National Strategy for Space Nuclear Power and Propulsion* (December 16, 2020).

[15] Presidential Memorandum, *Launch of Spacecraft Containing Space Nuclear Systems* (August 20, 2019) and Space Nuclear Power, *National Space Policy of the United States of America* (June 28, 2010).

New Technology Development Strategy Needs Improvement to Advance RPS Capabilities

One of the RPS Program's primary objectives is to develop new RPS technologies that advance NASA's capability to meet its ambitious science goals. Generally, these technology advancements seek to develop less costly and more efficient RPS by (1) reducing RPS cost, Pu-238 quantity requirements, and RPS mass and size; and (2) increasing power output and duration.

However, the RPS Program has not produced a viable new RPS technology since the Program began in 2010. We found that NASA lacks a clear resource allocation strategy to ensure completion of new technology developments. In addition, the Program's overly optimistic assumptions about the maturity of technologies and its lack of formal assessments, as well as associated technology maturation risks contributed to the termination of two technology development projects over the past 10 years and portend cost and schedule challenges for current and future RPS developments. Despite these past challenges the Program has elected not to implement required flight project management tools from NPR 7120.5F for Next-Gen RTG and DRPS—its two current technology development efforts.

The RPS Program's inability to bring new nuclear power technologies to fruition has negatively impacted its core objectives of enabling and enhancing science outcomes. These issues are creating strategic barriers to implementing new RPS flight systems because new SMD missions are less likely to propose projects incorporating unproven RPS technologies with known developmental challenges. Failing to integrate RPS investments into space flight projects can also negatively impact the quantitative and qualitative science return of NASA missions.

Lack of Clear Strategy for Technology Development Resource Allocation

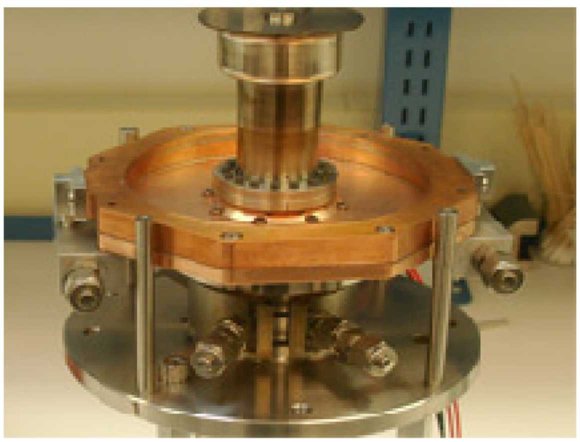
Solar and chemical battery power are not always viable options for deep space missions and the only available RPS, MMRTG, has lower efficiency and degrades faster when compared with older GPHS-RTG, making exploration in deep space more challenging. These limitations give rise to a technology gap in NASA's capability for exploring deep space and the outer planets that has existed since the New Horizons mission used Cassini's spare RPS unit in 2006.[16] Even if the RPS Program achieves its current plans and develops any of the Next-Gen RPS as scheduled, this capability gap will have persisted for more than 20 years despite nearly $500 million specifically allocated to new RPS technology development since 2010.

[16] NASA launched the Cassini mission to explore Saturn in October 1997. The spacecraft reached the planet in 2004 and was in operation until September 2017. The New Horizons mission launched in January 2006 to explore Pluto and after flying by the planet in July 2015, it continued its exploration of Kuiper Belt objects including the Arrokoth in January 2019, the farthest object ever explored by a spacecraft.

The development of a new RPS technology is both expensive and complicated, requiring decades of planning and careful stewardship of the required infrastructure. Beyond the technological development challenges, a lack of strategic focus by NASA has negatively affected development efforts over the past decade. Specifically, the Agency does not have adequate mechanisms in place to identify and address resource allocation priorities or ensure decision-making considers the effort's historical experience and current circumstances.

The RPS Program's first technology development was the ASRG, which was already in progress when the Program was established in 2010. However, in 2013, after 10 years in development, NASA canceled the project. A technical setback involving the piston and underestimation of cost and schedule posed significant challenges and fiscal constraints limited SMD's new technologies investment options. On top of all that, missions under development at the time failed to express interest in the new technology. Lastly, an expectation that Pu-238 supplies were increasing reduced the perceived need for a more efficient RPS system. Even though it was canceled nearly a decade ago, the RPS Program continues to incorporate aspects of ASRG technology into its DRPS project currently in development (see Figure 4).

Figure 4: Dynamic RPS Development with Stirling Technology



Glenn Research Center stated in 2012 that this Advanced Stirling Convertor manufactured with SunPower would be the workhorse component of a new generation of radioisotope power systems, the ASRG.

A demonstration unit of ASRG pictured here was designed to use a fourth of the fuel of an MMRTG. The convertor technology has in some versions operated for hundreds of thousands of hours at Glenn Research Center.

Source: NASA.

The RPS Program's next development project—the eMMRTG—was first formulated in 2014 with the goal to develop Skutterudite-based thermoelectric couple technology.[17] The eMMRTG hoped to have a longer constant power output level by improving the existing MMRTG system's power degradation rate. Technical reviews showed eMMRTG was recategorized from a research technology to a flight development project in 2018 before it had achieved sufficient maturity levels. Subsequently, it did not pass project reviews and was terminated in November 2019. However, like the ASRG, technology research underlying the eMMRTG continues and may be used in Next-Gen Mod-2 developments.

[17] Skutterudite is a cobalt arsenide mineral containing variable amounts of nickel and iron. Materials with a skutterudite structure are studied as a low-cost thermoelectric material with advanced thermoelectric properties.

ASRG and eMMRTG both experienced critical technical setbacks that barred their adoption into mission systems. While NASA missed an opportunity to mature these technologies for use on exploration missions due in large part to technical maturation issues, strategic funding decisions also contributed to their eventual failures. For example, ASRG was offered as a power source option in the NASA Discovery 2010 Announcement of Opportunity.[18] Though two proposals—the Titan Mare Explorer and Comet Hopper—included ASRGs, NASA ultimately selected only the solar-powered InSight proposal, resulting in no demand for further ASRG development.[19]

According to RPS Program management, the cancellation of technology development projects disincentivizes the already limited number of contractors remaining in the RPS industry, increasing costs and risks to future developments. This presents the RPS Program with yet another strategic challenge. However, the 2022 Planetary Decadal Survey suggests a possible demand for a more robust RPS with many priority missions such as the Uranus Orbiter and missions to Triton, a moon of Neptune, and Enceladus, a moon of Saturn, proposing to use Next-Gen RTG.[20] Specifically, of the 18 priority missions selected by the Decadal Survey committee for their technical risk and cost evaluation process, 12 included Next-Gen RTG systems.[21]

Push or Pull: Unclear Paths for Development of an Advanced RPS Technology

The RPS Program's requirement is to develop technologies for insertion into flight systems to enhance and enable NASA missions. Moreover, the RPS Program is required to recommend RPS investments that satisfy NASA's current and future needs. That said, while Next-Gen Mod-1, which is largely based on the heritage GPHS-RTG design, is solely funded through the RPS Program and has a high level of prospective mission interest, the prospects for DRPS and Next-Gen Mod-2 are less clear.

The sentiment that NASA needs advanced RPS technologies was reiterated in the 2020 Space Policy Directive-6 and encouraged in the 2022 Planetary Decadal Survey. However, the RPS Program has an unclear path forward to develop advanced RPS technology for NASA flight systems. Limited resources and risks to the RPS Program will make it difficult to "push" the technology through to a flight qualified system independent of a proposed flight project. Due to the Program's past performance in attempting to develop the ASRG and eMMRTG, the more conventional path of partnering with a mission that "pulls" the technology through the development process (and in doing so, adopts some of its risks) also seems less likely. Consequently, mission planners expressed concerns about incorporating advanced RPS technologies in their proposals because of historic delivery issues on ASRG and other technologies.

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[18] An Announcement of Opportunity is the process by which NASA announces, evaluates, and selects proposals for future NASA missions.

[19] NASA launched the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport mission (InSight) lander in May 2018 to study Mars' interior structure. The mission reached a successful end in December 2022 when dust accumulation on the solar panels caused the spacecraft's battery to run out of energy.

[20] National Academies of Sciences, Engineering, and Medicine, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (2022). The Decadal Survey is one of the most significant vehicles for the scientific community to provide input on NASA's strategic planning for allocating resources between spacecraft missions, research activities, and technology developments.

[21] Of the other six priority missions, five proposed to use solar and one battery only. See Appendix D for a description of the 18 priority missions.

Pushing RPS Technology Through Independent Development

An alternative to developing new RPS technology projects as part of a specific proposed mission is to develop new technologies to a flight-ready state so they are available when missions need them (i.e., "push" them to the flight missions as an available, ready-to-be-proven technology). However, new flight-ready system developments are costly and the RPS Program has yet to fully fund the development of a new RPS without an associated mission proposal. The expense and jeopardy of not having a customer or demonstration at the end of production increases the risk of this technology development strategy.[22]

In addition, DRPS has not been funded at the levels necessary to overcome its technology development challenges and like ASRG and eMMRTG is at risk of not completing development. The DRPS project is managed as a research and technology development project and has requested additional funding of $62.6 million for FYs 2025 through 2028 to transform their project into a flight development project.

Similarly, Next-Gen Mod-2 requested $43.1 million for FYs 2022 through 2027 in additional funds to continue maturing its technology. However, Next-Gen Mod-0 and Next-Gen Mod-1—heritage "Cassini-type" RPS—have been costlier than initial estimates by at least $65 million.[23] Because the RPS Program must prioritize its plan to develop and qualify an RPS by 2028 (currently planned to be the heritage technology Next-Gen Mod-1), the RPS Program's ability to provide additional funding requested for Next-Gen Mod-2—a new, advanced RPS technology development—will be unlikely.

[22] To reduce this risk, the RPS Program utilizes a Surrogate Mission Team to represent the flight-mission community in preparation for flight and includes spacecraft designers from NASA Centers.

[23] Heritage technology includes hardware or software subsystems or components with previous flight history that are used as part of a new mission system.

