POWERING EXPLORATION: AN UPDATE ON RADIOISOTOPE PRODUCTION AND LESSONS LEARNED FROM CASSINI

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

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October 4, 2017

POWERING EXPLORATION: AN UPDATE ON RADIOISOTOPE PRODUCTION AND LESSONS LEARNED FROM CASSINI

Wednesday, October 4, 2017

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to call, at 10:08 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Brian Babin [Chairman of the Subcommittee] presiding.

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CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

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House of Representatives
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini

Wednesday, October 4, 2017
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Mr. David Schurr, Deputy Director, Planetary Science Division, National Aeronautics and Space Administration

Ms. Tracey Bishop, Deputy Assistant Secretary for Nuclear Infrastructure Programs, Office of Nuclear Energy, Department of Energy

Dr. Ralph L. McNutt, Jr., Chief Scientist for Space Science in the Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory

Ms. Shelby Oakley, Director, Acquisition and Sourcing Management, Government Accountability Office

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE

Charter

TO:	Members, Committee on Science, Space, and Technology
FROM:	Majority Staff, Committee on Science, Space, and Technology
DATE:	October 4th, 2017
SUBJECT:	Space Subcommittee Hearing: "Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini"

On Wednesday, October 4th, 2017 at 10:00 a.m. in Room 2318 of the Rayburn House Office Building, the Committee on Science, Space, and Technology, Subcommittee on Space, will hold a hearing titled, "Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini."

Hearing Purpose

To evaluate NASA and DOE's efforts to reconstitute the production of Plutonium-238 (Pu-238), which is necessary for radioisotope thermonuclear generators (RTG) that provide electrical power for spacecraft that cannot use solar energy. Production ceased in the 1980s, and existing inventories were incorporated into planned missions. With the recent end of NASA's Cassini mission to Saturn, which used Pu-238 to enable its scientific discoveries, the hearing will evaluate current efforts to reconstitute Pu-238 production, and the science it makes possible. The Science, Space, and Technology Committee requested the Government Accountability Office (GAO) to review NASA and DOE's efforts to reconstitute domestic production of Pu-238. GAO will release the results of their review at the hearing.

Witnesses

- **Mr. David Schurr**, Deputy Director, Planetary Science Division, National Aeronautics and Space Administration
- **Ms. Tracey Bishop**, Deputy Assistant Secretary for Nuclear Infrastructure Programs, Office of Nuclear Energy, Department of Energy
- **Dr. Ralph L. McNutt, Jr.**, Chief Scientist for Space Science in the Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory
- **Ms. Shelby Oakley**, Director, Acquisition and Sourcing Management, Government Accountability Office

Staff Contact

For questions related to the hearing, please contact Mr. Tom Hammond, Staff Director, Space Subcommittee, or Ms. Sara Ratliff, Policy Assistant, Space Subcommittee, at 202-225-6371.

Chairman BABIN. The Subcommittee on Space will now come to order. Without objection, the Chair is authorized to declare a recess of the Subcommittee at any time. Welcome to today's hearing titled "Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini." I now recognize myself for an opening statement.

Exploration of our solar system continues to amaze and inspire us all. From rovers on the surface of our neighbor, Mars, to spacecraft visiting the distant reaches of Pluto, and the recent completion of the extraordinary Cassini mission to Saturn, their discoveries are truly awe-inspiring. The exploration and science achieved by these missions is enabled by the production of Plutonium-238, or Pu-238, and the radioisotope power systems, or RPS, that turn fuel into electricity for spacecraft. RPS are necessary for missions that go beyond Jupiter where the sun's energy is simply not strong enough to power solar arrays and for rovers that have unique mission requirements.

Unfortunately, America's stockpile of Pu-238 is low, despite efforts to reestablish production. This hearing allows us to review NASA and DOE's efforts to reconstitute Pu-238 production and better understand how critical it is to enabling scientific discovery and exploration. The Cassini mission was enabled by Pu-238 and its RPS system.