Pulling RPS Technology Via Mission Selection

Alternatively, funded missions can help "pull" the technology through development by providing funds and an opportunity to bring a technology through the challenging mid-TRL stages when the technology is demonstrated in a laboratory or relevant environment. However, because of the RPS Program's poor history of delivering on projects like ASRG, efforts to use a new RPS are viewed by proposers as a higher risk for a mission given the competitive mission selection process. Therefore, projects are reluctant to incorporate developing RPS technologies in their mission proposals, a critical step for a technology to be pulled to a flight-ready state and avoid taking on the risk that the new RPS experiences development delays and cost overruns.

This skepticism to use a new RPS technology was raised in our discussions with NASA experts. It was also reflected in the 2022 Planetary Decadal Survey where mission planners overwhelmingly leveraged heritage Next-Gen RTGs in their designs instead of eMMRTG, Next-Gen Mod-2, and DRPS. While the Decadal Survey authors felt optimistic about DRPS and the technology's ability to moderate Pu-238 use, they were not as optimistic about the development timetable, saying "Such units are not likely to be available for long duration missions endorsed by the 2022 Planetary Decadal Survey, but a demonstration of a Dynamic RPS for a mission of shorter duration could pave the way for future missions in later decades."

Of the 18 missions selected in the 2022 Planetary Decadal Survey for further analysis, almost none of the proposed mission concepts included new advanced systems (Next-Gen Mod-2 or DRPS) despite the prospective gains in power and reduced mass. Twelve missions proposed to use RPS, but almost exclusively with the heritage technologies Next-Gen Mod-0 or Next-Gen Mod-1. The missions' choice of using heritage technologies illustrates the community's skepticism of the unproven technologies of Next-Gen Mod-2 and DRPS.

Sunpower Robust Stirling Convertor and Generator Concept

The Sunpower Robust Stirling Convertor prototype is being developed by Sunpower, Inc., of Athens, Ohio. The prototype is based on the Advanced Stirling Convertor from the ASRG flight development project.

Source: NASA (Courtesy of Sunpower, Inc.).

The RPS Program's Unclear Future

The Agency's strategy to develop the required new systems, whether through a "push" or "pull" approach, is unclear and makes it difficult for prospective mission planners to understand what their role will be in sharing the development cost and risks associated with an advanced RPS.

The 2022 Planetary Decadal Survey noted that several important technologies could improve SMD's science return on investment but are not being integrated into flight projects because the projects deem the technologies too risky. Given the long lead time and significant costs associated with the development of new RPS technologies, it is essential that the Agency and RPS Program select a long-term strategic risk response to resolve the "push and pull" tension between technology development and mission users. Examples of the risk responses that the Agency could select for the RPS Program to manage that tension include:

- **Acceptance**. Fully funding ("pushing") the RPS technology to flight readiness but accepting the risk that there may be no end user.
- **Avoidance**. Avoiding the risk by ending development of new RPS technology and instead relying on MMRTG and Next-Gen Mod-1 for missions.
- **Reduction**. Reducing the likelihood or magnitude of the risk by, for example, funding and flying RPS demonstration missions.
- **Sharing.** Sharing the risks by incentivizing missions to "pull" new RPS technology through first-use applications, sharing development costs with other Agency stakeholders, or developing new technologies with external partners.

To date, NASA's lack of a clear strategy has resulted in RPS technologies being unable to provide missions with efficiencies related to cost and mass compared to other spacecraft power systems. Our analysis of three solar powered missions found that each would have more electrical power (watts) or less mass if they used RPS technologies as shown in Table 2. Given the significant savings in mass and improvements in power using advanced RPS technology, NASA could achieve more science with each mission, representing an opportunity cost.

Table 2: Hypothetical Impact on Mass and Power with Recent Mission Examples

	Current Solar	MMRTG	Next-Gen Mod-1	DRPS	Next-Gen Mod-2
***Juno*[a]**					
Units		5	2	2	2
Mission Watts	450	433	496	540	690
Mass (kg)	442	225	116	200	124
Cost (dollars in millions)	Unknown	$114	$95	$89	$95
Lucy					
Units		6	3	2	2
Mission Watts	500	519	744	540	690
Mass (kg)	168	270	174	200	124
Cost (dollars in millions)	$24	$129	$120	$89	$95
Europa Clipper					
Units		9	4	3	3
Mission Watts	798	779	992	810	1,035
Mass (kg)	525	405	232	300	186
Cost (dollars in millions)	$72	$174	$145	$114	$120

Source: NASA OIG analysis of Agency data.

Note: This table uses notional estimates and is intended only for a rough comparison. Power systems are complex and tailored per mission. Unit power shown is an average over design life.

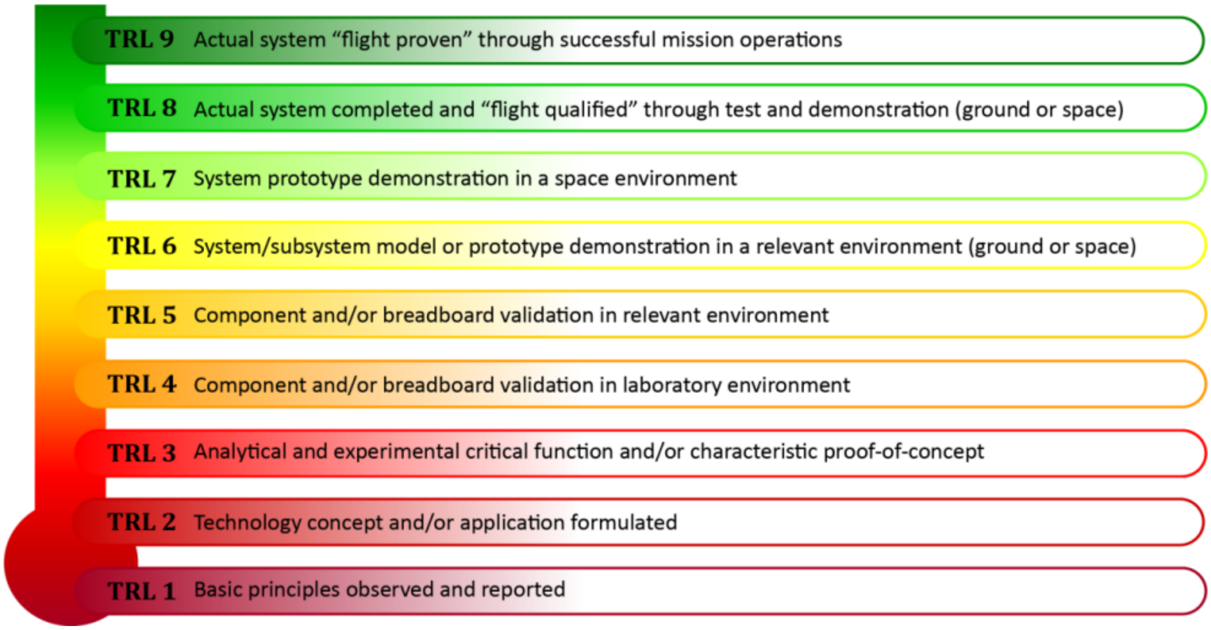
[a] The Juno spacecraft launched in August 2011 and arrived at Jupiter in July 2016 to study the origin and evolution of the planet, look for a solid planetary core, map its magnetic field, measure water and ammonia in the planet's atmosphere, and observe auroras.

The RPS Program's two ongoing technology developments are at significant risk of not being completed despite years of investment. The 2022 Planetary Decadal Survey noted NASA's historic challenges with maturing space flight technologies, emphasizing the importance that the planned development and delivery of improved RTGs with higher power output stay on schedule given that multiple missions planned for the upcoming decade will depend on this technology as a power source.

RPS Program Assessment of Technology Readiness Levels and Associated Risks Needs Improvement

Historically, the RPS Program has not properly assessed the maturation risks for its technology development projects. Accurate assessment of technology readiness to advance to the next level of maturation—the next TRL—is critical to ensure the reliability of cost and schedule estimates to complete development. Figure 5 shows how the TRL number increases based upon the level of progress or milestones achieved. Overestimation of a technology's readiness underestimates the work needed to complete development to achieve the next TRL.

Figure 5: Technology Readiness Levels



Source: NASA OIG presentation of Agency data.

The mechanism typically used by project personnel to evaluate TRL is the Technology Readiness Assessment (TRA). The Government Accountability Office's (GAO) TRA best practices guidance states that a high-quality TRA serves as the basis for realistic discussions on how to mitigate risks as programs move forward from the early stages of technology development.[24] Consequently, GAO determined that a lack of high-quality TRAs that should be performed by project management between programmatic milestone reviews can result in overly optimistic cost and schedule estimates.

We believe that NASA's inadequate TRAs significantly contributed to cost overruns and development delays that ultimately resulted in the termination of both the ASRG and eMMRTG projects. The ASRG and eMMRTG projects failed to perform high-quality TRAs, and as a result the RPS Program was overly optimistic about the TRLs and underestimated the technology maturation risks associated with maturing those technologies to flight-ready systems.

[24] GAO, *Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects* (GAO-20-48G, January 20, 2020). A TRA is a systematic, evidence-based process that evaluates the maturity of technologies (hardware, software, and processes) critical to the performance of a larger system or the fulfillment of the key objectives of an acquisition program, including cost and schedule. GAO guidance identifies two types of required TRAs: (1) a programmatic TRA held at milestone reviews for decision-makers and (2) a self-assessment TRA conducted by project management to quantify risk in maturing technology between specific TRL levels.

Next-Gen Mod-1 May Exceed Cost and Schedule Estimates Due to Poor Classification of Heritage Technology and Underestimation of Technology Maturation Risk

The RPS Program's Next-Gen Mod-1 development project is at a high risk of experiencing similar cost and schedule delays as ASRG and eMMRTG due to the challenges associated with the planned reconstitution of a heritage technology manufacturing process. We believe the RPS Program is overly optimistic about the risks associated with the reconstitution of the heritage technology manufacturing process in Next-Gen Mod-1 and is therefore not properly assessing it as a critical technology—that is, a technology needed for a system to meet its operational performance requirements within defined cost and schedule parameters.[25] Overly optimistic TRLs and underestimation of maturation risk by project management during development are known inherent risks to successful technology development projects. Therefore, high-quality and regular self-assessments are a best practice when determining a project's critical technology maturity levels starting at the beginning of the development phase of the project, but such assessments are not being conducted by RPS project managers.

According to GAO guidance, a heritage technology can become a critical technology if process changes have been made in its manufacture.[26] Specifically, technologies may become critical technologies, and therefore no longer a true heritage technology, from a manufacturing process or material, measurement, or infrastructure perspective, including whether an organization has a workforce with the necessary skills, knowledge, and experience to develop the technology. Furthermore, the determination of what constitutes a critical technology requires knowledge, experience, and due professional care. GAO found that in many projects, cost growth and schedule delays have resulted from overly optimistic assumptions and underestimation of risk to mature a technology.

The Next-Gen Mod-1 project carries a high risk that the manufacturing production line cannot be reestablished, as well as a significant risk of parts obsolescence. Specifically, the original contractor who produced the heritage SiGe thermocouple went out of business. Furthermore, the current DOE subcontractors, Aerojet Rocketdyne and Teledyne Energy Systems, have no previous experience with the SiGe thermocouple technology and therefore face a significant learning curve for the project.[27]

Despite these recognized risks, project managers insist that the thermocouple technology is heritage and therefore not characterized as a critical technology that needs frequent TRAs. Next-Gen RTG project management stated that the project can use the requirements of the *NASA Technology Readiness Assessment: Best Practices Guide* at the end of the project to assess the Next-Gen Mod-1 project's technology development if they determine the contractor deviated significantly from the heritage design concepts.[28] In addition, the Program's *RPS Technology Readiness Assessment–Best Practices Guide* recommends evaluating TRLs for the Next-Gen RTG project and states the subcontractor is required to perform TRAs in support of the Mod-1 Design/Initial Maturity Review and Mod-1

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[25] Critical technologies are technology elements deemed critical if they are new, novel, or used in a new or novel way. These technology elements may be hardware, software, a process, or a combination that is therefore vital to the performance of a larger system or the fulfillment of the key objectives of an acquisition program.

[26] GAO-20-48G.

[27] In May 2020, the RPS Program chartered a Thermo Electric SiGe taskforce comprised of personnel from the Johns Hopkins University Applied Physics Laboratory, Glenn Research Center, Jet Propulsion Laboratory, Oak Ridge National Laboratory, and the University of Dayton Research Institute to support Aerojet Rocketdyne.

[28] NASA SP-20205003605, *NASA Technology Readiness Assessment: Best Practices Guide* (June 30, 2020).

Design/Final Maturity Review. Furthermore, the subcontractor is also required to produce a TRA Report that documents the TRA process and provide an explanation of the assessed TRL for each critical technology. However, we do not believe that assessments conducted later in the development cycle are adequate to ensure proper risk mitigation and adherence to cost and schedule or meet the intent of GAO's best practices guidance that recommends high-quality, frequent, and routine TRAs be conducted by project management beginning with initiation of the project.

Consequently, we believe the RPS Program's Next-Gen Mod-1 flight system development project is at high risk of experiencing cost and schedule delays due to the challenges associated with the planned reconstitution of a heritage technology manufacturing process because it is not adequately evaluated on a continuing basis by project management. The RPS Program did not properly use TRAs to assess the technology maturation risks for the ASRG and eMMRTG space flight system development projects and project management appears to be on the same path for the Next-Gen Mod-1 project.

RPS Program Can Benefit from Implementing Required Oversight Tools

Project management for both Next-Gen RTG and DRPS projects have stated that they do not intend to implement earned value management (EVM) or Joint Cost and Schedule Confidence Level (JCL) tools for their projects when they transition from research and development to space flight projects.[29] These positions, supported by RPS Program management, do not comply with NASA policy and congressional requirements that major space flight acquisitions—those with life-cycle costs estimated to be greater than $250 million, which both projects' planning and budget forecasts indicate they will exceed—must implement these management tools.[30] Specifically, although the Next-Gen RTG project has not yet established a cost and schedule baseline, its budget and requested budgets from 2017 through 2028 totals $301.2 million. Likewise, DRPS project management requested funding through 2030 totaling $326.6 million.

To meet NASA and congressional requirements to help ensure major acquisitions have realistic cost estimates and achievable schedules, projects must use probabilistic cost and schedule estimating processes. To this end, NPR 7120.5F has several tiered requirements at certain financial benchmarks:

- Projects with an estimated life-cycle cost greater than $250 million are required to implement EVM and comply with EIA-748, *Standard for Earned Value Management Systems*, for all portions of work including in-house and contracted portions of the project.
- EVM System requirements for contracted work shall be applied to suppliers in accordance with the NASA Federal Acquisition Regulation (FAR) Supplement, independent of the project's phase

[29] EVM is a project management approach for assessing project performance through the integration of technical scope with schedule and cost objectives during the execution of the project. JCL is a probabilistic analysis intended to provide a risk-based estimate of cost and schedule to help predict the likelihood that a project or program will achieve its objectives within budget and on time.

[30] NPR 7120.5F and Title 51, U.S.C. § 30104 (2016), *National and Commercial Space Programs*, defines the term "major program" as an activity approved to proceed to implementation that has an estimated life-cycle cost of more than $250 million and requires the status of these major acquisitions be reported to Congress on the Major Program Annual Report.

if life-cycle costs are above $100 million. Moreover, the FAR requires the federal government to implement EVM for major development acquisitions.[31]

- Projects with an estimated life-cycle cost greater than $250 million must develop probabilistic analyses of cost and schedule estimates to obtain a quantitative measure of the likelihood that the estimate will be met.

The RPS Program has erroneously concluded that they are not required to follow NPR 7120.5F EVM and JCL requirements because funds that will pass through DOE for developing the projects are not considered part of the projects' life-cycle costs. For example, Next-Gen RTG project documentation we reviewed during this audit shows that they consider funds transferred through DOE are not currently considered part of the projects' life-cycle cost.[32] However, we believe since NASA provides DOE the funds for development, those funds should be considered part of the project's life-cycle cost.

Additionally, as part of the National Aeronautics and Space Administration Authorization Act of 2005, NASA must provide Congress a Major Program Annual Report (MPAR) for programs and projects in development with an estimated life-cycle cost exceeding $250 million.[33] For new major programs and projects for which NASA establishes a cost and schedule baseline, the MPAR must provide a Baseline Report that, at a minimum, includes an estimate of the program's or project's life-cycle cost with a detailed breakout of development cost and program or project reserves, as well as an estimate of the annual costs until development is completed.

The NASA Office of Inspector General has reported in multiple audits on the criticality of these controls.[34] RPS Program management's decision to ignore requirements for EVM, JCL, and future MPAR reporting without adequate justification or compensating controls means that NASA management will have less information to make informed decisions about cost and schedule estimates and the progress of each RPS project.

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[31] FAR 34.201, *Policy* (2022), states that an EVM System is required for major acquisitions for development in accordance with Office of Management and Budget Circular A-11.

[32] As of November 2022, Next-Gen RTG and DRPS projects have already spent $54.3 million and $31.1 million, respectively.

[33] National Aeronautics and Space Administration Authorization Act of 2005, Pub. L. No. 109–155 (2005).

[34] Most recently in our audits of *NASA's Volatiles Investigating Polar Exploration Rover (VIPER) Mission* (IG-22-010, April 6, 2022) and *NASA's Cost Estimating and Reporting Practices for Multi-Mission Programs* (IG-22-011, April 7, 2022) we document instances of the Agency choosing to ignore Title 51 and NPR 7120.5F provisions, resulting in less transparency and accountability for major acquisitions' cost and schedule to external stakeholders, namely Congress and the Office of Management and Budget.

Better Communication Can Reduce Risks to the RPS Program and NASA Projects

The RPS Program faces communication challenges with both DOE and internal stakeholders that negatively impact NASA's use of nuclear power system technologies for mission proposals, during mission planning, and with other nuclear power development activities within NASA. Restrictions in the level of detail DOE can share with the RPS Program due to national security concerns regarding Pu-238 production affect ongoing mission planning and new mission proposals. Internally, NASA's lack of coordination, including between SMD and STMD, for nuclear power development activities limit opportunities for leveraging technical advancements, potential codevelopment cost efficiencies, and knowledge sharing.

NASA Does Not Have Sufficient Information to Assess Risks Regarding Rates of Pu-238 and Fueled Clad Production for Potential Missions

As one of its three primary objectives, the RPS Program is responsible for procuring RPS for NASA missions when needed, including acquiring Pu-238 and the resulting fueled clads from DOE.[35] Pu-238 is manufactured by DOE and its contractors from neptunium.[36] The process of transforming the neptunium into Pu-238 remains costly and requires long lead times. Moreover, mission power needs, funding, and the type and quantity of power systems missions use dictate the amount of fueled clads needed. Newer, more efficient systems like DRPS plan to use fewer fueled clads than current MMRTG systems.

Accordingly, to better manage mission planning challenges, DOE and NASA established constant rate production, or CRP, to make the volume of Pu-238 available for NASA missions more predictable.[37] However, the RPS Program faces three challenges that affect the predictability of Pu-238 availability and insert risk into mission planning:

1. Current production is lower than planned,
2. Overly optimistic expectations about DOE flexibility to increase Pu-238 production beyond CRP plan levels, and
3. Lack of transparency into DOE inventory of Pu-238 and base elements.

[35] Fueled clads are the encapsulated form of Pu-238 fuel used in RPS.

[36] Neptunium-237 is a byproduct of irradiating uranium with neutrons in a nuclear reactor.