Over the last 50 years, NASA has relied on RPS to power many of its missions into deep space. This was made possible by a ready supply of Pu-238 that was derived from weapons production. After the U.S. ended the production of nuclear weapons in the 1980s, Pu-238 was less plentiful. And so America has had to purchase Pu-238 from Russia. We no longer purchase Pu-238 from Russia and now find ourselves in a quandary. The existing stockpile of Pu-238 is all but gone. The infrastructure necessary to produce Pu-238 is being reconstituted, but, as GAO will highlight, challenges remain.

NASA funds the entire enterprise, but DOE owns and operates the facilities. Not all of the reactors involved in the production are currently active. Future missions to the outer planets will undoubtedly require Pu-238. Current assessments of the volume of Pu-238 that DOE can produce each year and NASA's assessment of its needs for future missions remain uncertain.

For instance, when NASA assumes how much Pu-238 it needs, does it assume the fuel will be used in legacy multi-mission radioisotope thermoelectric generators, or MMRTGs, or in future advanced sterling radioisotope generators, ASRGs? ASRGs are much more efficient and use less Pu-238, but the program was cancelled a few years ago. Are NASA's estimated needs based on systems that are no longer being developed?

NASA is also exploring plans to blend fuel to stretch its supply. Does this impact the quality of the supply and the missions that it can support? Since NASA is wholly dependent on DOE for isotope production, how will DOE's future management of its laboratories and reactors impact NASA missions? Is NASA planning missions based on low production rates or are DOE's production rates determined by a lack of requirements from NASA?

The recent completion of the Cassini mission offers us an opportunity to reflect on the amazing science and discoveries that were enabled by Pu-238. Stunning images and findings still stream in from the Curiosity rover on Mars, which is also enabled by Pu-238. NASA currently has roughly 35 kilograms of fuel left. NASA and DOE plan to produce 1.5 kilograms a year by 2025. A single MMRTG uses 4.8 kilograms of fuel. To put that into perspective, Cassini used 33 kilograms in one mission.

I look forward to your insightful testimony about the future of exploration and how we can ensure that we continue to push the envelope of discovery. Thank you to our witnesses and their staff. You were able to accommodate a compressed schedule to appear today. Your service to the Committee and the nation is greatly appreciated.

[The prepared statement of Chairman Babin follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
October 4, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Space Subcommittee Chairman Brian Babin (R-Texas)

Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini

Chairman Babin: Exploration of our solar system continues to amaze and inspire us all. From rovers on the surface of our neighbor, Mars, to spacecraft visiting the distant reaches of Pluto, and the recent completion of the extraordinary Cassini mission to Saturn, their discoveries are truly awe-inspiring. The exploration and science achieved by these missions is enabled by the production of Plutonium-238 (Pu-238), and the radioisotope power systems (RPS) that turn fuel into electricity for spacecraft. RPS are necessary for missions that go beyond Jupiter where the sun's energy is not strong enough to power solar arrays, and for rovers that have unique mission requirements. Unfortunately, America's stockpile of Pu-238 is low, despite efforts to reestablish production. This hearing allows us to review NASA and DOE's efforts to reconstitute Pu-238 production, and better understand how it enables scientific discovery and exploration by hearing about the Cassini mission, which was enabled by Pu-238 and its RPS system.

Over the last 50 years, NASA has relied on RPS to power many of its missions into deep space. This was made possible by a ready supply of Pu-238 that was derived from weapons production. After the U.S. ended the production of nuclear weapons in the 1980s, Pu-238 was less plentiful, so America had to purchase Pu-238 from Russia. We no longer purchase Pu-238 from Russia, and now find ourselves in a quandary. The existing stockpile of Pu-238 is all but gone. The infrastructure necessary to produce Pu-238 is being reconstituted, but, as GAO will highlight, challenges remain.

NASA funds the entire enterprise, but DOE owns and operates the facilities. Not all of the reactors involved in the production are currently active. Future missions to the outer planets will undoubtedly require Pu-238. Current assessments of the volume of Pu-238 that DOE can produce per year, and NASA's assessment of its needs for future missions, remain uncertain.

For instance, when NASA assumes how much Pu-238 it needs, does it assume the fuel will be used in legacy Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) or in future Advanced Sterling Radioisotope Generators (ASRGS). ASRGs are much more efficient, and use less Pu-238, but the program was cancelled a few years ago.

Are NASA's estimated needs based on systems that are no longer being developed? NASA is also exploring plans to blend fuel to stretch its supply. Does this impact the quality of the supply and the missions it can support? Since NASA is wholly dependent on DOE for isotope production, how will DOE's future management of its laboratories and reactors impact NASA missions? Is NASA planning missions based on low production rates, or are DOE's production rates determined by a lack of requirements from NASA?

The recent completion of the Cassini mission offers us an opportunity to reflect on the amazing science and discoveries that were enabled by Pu-238. Stunning images and findings still stream in from the Curiosity rover on Mars, which is also enabled by Pu-238. NASA currently has roughly 35 kilograms of fuel left. NASA and DOE plan to produce 1.5 kilograms a year by 2025. A single MMRTG uses 4.8 kilograms of fuel. To put that into perspective, Cassini used 33 kilograms in one mission.

I look forward to your insightful testimony about the future of exploration and how we can ensure that we continue to push the envelope of discovery. Thank you to our witnesses and their staff. You were all able to accommodate a compressed schedule to appear today. Your service to the Committee and the nation is greatly appreciated.

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Chairman BABIN. And now I'd like to recognize the Ranking Member, the gentleman from California, Mr. Bera, for an opening statement.

Mr. BERA. Thank you, Mr. Chairman, and thank you for calling this hearing. Good morning and welcome to the distinguished panel.

You know, part of the reason why I like these hearings is, you know, I'm a simple doctor, a physician, and I get to interact and listen to the scientists. I would not have thought I would be talking about Plutonium-238.

But in truth, this is an exciting time for space. It's an exciting time for space exploration. Just thinking about how we're going further and further into space, you know, the dramatic discoveries of Cassini, looking at the Moon and Enceladus and you know, perhaps harboring the ingredients of life. And the more we want to go further and further—we're starting to recapture the imagination of the public with these discoveries.

But that then comes in, as we go further, what are our energy sources going to be in terms of communicating with us? And I think that's why this is such an important hearing. When Cassini was operated, the radio power systems were operated by Plutonium-238 and we stopped producing that a while ago. I think the Chairman's highlighted the challenges there and the big questions that we have that we look forward to hearing from all of you about.

A couple questions that I have is, is the DOE on track to produce NASA's supply requirements of Pu-238 in the anticipated timeframe? A second question that I would hope that you are able to address is what impact would Pu-238 shortfalls have on NASA's Planetary Science plans and future portfolio? A third question would be are there mitigating actions available to address the constraints of the Pu-238 supply? And a fourth question that I would hope that you're able to address is have NASA and the science community already been making science-limiting decisions based on the Pu-238 supply constraints?

So Mr. Chairman, with that, I look forward to hearing what the witnesses have to say and I yield back.

[The prepared statement of Mr. Bera follows:]

OPENING STATEMENT
Ranking Member Ami Bera (D-CA)
of the Subcommittee on Space

House Committee on Science, Space, and Technology
Subcommittee on Space
"Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini"
October 4, 2017

Good morning. And welcome to our distinguished panel. Thank you, Mr. Chairman, for calling this hearing to examine the status of radioisotope power production for NASA's mission.

On September 15, 2017, NASA and its partners, the scientific community, and many of the interested public said goodbye to the Cassini spacecraft after a mission that studied the Saturn system for over a decade. That mission yielded significant scientific returns, including indications that Saturn's moon, Enceladus, may harbor the necessary ingredients to support life. Cassini, and many of the missions that have explored the outer regions of the solar system, including the current New Horizons mission that flew by Pluto, would not have been possible without Radioisotope Power Systems (RPSs).

NASA needs access to Plutonium-238 (Pu-238) because some missions have power requirements that cannot be met by using solar arrays, given the spacecraft's distance from the Sun, its operating requirements, or in the case of rovers, the conditions on the surface of a planet. Therefore, Mr. Chairman, there is no doubt that access to a constant supply of Pu238 is essential if we are to maintain the nation's leadership in solar system exploration and scientific discovery.

In the past decade, the nation's ability to have a dependable access to Pu238 has been a source of concern. The Department of Energy (DOE) stopped producing Pu238 in the late 1980s, and Pu238 was then procured from Russia. But when it was clear that Russian supply would be no longer available, NASA requested in 2011 that DOE restart Pu238 production.