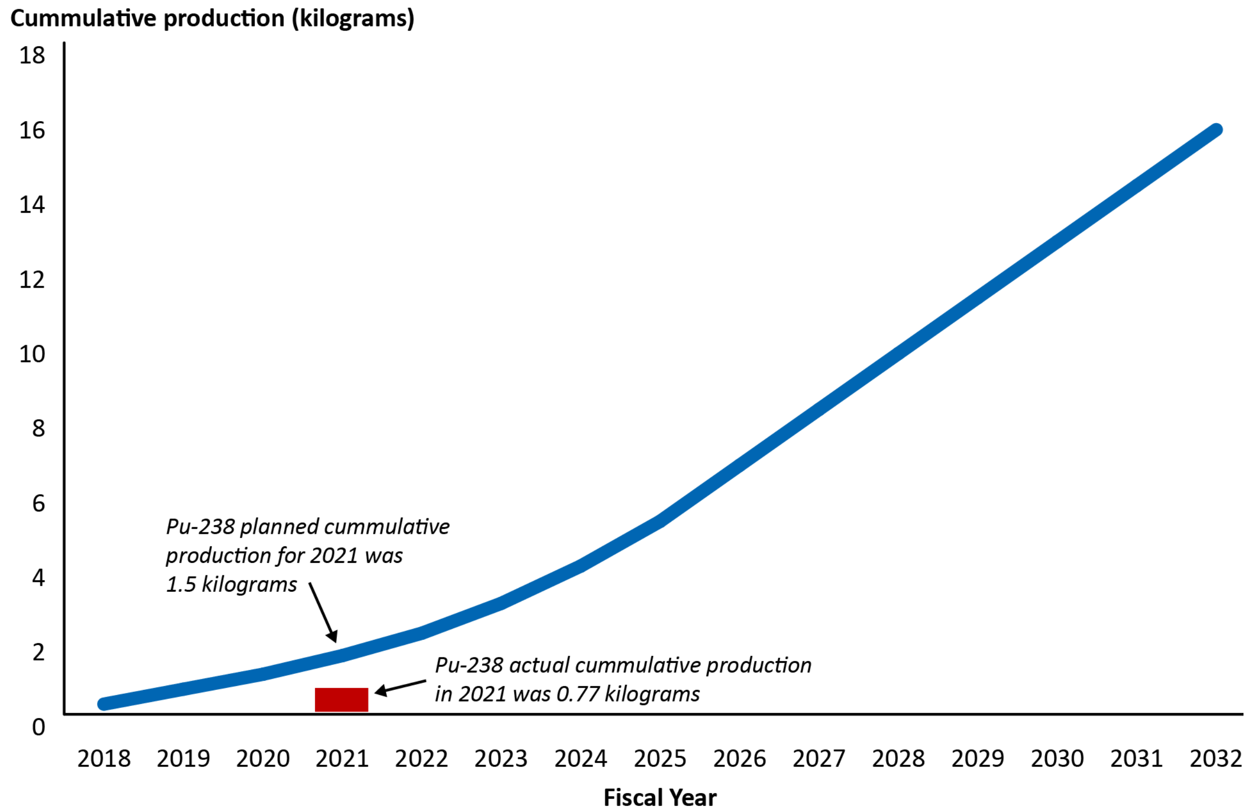
[37] CRP involves a higher level of base capability at Los Alamos National Laboratory, Idaho National Laboratory, and Oak Ridge National Laboratory to provide a stabilized work force and have quantities of Pu-238 more quickly available to support production of RPS and when a NASA mission is selected.

Mission advisers and planners—like the National Academies of Sciences, Engineering, and Medicine through the decadal surveys and PSD; missions in development like Dragonfly; and proposers of potential missions—rely on RPS Program information about the availability of Pu-238 and the possibility to increase production.[38] But lack of DOE transparency into actual production rates and risks can result in unrealistic expectations that inhibit sound mission planning. It can also deter mission planners' interest in RPS because of the uncertainty.

DOE Production Levels Lower than Planned

The RPS Program and DOE created the CRP process to align RPS fuel production needs with expected output. Pu-238 and the number of fueled clads are the two major production outputs from the CRP process that are critical for NASA to track. DOE plans to steadily increase Pu-238 production until reaching an annual CRP goal of 1.5 kg per year by 2026.[39] The agreement also provides for between 10 to 15 fueled clads per year using other DOE Pu-238 sources (e.g., existing inventory or international purchases). However, as shown in Figure 6, although DOE planned to produce a total of 1.5 kg from 2018 through 2021, they produced only 0.77 kg—about half the projected amount.

Figure 6: Planned vs Actual Pu-238 Cumulative Production, 2018 through 2032



Source: NASA OIG presentation of Agency and DOE data.

[38] Dragonfly, planned to launch in June 2027, is a multi-rotor vehicle designed to examine sites around Titan—Saturn's richly organic, icy moon—to advance the search for the building blocks of life in the universe.

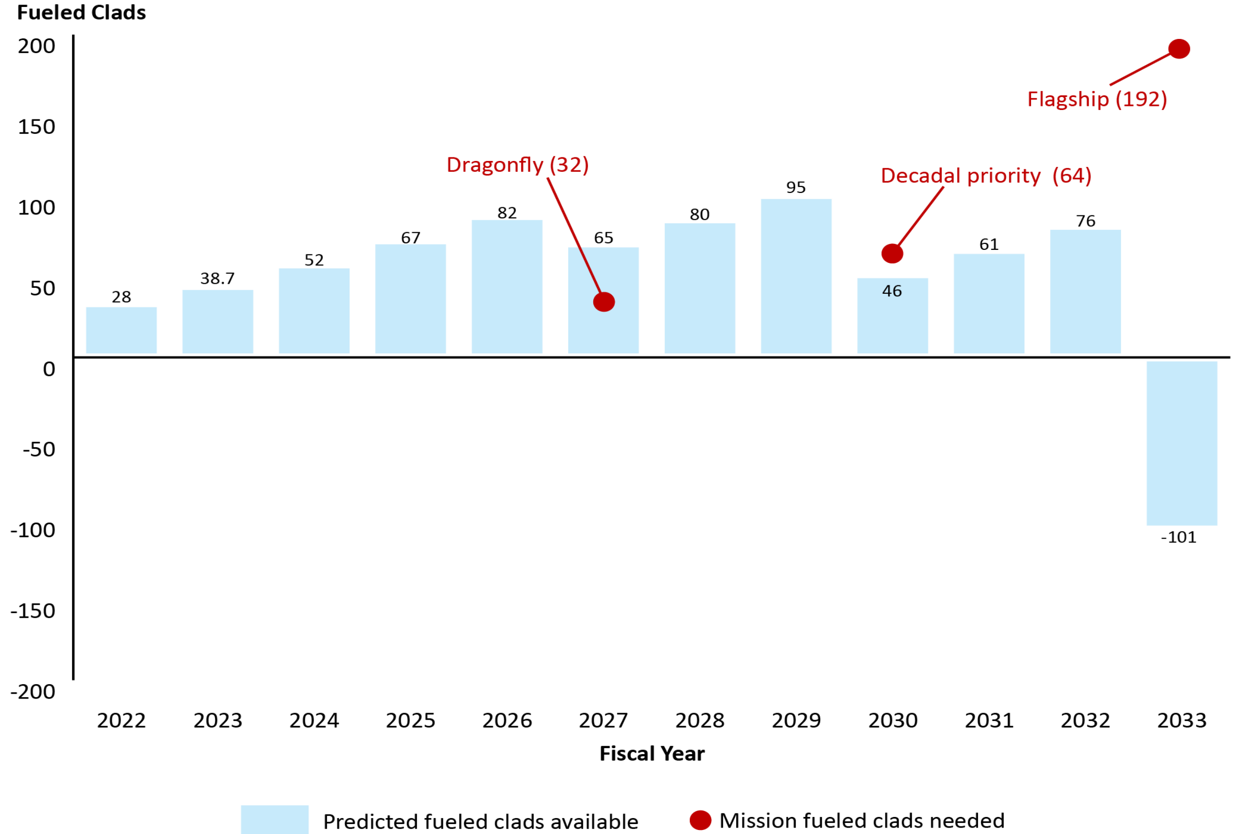
[39] This goal is an average value due to annual manufacturing variances. 1.5 kg yields 10 fueled clads (about 0.15 kg of Pu-238 is required per fueled clad).

The RPS Program relies on DOE-provided information about Pu-238 production volumes to plan RPS availability for NASA missions. However, the Program's current analysis for these projections has low fidelity because of the low quality of information DOE provides NASA. The current information is inadequate for missions to properly incorporate the cost and schedule impacts of these risks in their project estimates. Mission power system components need high fidelity analysis given that power systems are potentially single-point failures. According to DOE, any estimates beyond current production plans would only be provided to NASA in response to a formal request for specific missions and timelines. Instead, NASA accepts the risk of relying on the limited information provided by DOE due to national security concerns related to Pu-238 production and availability. That said, we could not identify how the RPS Program is communicating this risk to mission planners or reflecting it in mission plans.

Pu-238 Levels Beyond Current CRP Plans and DOE Inventory

Based on NASA and DOE production plans, our analysis shows that Pu-238 and fueled clad production will be insufficient under the various potential mission scenarios suggested in the 2022 Planetary Decadal Survey. Specifically, the Dragonfly rotorcraft is being designed with one MMRTG requiring 32 fueled clads. The next Decadal priority mission was suggested for launch in 2030 with one Next-Gen Mod-1 RTG consisting of 64 fueled clads. Finally, a Flagship mission—NASA's largest—in the 2033 timeframe with three Next-Gen Mod-1 RTGs would require 192 fueled clads. Taken together, the Decadal recommendations require a total of 288 fueled clads through 2033. However, based on our calculations using the high end of the 10 to 15 fueled clads produced per year, without a major ramp-up in production DOE can only produce about 187 fueled clads over that time period—101 fewer than needed (see Figure 7). Moreover, not included in the calculations for Figure 7 is the potential need for fueled clads to complete development of the Next-Gen and DRPS projects.

Figure 7: Predicted Available and Needed Mission Fueled Clads



Source: NASA OIG presentation of 2022 Decadal Survey information.

Note: The 2030 Decadal priority is a New Frontiers-class mission (see Appendix D).