I look forward to hearing from our witnesses about the status of DOE's Pu238 production process and any issues that must be addressed to ensure the Pu238 supply. In particular,

- Is DOE on track to produce NASA's supply requirements for Pu238 in the anticipated timeframe?
- What impact would Pu238 shortfalls have on NASA's planetary science plans and future portfolio?
- Are there mitigating actions available to address the constraints of the Pu238 supply?
- Have NASA and the science community already been making science-limiting decisions based on the Pu238 supply constraints?

Thank you, Mr. Chairman, and I yield back.

Chairman BABIN. Absolutely. Thank you. Good statement. And I'm a simple dentist. You're a simple physician, right. Okay. And let's see, I'd like to recognize the Ranking Member of the Full Committee for a statement, the gentlewoman from Texas, Ms. Johnson.

Ms. JOHNSON. Thank you very much, Mr. Chairman, and thank you for calling this hearing. I look forward to hearing the witnesses.

We hope that this hearing will assess the state of the supply of the radioisotope power that NASA relies on to carry out science missions in the outer regions of the solar system and on the surface of Mars.

Today is the 60th anniversary of Sputnik launch that ignited the space race with the former Soviet Union. In the intervening decades, federal investment in NASA's Planetary Science program has enabled NASA to send spacecraft to the farthest reaches of our solar system and beyond. Thanks to Curiosity, which landed on Mars in 2012, we know that ancient Mars could have had chemistry necessary to support life. Curiosity also has detected methane in the Martian atmosphere, a possible sign of microbic activity, and evidence for ancient water flows.

The recently completed Cassini mission spent more than a decade observing storms in Saturn's cloud tops, probing the planet's hidden interior, observing Saturn's rings with unprecedented detail, and flying through the geysers of Saturn's moon, Enceladus. The New Horizons mission became the first mission to perform a fly-by of Pluto and subsequently discovered that Pluto is still geologically active, has an extensive blue atmosphere, and is home to the largest known glacier in the solar system.

What do all of these missions have in common? All of these missions and the groundbreaking science they enable are driven by radioisotope power. NASA is developing future missions that require radioisotope power as well, including the Mars 2020 rover that is currently in development. In 2009 and '11 National Academies reports sounded alarm about the supply of material needed for radioisotope power and underscored the need for immediate action to restart domestic production of Pu-238 and the non-weapons grade isotope that makes radioisotope power systems work.

Mr. Chairman, it is vital that NASA is equipped with the power resources that it needs to continue to lead in the scientific exploration of the solar system. NASA's partnership with the Department of Energy has been and will continue to be essential in enabling the use of radioisotope power systems. I look forward to a fruitful discussion on what NASA and DOE are doing to cost-effectively ensure a sufficient supply of materials needed for radioisotope power systems to meet NASA's needs in the future.

I thank you, and I yield back.

[The prepared statement of Ms. Johnson follows:]

OPENING STATEMENT
Ranking Member Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology
Subcommittee on Space
"*Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini*"
October 4, 2017

Good morning and welcome to our witnesses. I look forward to your testimony. Mr. Chairman, thank you for holding this hearing to assess the state of the supply of the radioisotope power that NASA relies on to carry out science missions in the outer regions of the solar system and on the surface of Mars.

Today is the 60th anniversary of the Sputnik launch that ignited the space race with the former Soviet Union. In the intervening decades, federal investment in NASA's planetary science program has enabled NASA to send spacecraft to the farthest reaches of our solar system and beyond. Thanks to Curiosity, which landed on Mars in 2012, we know that ancient Mars could have had the chemistry necessary to support life. Curiosity also has detected methane in the Martian atmosphere, a possible sign of microbial activity, and evidence for ancient water flows.

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What do all of these missions have in common? All of these missions, and the groundbreaking science they enable, are driven by radioisotope power. NASA is developing future missions that require radioisotope power as well, including the Mars 2020 rover that is currently in development. In 2009 and 2011, National Academies reports sounded alarms about the supply of material needed for radioisotope power and underscored the need for immediate action to restart domestic production of Pu238, the non-weapons grade isotope that makes radioisotope power systems work.