Several NASA officials believe that the RPS Program can meet mission needs since the Decadal missions and timelines are merely recommendations and not a designated requirement.[40] They stated that missions can be designed with lower power output needs (using solar power, MMRTG, or fewer Next-Gen RTG units) or scheduled for a later launch date to accommodate production needs. Although some NASA officials are optimistic DOE can increase Pu-238 production to meet NASA requirements by converting other nuclear materials—which has not yet been proven efficient or effective—and ramp-up fueled clad production by investing in infrastructure and equipment, these processes and associated infrastructure (and the associated funding) carry significant challenges and uncertainty. In addition, DOE has identified key challenges to meeting potential increases in CRP goals—such as scaling up chemical processing—that put achieving production goals at risk.[41]

[40] Although NASA considers the Decadal Survey to be guidance for mission planning, the Agency historically has attempted to incorporate the recommendations in their planning and Congress often directs NASA to do so.

[41] According to DOE, as of March 2023 they have an optimization process underway to reduce waste from chemical processing to meet current CRP goals.

Additional risks that contradict the RPS Program's optimism regarding DOE capability to ramp-up production and flexibility, as identified by NASA and DOE, include:

- The potential that the NASA-funded Pu-238 supply is needed by other organizations for national security or other applications, in which case NASA may not have sufficient Pu-238 to support missions or will have to delay missions.
- DOE's aging infrastructure for fueled clad production requires refurbishment, modernization, expansion, and replacement.
- The RPS Program lacks the funding flexibility to increase Pu-238 production beyond CRP of 1.5 kg per year if needed. The RPS Program is operating under a constrained budget with new technology developments, Next-Gen RTG, and DRPS requesting additional funding above planned levels. RPS Program estimates indicate they would require an additional $5 million to $25 million per year for the next 5 years to ramp up fueled clad production to a sustained 25 clads per year.

Based on discussions with RPS Program management, no formal process exists to ensure that a comprehensive, current, and detailed list of risks is communicated to mission planners and user missions. Consequently, NASA missions are unable to make informed decisions about the risks of incorporating RPS in their missions or the risks associated with timely delivery of RPS, dependent on Pu-238 and fueled clads production by DOE.

Lack of Coordination Between NASA's Nuclear Power Development Activities

Significant differences and incompatibilities exist between RPS and fissions power systems (FPS) because of power output capabilities. However, as development of these technologies advance independently of each other, opportunities for leveraging technical advancements, potential codeveloped cost efficiencies, and knowledge sharing may be lost. Moreover, NASA's current oversight structure does not adequately ensure these opportunities will be identified and leveraged.

NASA has a long history of developing and using RPS but less so with FPS.[42] According to several science mission studies, FPS could provide a higher-power alternative to RPS, especially for missions requiring electric propulsion.[43]

STMD is advancing two primary FPS:

- The Fission Surface Power project is developing a 40-kilowatt, lightweight FPS designed to enable long-duration lunar surface operations with potential for later application on Mars.
- The Nuclear Propulsion Project is working on propulsion systems that can support the next steps of the Moon to Mars initiative. For FY 2022, even though NASA did not request funding Congress allocated NASA $110 million for the development, production, and demonstration of a nuclear propulsion system. For FY 2023, NASA then requested $15 million for the preliminary

[42] NASA started the Kilopower Reactor Using Stirling Technology, nicknamed KRUSTY, project in 2015, which was the first space-based fission reactor power system test to be successfully completed in over 50 years. The demonstration concluded in 2018 and suggests to some experts that FPS can be affordably developed.

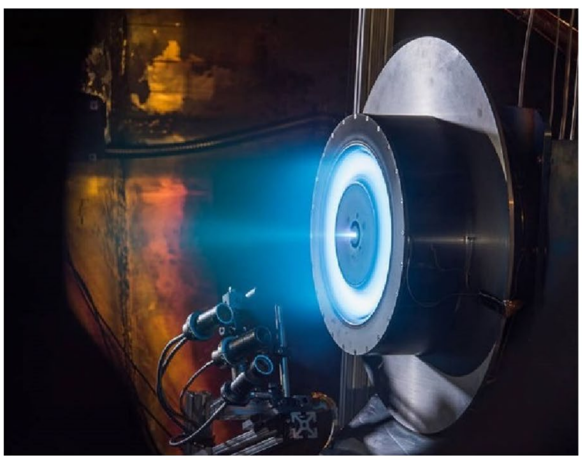
[43] Electric propulsion converts energy from solar, or in this case nuclear, and ionizes—or positively charges—inert gas propellants like Xenon and Krypton and accelerates the ions out of the thruster driving the spacecraft.

design of nuclear thermal propulsion fission reactors and an evaluation of nuclear electric propulsion. However, in the FY 2023 Appropriations Act, Congress again provided more funding than NASA requested by allocating an additional $110 million, underscoring congressional support for development of FPS capabilities.[44]

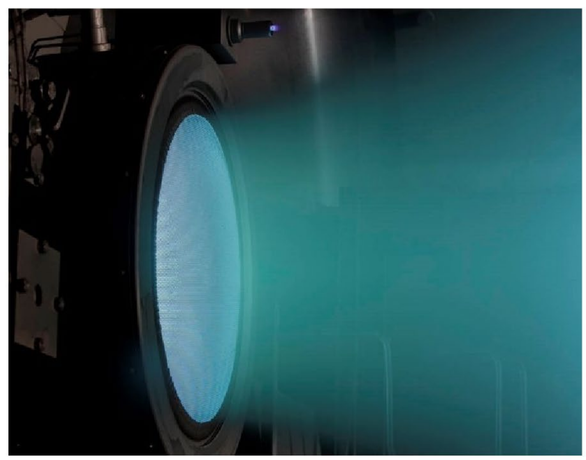
Fission Power Systems' Role in Science Mission Directorate Missions

Even though NASA's FPS development is managed by STMD, the need for SMD to be more engaged with FPS is increasing. The 2022 Planetary Decadal Survey recommended that "NASA should maintain cognizance of emerging new technologies and encourage the science and engineering communities to explore new ways that these technologies can enable greater science while reducing development and operations costs." NASA repeated the idea in its July 2022 response to Executive Order 13972 that promotes the development and use of nuclear energy.[45] NASA stated that advanced FPS will enable more demanding robotic missions throughout the solar system and beyond. Congress also noted that advanced fission propulsion is intended to be used in "robotic [SMD missions] and human exploration activities."[46] However, as of April 2022 all SMD missions planned for the next 10 years can be met with chemical, solar, or RPS capabilities with FPS capabilities generally far exceeding SMD mission power requirements, even for electric propulsion (see Figure 8).

Figure 8: Electric Propulsion



A 13-kilowatt Hall thruster, shown here being tested at Glenn Research Center, uses solar-electric power and will propel Psyche on its mission in 2023 to explore a metallic asteroid in the main asteroid belt between Mars and Jupiter.



The Double Asteroid Redirection Test mission used a 7-kilowatt Xenon ion thruster, also at Glenn Research Center, to propel it to its successful intercept with the asteroid, Dimorphos, in September 2022.

Source: NASA.

[44] Consolidated Appropriations Act, 2023, Pub. L. No. 117-328 (2022).

[45] Exec. Order No. 13972, *Promoting Small Modular Reactors for National Defense and Space Exploration* (January 5, 2021).

[46] NASA Authorization Act of 2022, Pub. L. No. 111–167 (2022).

The level of SMD interest in FPS is tempered by the lower power needs of NASA's science missions. A Nuclear Power Assessment Study by the Johns Hopkins University Applied Physics Laboratory observed that "without significant budget increases in mission cost caps, single-mission power requirements are unlikely to exceed 600 watts," and that "a power requirement not exceeding 600 watts is more efficiently fulfilled with an RPS than an FPS."[47] The Assessment Study cautioned that FPS development means high development costs and that current SMD mission plans did not require an FPS-sized power system. Conversely, they warned that the power limits and Pu-238 production rates could become a "self-fulfilling, mission-limiting prophecy" since Pu-238 is a precious resource that needs efficient utilization and preservation.

Neither the RPS Program, nor any other SMD group, currently has a fission system development requirement. The RPS Program does track "nuclear [technology] investment diversity" as a risk to the RPS Program given that stakeholders may not perceive them as distinct from each other and recognize the need to support development and funding for both. The size difference between FPS needed to generate surface power and propulsion for human exploration compared to a system SMD could use on a satellite or rover system requires significantly different technology development efforts. However, any developments in FPS technologies will help all prospective users leverage commonalities between prospective fission systems.

Maintaining Cognizance and Communicating a Path Forward

Nuclear technology systems have a long development lead time, are expensive, and require advocates to promote the technology for mission applications. No group within NASA has sufficient authority to coordinate and provide direction on the nuclear power and propulsion approach across the Agency's Mission Directorates.

The Nuclear Power and Propulsion Technical Discipline Team was established in 2015 to coordinate the diverse nuclear technology efforts across the Agency. The Team is responsible for:

- Developing a nuclear technology development plan that includes pathways for in-space propulsion systems and surface power systems.
- Bringing Exploration Systems Development Mission Directorate, Space Operations Mission Directorate, SMD, and STMD commonality of use forward to guide the Agency's nuclear investment strategy.

However, the Team reports to the NASA Engineering and Safety Center instead of the Agency Program Management Council (APMC) like other System Capability Leadership Teams.[48] We believe positioning the Team to report to the APMC would be more effective since the Safety Center's primary function is technical evaluation and consultation products while reporting to the APMC would provide access and authority to monitor nuclear technologies across the Agency and with external partners.

[47] Johns Hopkins University Applied Physics Laboratory, *Nuclear Power Assessment Study* (February 4, 2015). The objective of the study was to discuss a sustainable strategy and present findings for the provisioning of safe, reliable, and affordable nuclear power systems that enable NASA science missions and its human exploration needs over the next 20 years.