Mr. Chairman, it is vital that NASA is equipped with the power resources it needs to continue to lead in the scientific exploration of the solar system. NASA's partnership with the Department of Energy has been and will continue to be essential in enabling the use of radioisotope power systems. I look forward to a fruitful discussion on what NASA and DOE are doing to cost-effectively ensure a sufficient supply of material needed for radioisotope power systems to meet NASA's needs into the future.

Thank you, Mr. Chairman, and I yield back.

Chairman BABIN. Now I'd like to introduce our witnesses. Mr. David Schurr—is it Schurr or Schurr?

Mr. SCHURR. Schurr.

Chairman BABIN. Schurr? Our first witness today is Mr. David Schurr, Deputy Director of the Planetary Science Division in NASA. He received a bachelor of science degree in aerospace engineering from the University of Notre Dame and a master's of science degree in process control from the University of Houston. He also received a master's of business administration degree from the University of Houston. Thank you. Good to have you today.

Ms. Tracey Bishop, our second witness today, Deputy Assistant Secretary for Nuclear Infrastructure Programs at the Office of Nuclear Energy at the Department of Energy. She holds a bachelor's of nuclear engineering degree from the Georgia Institute of Technology and a master's of business administration degree from the University of Maryland. Welcome.

Dr. Ralph L. McNutt, Jr., our third witness today. He's Chief Scientist for Space Science in the Space Exploration Sector at the Johns Hopkins University Applied Physics Laboratory. He received his bachelor of science and physics at Texas A & M University and his Ph.D. in physics at MIT. Welcome to today's hearing.

And Ms. Shelby Oakley, our fourth witness today, Director of Acquisition and Sourcing Management at the GAO, Government Accountability Office. She earned her bachelor of arts degree in both psychology and sociology from Washington and Jefferson College as well as a master's degree in Public Administration from the University of Pittsburgh's Graduate School of Public and International Affairs. And we welcome you as well.

I'd like to now recognize Mr. Schurr for five minutes to present his testimony.

**TESTIMONY OF MR. DAVID SCHURR,
DEPUTY DIRECTOR,
PLANETARY SCIENCE DIVISION,
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

Mr. SCHURR. Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity to discuss how NASA's Radioisotope Power Systems (RPS) Program enables our planetary exploration portfolio.

My office pursues NASA's goal to ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere. For many destinations in the solar system, solar power is not effective for powering our spacecraft, and we rely on the use of radioisotope power.

NASA, in partnership with the Department of Energy, has deployed radioisotope power on 22 of our space missions since 1969. Use of radioisotope power has enabled many first-time missions, including the first visits to Jupiter and Saturn with Pioneer 10 and 11; the first landings on Mars with Viking 1 and 2; the first visits to Uranus and Neptune during the Grand Tours of Voyager 1 and 2; the first rovers on Mars with Pathfinder, Spirit, Opportunity, and Curiosity; the first mission to orbit Jupiter with Galileo; the first mission to orbit Saturn with the just-completed Cassini; and the first visit to Pluto with New Horizons.

These missions would not have been possible without using the heat generated by the natural radioactive decay of Plutonium-238 to generate electrical power. To ensure that NASA is capable of conducting these missions, NASA and DOE work together to sustain and improve the technology to convert heat into electrical power, and the processes for producing Plutonium-238 and preparing it for flight.

NASA funds the implementation of the DOE-led Plutonium-238 production and the associated infrastructure needed to fuel and test radioisotope power systems to fulfill NASA mission requirements. Progress in re-establishing a Plutonium-238 production capability has been good, with initial batches already produced and shipped to Los Alamos National Laboratory, for mixing with existing inventory and pressing into fuel clads for NASA's upcoming Mars 2020 mission.

NASA's mission requirements for Plutonium-238 are driven by the mission priorities established in the Planetary Science Decadal Survey, as well as other potential NASA missions. At this time, the Mars 2020 mission represents the only firm NASA requirement for radioisotope power needing one multi-mission radioisotope thermal generator requiring 4.8 kilograms of plutonium dioxide.

NASA has also offered mission proposers the option to use radioisotope power for the current New Frontiers 4 Competition for possible launch in 2025 and has forecast the potential to offer radioisotope power for New Frontiers 5 or to a potential flagship mission launching around 2030.