[48] The NASA Engineering and Safety Center's mission is to perform value-added independent testing, analysis, and assessments of NASA's high-risk projects to ensure safety and mission success. The APMC serves as the Agency's senior decision-making body regarding the integrated Agency mission portfolio and enabling programmatic and technical capabilities. APMC membership includes the Associate Administrator, Directorate Associate Administrators, Center Directors, and other NASA Chiefs.

In 2018, the APMC was briefed on creating a Nuclear Power and Propulsion System Capability Leadership Team to ensure access and authority across the Agency and Mission Directorates. The Acting Administrator at the time authorized a position for the engineering lead, but the position was never filled because fission technology development at the time was limited. As a result, this oversight function is not in place. We believe that with increased funding and focus on FPS, not having an empowered NASA-wide perspective on nuclear power and propulsion development activities, and the RPS Program not being more officially involved in FPS developments, could result in the Agency missing opportunities for leveraging potential technical benefits, cost efficiencies, and knowledge sharing.

CONCLUSION

The RPS Program has been tasked with three important responsibilities: advancing NASA's RPS capability by making the systems more efficient and more affordable, ensuring sufficient Pu-238 is produced to meet NASA mission needs, and producing RPS for missions and supporting missions through launch. However, we found that the Program is struggling to meet the expectations of two of those responsibilities.

Of primary concern is the RPS Program's inability to complete a new technology since its inception 13 years ago, despite an average annual investment of $40 million per year. Management decisions that affected prior failed developments are again repeating themselves and need to be resolved to ensure current projects do not meet the same fate. In addition, the Program's overly optimistic assumptions about the maturity of technologies, lack of formal assessments, and associated technology maturation risks are again threatening cost and schedule for new RPS developments. Lastly, we believe that Program management's reluctance to implement both EVM and JCL as required by NPR 7120.5F to help inform decision-making will exacerbate an already challenging development effort.

We also found ineffective coordination and communication between the RPS Program and DOE and other NASA Directorates increases risks for NASA missions and the Agency may miss opportunities for leveraging advancements, cost efficiency, and knowledge sharing. Mission proposers rely on the RPS Program having current, complete, and accurate information regarding Pu-238 availability when considering power source options for their mission designs; likewise, missions in formulation and development rely on this information to manage project risks and make effective decisions. Complete information about the level of transparency NASA has into DOE's Pu-238 production process would help missions accurately assess the likelihood of sufficient Pu-238 being available for their mission. Likewise, we believe establishing a more collaborative, strategic relationship between the NASA entities responsible for RPS and FPS will benefit both and help inform stakeholder decisions regarding funding and developing their respective capabilities.

Recommendations, Management's Response, and Our Evaluation

To ensure the RPS Program effectively and efficiently meets its requirements, we recommended the Associate Administrator for Science Mission Directorate direct the PSD Director to:

1. Create an RPS resource allocation and technology development strategic plan that includes an evaluation and mitigation of risks for each project through its completion and provide a communication plan to stakeholders and mission managers.
2. Conduct high quality, frequent, and routine self-assessment TRAs by project management beginning after the initial implementation of a technology development project as a basis for TRL assessment and risk management discussions.
3. Per Title 51 and NPR 7120.5F, recalculate the life-cycle costs for Next-Gen RTG and DRPS projects to include funding NASA provides to DOE.
4. Institute an EVM process for Next-Gen RTG and DRPS projects that conforms with NASA policy, FAR requirements, and industry best practices.
5. For Next-Gen RTG and DRPS development efforts that transition to a space flight project, execute a JCL analysis at the proper phases in accordance with NPR 7120.5F.
6. In coordination with DOE, develop a means for the RPS Program to obtain high-fidelity Pu-238 and fueled clad current and future inventory information.
7. Develop a means to quantify risk of future Pu-238 and fueled clad availability that can be communicated to NASA mission managers and incorporated into mission development proposals and plans.
8. Leverage the RPS Program's existing business processes with its element structure to monitor fission technology development for SMD feasibility and educate stakeholders on the possibilities and differences.

To enable an Agency-wide perspective for the efficient development of new nuclear technologies, we recommended the Associate Administrator for Space Technology Mission Directorate in coordination with the Associate Administrator for Science Mission Directorate:

9. Reevaluate the need and if appropriate reauthorize the organizational position of the Nuclear Power and Propulsion System Capability Leadership Team through the appropriate Mission Directorate and provide the Team responsibility for monitoring and advocating strategic nuclear power coordination across NASA.

We provided a draft of this report to NASA management who concurred or partially concurred with our recommendations and described planned actions to address them. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions.

Management's comments are reproduced in Appendix E. Technical comments provided by NASA and DOE and revisions to address them have been incorporated as appropriate.

Major contributors to this report include Raymond Tolomeo, Science and Aeronautics Research Audits Director; Gerardo Saucedo, Assistant Director; L. Scott Collins, John Schultz, and Karlo Torres. Matt Ward, Justin Lafreniere, Lauren Suls, and Amanda Perry provided editorial support, Sarah McGrath provided graphics support, and Sashka Manion provided legal support.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

PAUL MARTIN

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Paul K. Martin
Inspector General

Appendix A: Scope and Methodology

We performed this audit from November 2021 through February 2023 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.

The scope of this audit was NASA's management of the RPS Program. Our overall objective was to assess whether the Program had adequate performance management practices and measurements in place regarding Pu-238 production, technology development maturation, and space flight project mission planning.

To gain an overall understanding of the Program, we interviewed RPS Program Office officials; RPS managers; leadership at NASA Headquarters, STMD, the Langley and Glenn Research Centers, Jet Propulsion Laboratory; and other subject matter experts. Additional information regarding nuclear fuel inventory, production, and development was obtained from DOE. Our primary criteria for assessing practices and procedures were federal and NASA directives included in the "Review of Internal Controls" section below.

Assessment of Data Reliability

No computer-processed data was relied upon during the performance of this audit.

Review of Internal Controls

We assessed internal controls and compliance with laws and regulations necessary to satisfy the audit's objectives based on NPR 7120.5F, NPR 7120.8A, GAO's Technology Readiness Assessment Guide, and U.S.C. Title 51, as well as various memoranda between NASA and DOE regarding plutonium production and supply. We determined that NASA's technology capability strategy needs improvement for the Program to advance RPS capabilities and better communication can reduce risks to the RPS Program and NASA projects. Specifically, the RPS Program has significant historical weaknesses in developing and delivering new technologies and the Program is poised to repeat some of the same mistakes in its current development efforts. We believe that our recommendations, if implemented, will improve the RPS Program deficiencies identified in this report.

Prior Coverage

During the last 5 years, the NASA Office of Inspector General and GAO have issued five reports relevant to the subject of this report, which can be accessed at https://oig.nasa.gov/audits/auditReports.html and http://www.gao.gov, respectively.

NASA Office of Inspector General

NASA's Cost Estimating and Reporting Practices for Multi-Mission Programs (IG-22-011, April 7, 2022)

NASA's Volatiles Investigating Polar Exploration Rover (VIPER) Mission (IG-22-010, April 6, 2022)

NASA's Planetary Science Portfolio (IG-20-023, September 16, 2020)

Management of NASA's Europa Mission (IG-19-019, May 29, 2019)

Government Accountability Office

Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges (GAO-17-673, September 8, 2017)

Appendix B: Components of a General Purpose Heat Source and RTG Example

RPS are compact and rugged and provide reliable power in harsh environments where solar arrays are not practical. RPS are particularly useful for planetary missions where solar energy experiences a substantial falloff and is not effective. For example, Saturn is about 10 times farther from the Sun and receives only 1 percent of the solar energy that Earth does. The size of solar arrays needed to support planetary missions at that distance from the Sun ranges from impractical to impossible.

Pu-238 Pellet in its Protective Iridium Cladding

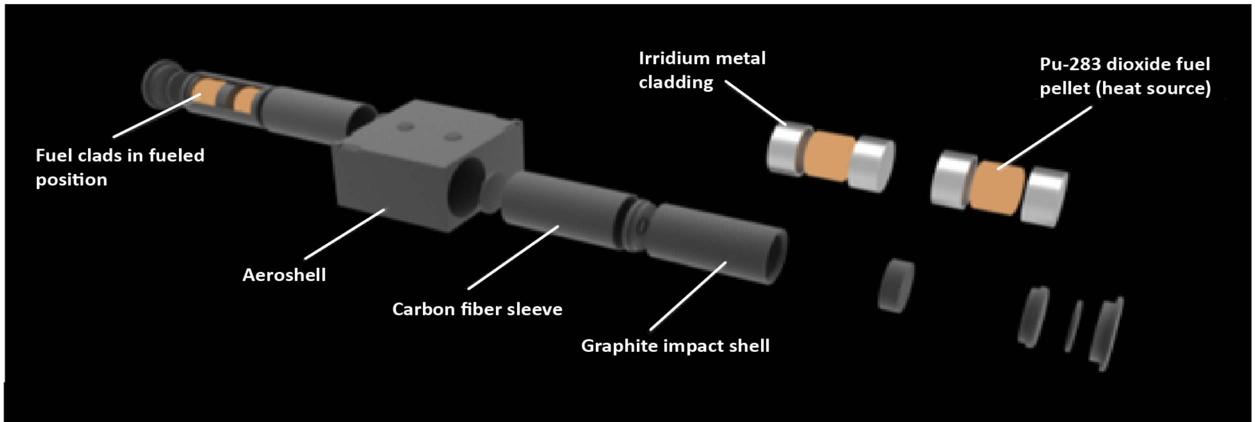
Source: U.S. Department of Energy.

The General-Purpose Heat Source (GPHS) module is the essential building block for the radioisotope generators used by NASA. These modules contain and protect the Pu-238 fuel. Pu-238, a radioactive isotope of plutonium, gives off heat that is converted into electricity.

GPHS fuel is fabricated ceramic pellets of Pu-238 dioxide encapsulated in a protective casing of iridium, forming a fueled clad. Fueled clads are encased within nested layers of carbon-based material and placed in an aeroshell housing to form the complete GPHS module.

Each GPHS is a 4x4x2-inch block weighing approximately 3.5 pounds (1.5 kg). Each block is designed to produce thermal power at 250 watts at the beginning of a mission and can be used individually or stacked together. Figure 9 shows the basic structure of the GPHS module.