With the current allocation to civil space of approximately 35 kilograms of plutonium and with new production ramping up to 1.5 kilograms of plutonium dioxide per year, DOE will have sufficient material for fabrication into heat sources for expected Planetary Science missions through 2030. In addition, NASA and DOE have been begun exploring options to increase production rates above if needed to support any increased future demand.

NASA also conducts basic and applied energy conversion research to advance state-of-the-art performance in heat-to-electrical-energy conversion. Both static and dynamic energy conversion projects are underway. All missions to date have used a static conversion system based upon thermocouples. Dynamic conversion can achieve higher efficiency, but the moving parts introduce challenges that must be addressed before committing to flight development. The goal of these investments is to provide higher conversion efficiency and improve performance for future missions. Increased efficiency would benefit the program by enabling more capable missions or extending the effective use of the Plutonium-238 supply.

With the 2016 New Horizons flyby of Pluto, humankind has completed its initial survey of our solar system. Through the use of radioisotope power, the U.S. remains the first and only nation to reach every major body from Mercury to Pluto with a space probe. With your continued support, we will use these capabilities to continue to explore the solar system through more capable orbiters, landers, and sample return missions in the years to come.

I look forward to responding to any questions you may have.

[The prepared statement of Mr. Schurr follows:]

Statement of
David C. Schurr
Deputy Director, Planetary Science Division
Science Mission Directorate
National Aeronautics and Space Administration

before the

Committee on Science, Space and Technology
Subcommittee on Space
U.S. House of Representatives

October 4, 2017

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity to appear today to discuss NASA's Radioisotope Power Systems (RPS) Program. In my opening statement, I would like to explain how radioisotope power is used to enable our planetary exploration portfolio.

NASA Planetary Science pursues NASA's goal to ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere. NASA planetary missions advance the scientific understanding of all parts of the solar system, while pushing the limits of spacecraft and robotic engineering design and operations. For many destinations in the solar system, solar power is not effective for powering our spacecraft due to such long distances from the sun, and we rely on the use of radioisotope power.

NASA, in partnership with the Department of Energy (DOE), has deployed radioisotope power on 22 of our space missions since 1969. Use of radioisotope power has enabled many first-time missions, including the first visits to Jupiter and Saturn with Pioneer 10 and 11, the first landings on Mars with Viking 1 and 2, the first visits to Uranus and Neptune during the Grand Tours of Voyager 1 and 2, the first rovers on Mars with Pathfinder, Spirit, Opportunity and Curiosity, the first mission to orbit Jupiter with Galileo, the first mission to orbit Saturn with the just-completed Cassini, and the first visit to Pluto with New Horizons.

These missions would not have been possible without using the heat generated by the natural radioactive decay of plutonium 238 to generate electrical power. To ensure that NASA is capable of conducting these missions, NASA and DOE work together to sustain and improve the technology to convert heat into electrical power, and the processes for producing plutonium 238 and preparing it for flight.

The United States ceased production of plutonium 238 in 1988. Concerns over the lack of production, and a dwindling inventory led to the start of a new production project in 2012. To meet NASA's long-range planetary exploration requirements, DOE has begun to establish a production capacity that will ultimately support an average production rate of 1.5 kilograms of plutonium dioxide per year. This production rate would satisfy expected NASA Planetary Science mission requirements through 2030.

NASA funds the implementation of this DOE-led plutonium 238 production and the associated infrastructure required to fuel and test radioisotope power systems to fulfill NASA mission requirements. The plutonium project effort consists primarily of developing new procedures and processes, and demonstrating a production capability at the required annual production rate. Based on progress to date, the plutonium project is expected to transition from development to initial operations in 2019, with an initial goal of producing 400 grams of plutonium dioxide annually. The current plan then ramps up to a full-rate production of 1.5 kilograms per year on average by 2025. Progress in re-establishing a plutonium 238 production capability has been good, with initial batches already produced and shipped to Los Alamos National Laboratory, for mixing with existing inventory and pressing into fuel clads for NASA's upcoming Mars 2020 mission.