Figure 9: General-Purpose Heat Source Module

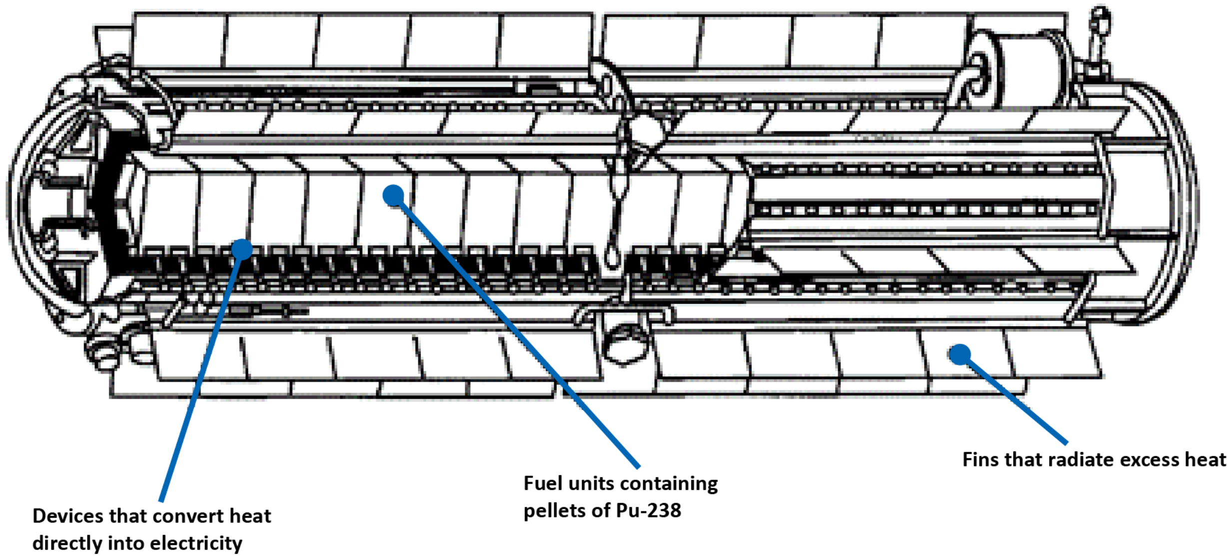


The GPHS module provides steady heat for a radioisotope power system.

Source: NASA OIG presentation of Agency information.

Figure 10 shows the configuration of an RTG. The RTG is designed to produce power by converting thermal energy (heat) into electricity using the GPHS modules and a downstream convertor.

Figure 10: Radioisotope Thermoelectric Generator



Source: NASA OIG presentation of Agency information.

APPENDIX C: RECENT REVIEWS AND STAKEHOLDER INPUT

National Research Council, *Vision and Voyages for Planetary Science in the Decade 2013-2022*

In 2011, this report registered alarm at the limited availability of Pu-238 for planetary exploration. It also noted that without a restart of domestic production of Pu-238, it will be impossible for the United States, or any other country, to conduct certain important types of planetary missions after this decade. The report recommended that the ASRG development and maturation process receive the same priority and attention as a flight project because it was important to a broad range of exploration missions.

GAO, *Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges* (GAO-17-673)

GAO made three recommendations in 2017, including that DOE develop a plan with milestones and interim steps for its Pu-238 and RPS production approach and assess the long-term effects of known production challenges and communicate these effects to NASA. Consequently, DOE reported the implementation of the CRP plan to produce a certain amount of Pu-238 each year for 10 years. CRP is updated yearly in coordination with NASA.

National Academies of Sciences, Engineering, and Medicine, *Visions into Voyages for Planetary Science in the Decade 2013–2022: A Midterm Review*

This review noted in 2018 that NASA had made dramatic progress in reestablishing a viable production source for Pu-238. NASA and DOE established a long-term relationship where NASA will fund the establishment and maintenance of a constant production line for Pu-238. The review also noted that ASRG development had ceased in favor of the MMRTG and "longer term developments of advanced energy conversion techniques" without an adverse finding.

NASA, *Key Decision Point IV Program Implementation Review*

In 2021 the Standing Review Board found the RPS Program was meeting success criteria. However, they identified two issues, one concern, and three observations focused on the continued maturation of the RPS Program's business processes and relationships.

National Academies of Sciences, Engineering, and Medicine, *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*

In 2022, this report made several updates to their earlier positions. NASA's and DOE's continued CRP of Pu-238 and fueled clads—independent of mission selections—was still praised. However, they estimated that the currently planned production rate will be a significant limiting factor in NASA's ability to develop new deep space missions because the use of Next-Gen Mod-1 requires significantly more Pu-238 and fueled clads than MMRTG or ASRG. Moreover, they noted that limitation ignored any additional demands from the Discovery, Lunar, or Mars programs; human exploration needs; or other NASA programmatic needs. After the current Pu-238 inventory is exhausted, production of new supply will be a deciding factor in mission selection.

They recommended that NASA evaluate Pu-238 production capacity against the mission portfolio recommended in their report and other NASA needs. They also recommended that NASA should continue to invest in maturing higher efficiency RPS technology to better manage its supply of Pu-238. They noted that a dynamic RPS could improve the power and conversion efficiency and enable missions beyond this decade. They also noted that an FPS may represent a disruptive and game-changing trend in technology.

APPENDIX D: 2022 PLANETARY DECADAL SURVEY PRIORITIES

From an initial group of 33 concepts, the Decadal Survey's panels and steering group identified 17 priority missions—Endurance has two mission versions for a total of 18—shown in Tables 3, 4, and 5.

Table 3: Decadal Survey Flagship Priority Missions

Mission Name	Nominal Launch Date	Primary Power	Estimated Cost (millions)	Description
Flagship missions are the highest costing and most capable large strategic science missions and are designed to answer the most compelling and challenging questions about our solar system. Because of their complexity, NASA usually assigns these missions directly to a NASA Center or other implementing organization.				
Enceladus Orbilander *(Second highest priority)*	September 2037 through December 2038	Next-Gen	$4,234	A spacecraft that will sample an extant subsurface ocean through study of freshly ejected plume material originating from a well-characterized location.
Europa Lander	November 2026	Battery	$5,757	A lander to characterize the biological potential of Europa's ocean through direct study of any chemical, geological, and possibly biological, signatures as expressed at the surface of the moon.
Mercury Lander	March 2035	Next-Gen	$2,785	A lander to gain insight into distribution of elements in the earliest stages of solar system development and learn how planets and exoplanets form and evolve in close proximity to their host star.
Neptune Odyssey, Neptune-Triton Orbiter and Probe	2033	Next-Gen	$5,177	An orbiter and atmospheric probe to Neptune to study an ice giant planet, its rings, small satellites, space environment, and its large irregular moon, Triton.
Uranus Orbiter and Probe *(Highest priority)*	2031 through 2038	Next-Gen	$4,164	Deliver an in situ atmospheric probe and conduct a multi-year orbital tour that would transform our knowledge of ice giants in general and the Uranian system.
Venus Flagship	2031	Solar	$7,821	An orbiter, lander, variable-altitude aerobot, and two small satellites on a single launch that will use multiple instruments to probe and measure the exosphere, atmosphere, and surface of Venus.

Source: 2022 Planetary Decadal Survey.

Table 4: Decadal Survey New Frontiers Priority Missions

Mission Name	Nominal Launch Date	Primary Power	Estimated Cost (millions)	Description
New Frontiers missions are competitively selected, midsize planetary missions that take on priority goals established by the planetary science community. They are launched about every 60 months and have an $850 million cost-cap per mission, excluding launch vehicle, mission operations, data analysis, or partner contributions.				
Ceres Sample Return	December 2030	Solar	$2,377	An orbiter and lander to quantify Ceres' current habitability potential and its origin, which is important for understanding habitability of mid-sized planetary bodies.
Enceladus Multiple Flyby	October 2038	Next-Gen	$1,966	A flyby vehicle to characterize Enceladus' habitability and look for evidence of life via multiple flybys and analysis of plume material.
Titan Orbiter (Sea Probe Descoped)	2031 to 2039	Solar	$2,174	An orbiter to characterize Titan's dense atmosphere that harbors prebiotic molecules, its Earth-like methane hydrological cycle and seas, and its subsurface liquid water ocean.
Centaur Orbiter and Lander	January 2040	Next-Gen	$2,576	An orbiter and lander to investigate a Centaur from orbit and in situ, exploring one of a population of dynamically evolved but primitive small icy bodies from the Kuiper Belt that currently reside between Jupiter and Neptune.
Calypso: Uranus Moon and KBO Flyby	2035	Next-Gen	$1,992	A flyby vehicle to explore the Uranus system and impact generated moons that may be ocean worlds. Study large Kuiper Belt objects.
Triton Ocean Worlds Surveyor	2031 to 2032	Next-Gen	$2,233	An orbiter and lander to orbit Neptune and perform multiple flybys of Triton, a candidate ocean world with a geologically young surface and active geysers.

Source: 2022 Planetary Decadal Survey.

Table 5: Decadal Survey Mars Exploration Program and Lunar Discovery and Exploration Program Priorities

Mission Name	Nominal Launch Date	Primary Power	Estimated Cost (millions)	Description
The goal of the Mars Exploration Program is to explore Mars and to provide a continuous flow of scientific information and discovery through a carefully selected series of robotic orbiters, landers, and mobile laboratories interconnected by a high-bandwidth Mars/Earth communications network.				
Mars In Situ Geochronology	July 2030	Solar	$2,326	A lander to improve models for planetary evolution, calibrate Mars chronology, and history of habitability in the solar system.
Mars Life Explorer	May 2035	Solar	$2,123	A lander that will seek extant life and assess modern habitability through examination of low latitude ice.
The Lunar Discovery and Exploration Program develops lunar surface science instruments that address Decadal Survey and other community document science priorities using NASA-internal payloads, community-developed payloads, and commercial companies to deliver payloads to the Moon. The Program also defines, integrates, and leads Artemis science efforts across SMD, other NASA Mission Directorates, and with other U.S. and international agencies.				
Intrepid: Long-Range Lunar Rover	April 2030	Next-Gen	$1,792	A rover to study the lunar interior, diversity of magmatism, and crater formation.
Endurance-A, South Pole Aitken Basin Sample Collecting Rover	April 2030	Next-Gen	$1,933	A rover to study solar system chronology and planetary evolution.
Endurance-R, South Pole Aitken Basin Sample Collecting Rover	April 2030	Next-Gen	$2,950	A rover to study solar system chronology and planetary evolution.
INSPIRE: Lunar Polar Volatiles Rover	April 2030	Next-Gen	$1,870	A rover to study origins, evolution, and age of volatiles in the inner solar system.

Source: 2022 Planetary Decadal Survey.

Appendix E: Management's Comments

National Aeronautics and
Space Administration

Mary W. Jackson NASA Headquarters
Washington, DC 20546-0001

March 13, 2023

Reply to Attn of: Science Mission Directorate and Space Technology Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Science Mission Directorate
Associate Administrator for Space Technology Mission Directorate

SUBJECT: Agency Response to OIG Draft Report, "NASA's Management of Its Radioisotope Power Systems Program" (A-22-02-00-SARD)

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Management of Its Radioisotope Power Systems Program" (A-22-02-00-SARD), dated February 9, 2023.

The NASA Radioisotope Power Systems (RPS) Program, in partnership with the Department of Energy (DOE) has enabled notable space exploration. This longstanding collaboration has made possible multiple missions to Mars, Cassini's mission to Saturn, and the New Horizons mission to Pluto and beyond. RPS has allowed NASA to develop and execute more distant and increasingly longer missions. Indeed, the Curiosity Rover has been exploring Mars for over ten years, and the Perseverance Rover is collecting samples for the future Mars Sample Return Campaign over the next decade. The New Horizons mission will continue to send back valuable data as it heads out of our Solar System in the next decades, joining the Voyager missions in interstellar space.

For over 50 years, NASA and DOE have been strong collaborators, and NASA looks forward to furthering this longstanding partnership as it prepares for new missions, such as Dragonfly to Saturn's moon Titan and the Uranus Orbiter and Probe. Together we will mature and ready systems for exploring well into the future.

In the draft report, the OIG makes nine recommendations addressed to NASA to help ensure the RPS Program has adequate performance management practices and measurements in place to achieve its stated goals.

Specifically, the OIG recommends the following:

Recommendation 1: Create an RPS resource allocation and technology development strategic plan that includes an evaluation and mitigation of risks for each project through its completion and provide a communication plan to stakeholders and mission managers.

Management's Response: NASA concurs. The RPS Program will create an RPS resource allocation and systems development strategy informed by the annual program planning, budget, and execution process that includes the evaluation and mitigation of risks for each project through its completion and will utilize the RPS Program's stakeholder engagement element to effectively communicate as appropriate with stakeholders.

Estimated Completion Date: December 1, 2024.

Recommendation 2: Conduct high quality, frequent, and routine self-assessment technology readiness assessments (TRAs) project management beginning after the initial implementation of a technology development project as a basis for technology readiness assessment and risk management discussions.

Management's Response: NASA concurs. The frequency of technology readiness assessments (TRAs) for projects within the RPS Program will be updated in alignment with key project milestone reviews per NASA Procedural Requirement (NPR) 7120.5F "NASA Space Flight Program and Project Management Requirements", such as Preliminary Design Review (PDR) and Critical Design Review.

The RPS Program will utilize the content from its existing technology-maturation gate review process to develop a set of standards within a specific plan for technology assessments of RPS and formalize it in program documentation. The Program will review the plan with the Office of Chief Engineer, Planetary Science Division in addition to Science Mission Directorate's (SMD) Chief Technologist, and other technology assessment expertise before approval in the Program Control Board.

NASA will share the TRA for the Next Generation Radioisotope thermoelectric generator (Next Gen-RTG) project and the plan for augmenting the current process for projects governed under NPR 7120.8 "NASA Research and Technology Program and Project Management Requirements".

Estimated Completion Date: December 31, 2024, at completion of PDR.

Recommendation 3: Per Title 51 and NPR 7120.5F, recalculate the life-cycle costs for Next-Gen RTG and DRPS projects to include funding NASA provides to DOE.

Management's Response: NASA concurs. As stated in the RPS Program Plan, Sec. 1.5.1.7, Next-Gen RTG and Dynamic Radioisotope Power Systems (DRPS) are subject to NPR 7120.8 during the technology maturation phase and then subject to NPR 7120.5F once a commitment to a qualification system development has been made. The Next-Gen RTG Project recently became subject to NPR 7120.5F, while DRPS currently remains subject to NPR 7120.8. These projects will be managed in alignment with their respective NPR as required, including requirements for Life Cycle Cost (LCC) calculations.

Funds sent to DOE that are directly supporting DRPS and Next-Gen RTG will be included in life-cycle costs per 7120.8 and 7120.5F requirements for those projects. Additionally, NASA will report these funds as part of external reporting requirements (e.g., Major Program Annual Report).

Estimated Completion Date: LCC for the NextGen RTG project will be reported March 31, 2026, or when KPD-C is completed. NASA has not yet made a commitment to a DRPS qualification system development; therefore, it is unclear when an LCC will be developed for that project.

Recommendation 4: Institute an EVM process for Next-Gen RTG and DRPS projects that conforms with NASA policy, FAR requirements, and industry best practices.

Management's Response: NASA concurs. NASA agrees that it needs insight into cost, schedule, and management of the development of Next-Gen RTG and DRPS. Commercial contracts, managed by DOE and funded by NASA, will be governed under the DOE Federal Acquisition Requirements (FAR) supplement, which requires contractors to perform EVM (earned value management). Any in-house work conducted by DOE with NASA funds will be subject to DOE internal performance requirements. Commercial contracts actively managed by NASA will be governed under NASA FAR supplement. Additionally, any NASA in-house work governed by NPR 7120.5F will comply with EVM requirements as appropriate.

Estimated Completion Date: Once a baseline is set for NextGen RTG at Key Decision Point-C (KDP-C), likely March 31, 2026.

Recommendation 5: For Next-Gen RTG and DRPS development efforts that transition to a space flight project, execute a JCL analysis at the proper phases in accordance with NPR 7120.5F.

Management Response: NASA concurs. Because the Next-Gen RTG project has now transitioned to governance under NPR 7120.5F, a joint cost and schedule confidence Level (JCL) will be performed as required.

Estimated Completion Date: A JCL for NextGen RTG will be completed for KDP-C, likely March 31, 2026.

Recommendation 6: In coordination with DOE, develop a means that someone within the RPS Program can obtain high-fidelity Pu-238 and fueled clad current and future inventory information.

Management Response: NASA concurs. NASA will continue to work with DOE to ensure it has the necessary knowledge about fuel clad production rates and inventory to understand whether current and future mission needs are being met. NASA will continue to hold Director's Management Meetings (roughly quarterly) to develop and maintain ongoing strategies to complete objectives and mitigate risk. NASA will also continue to coordinate with DOE to ensure that CRP of RPS fueled clads and associated components are aligned with mission demand. As evidence, NASA will share one-year's worth of agendas from those meetings with OIG. The next meeting will be in May 2023.

Estimated Completion Date: May 30, 2024.

Recommendation 7: Develop a means to quantify risk of future Pu-238 and fueled clad availability that can be communicated to NASA mission managers and incorporated into mission development proposals and plans.

Management Response: NASA partially concurs. NASA has developed several methods and formats to communicate Pu-238 and fuel clad availability to existing and planned NASA missions. NASA has worked with DOE to develop an acceptable method and format, and for a time this was successful. NASA will review the reasons why the prior method and format are no longer acceptable to DOE and continue to work with DOE to ensure effective communication of material availability and risk to mission managers and the user community.

Estimated Completion Date: RPS availability to be shared via formal NASA communications within announcements of opportunity regarding RPS-enabled directed and competed missions. The next announcement will be for New Frontiers 5, in early Fiscal Year 2024.

Recommendation 8: Leverage the RPS Program's existing business processes with its element structure to monitor fission technology development for SMD feasibility and educate stakeholders on the possibilities and differences.

Management Response: NASA concurs. The RPS Program provides ongoing participation within the NASA Nuclear Power and Propulsion Technical Discipline Team meetings and forums, support at various conferences and nuclear forums, facilitation of stakeholder engagement media events, and training to the NASA nuclear stakeholder community. Further, the RPS program seeks opportunities to create synergies with other mission directorates such as the Space Technology Mission Directorate (STMD), which is advancing fission technology. As an example, advancing dynamic technology can increase confidence for its usage, which is impactful throughout the nuclear community. NASA will work to establish a Nuclear Systems Working Group between SMD, STMD, and the Exploration Systems Mission Directorate which can meet regularly to status Agency nuclear efforts, develop opportunities for collaboration, and seek synergies in technology, system development, and mission usage.

Estimated Completion Date: September 30, 2024.

To enable an Agency-wide perspective for the efficient development of new nuclear technologies, the OIG recommends the Associate Administrator for STMD in coordination with the Associate Administrator for Science Mission Directorate:

Recommendation 9: Reevaluate the need and if appropriate reauthorize the organizational position of the Nuclear Power and Propulsion System Capability Leadership Team through the appropriate Mission Directorate and provide the Team responsibility for monitoring and advocating strategic nuclear power coordination across NASA.

Management's Response: NASA concurs. STMD agrees with the intent of this recommendation and will look at the need for establishing an organization position of the Nuclear Power and Propulsion System Capability Leadership Team in coordination with SMD.

Estimated Completion Date: September 30, 2023.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Peter Meister at (202) 358-1557.

Nicola J. Fox, Ph.D.
Associate Administrator,
Science Mission Directorate

James L. Reuter
Associate Administrator,
Space Technology Mission Directorate

APPENDIX F: REPORT DISTRIBUTION

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