NASA's mission requirements for plutonium 238 are driven by the mission priorities established in the Planetary Science Decadal Survey, most recently completed in 2011, as well as other potential NASA mission priorities. Additionally, NASA's overall mission cadence is constrained by available budget resources, and radioisotope usage is constrained by the NASA-funded DOE infrastructure available for fuel and mission processing. At this time, the Mars 2020 mission represents the only firm NASA requirement for radioisotope power, with one multi-mission radioisotope thermal generator requiring 4.8 kilograms of plutonium dioxide. NASA's Planetary Science Division has also offered mission proposers the option to use up to 14.4 kilograms of plutonium dioxide for the competitive New Frontiers 4 Announcement of Opportunity, for possible launch in 2025. In addition, NASA has forecast a potential to either offer radioisotope power for New Frontiers 5 or to a potential flagship mission launching around 2030.

Use of radioisotope power must be mission-enabling or enhancing, and missions must evaluate alternative technologies before choosing radioisotope power. Continued improvements of solar array performance when operating further from the Sun are now enabling spacecraft to perform in orbits as far as Jupiter using solar power, where sunlight is only four percent as strong as at Earth. The Juno probe, in a radiation-minimizing orbit at Jupiter, and the Europa Clipper in development, are two such examples of missions that would have historically, such as the Galileo mission, been considered to require radioisotope power but are achieving Decadal-based science objectives through adjustments to mission design. The improvement in alternative power technologies is considered in forecasting future radioisotope power requirements.

With the current allocation to civil space uses of approximately 35 kilograms of plutonium dioxide, and with new production ramping up to 1.5 kilograms per year, DOE will have sufficient RPS material for fabrication into heat sources for NASA Planetary Science missions. In addition to current plans, NASA and DOE have been begun exploring options to increase production rates above 1.5 kilograms per year if necessary to support future mission demand. We will continue to develop options to be able to react to changes in future mission forecasts.

In addition to the DOE-led work, NASA conducts basic and applied energy conversion research and development to advance state-of-the-art performance in heat to electrical energy conversion. Both static and dynamic energy conversion projects are underway at this time. All missions to date have used a static conversion system based upon thermocouples. Dynamic conversion can achieve higher efficiency, but the moving parts introduce reliability challenges that must be addressed before committing to flight development. The goal of these investments is to provide higher conversion efficiency and improve mission performance over the design life for future missions. Increased efficiency would benefit the program by enabling more capable missions or extending the effective use of the plutonium 238 supply.

With the 2016 flyby of the New Horizons spacecraft through the Pluto system, humankind has completed its initial survey of our solar system. Through the use of radioisotope power, the United States remains the first and only nation to reach every major body from Mercury to Pluto with a space probe. With your continued support, we will use these capabilities to continue to explore the solar system through more capable orbiters, landers and sample return missions in the years to come.

Again, thank you for the opportunity to testify today and I look forward to responding to any questions you may have.

Bio – David Schurr

David C. Schurr is the Deputy Director of the Planetary Science Division of NASA's Science Mission Directorate, and is the Director of Solar System Exploration Programs. Prior to that, Schurr was the NASA Comptroller, and helped direct NASA's budget formulation, advocacy and execution processes for the Agency's institutions, programs and projects. Schurr began his career at the Johnson Space Center in Houston Texas in 1982, as a Shuttle flight controller in mission control. He was responsible for various defense and interplanetary satellites deployed using the Space Shuttle. Schurr received a Bachelor of Science degree in aerospace engineering from the University of Notre Dame in 1982, a master of science degree in process control from the University of Houston in 1987, and a master of business administration degree from the University of Houston in 1996.

Chairman BABIN. Thank you, Mr. Schurr. I appreciate that.

I now recognize Ms. Bishop for five minutes to present her testimony.

TESTIMONY OF MS. TRACEY BISHOP, DEPUTY ASSISTANT SECRETARY FOR NUCLEAR INFRASTRUCTURE PROGRAMS, OFFICE OF NUCLEAR ENERGY, DEPARTMENT OF ENERGY

Ms. BISHOP. Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity today to discuss the Department of Energy's efforts to ensure radioisotope power systems are available for NASA use.

The Department is committed to its partnership with NASA to provide radioisotope power systems for space exploration. This successful partnership has extended over 50 years and 22 missions. Radioisotope power systems have a proven track record with no failures and long power lifetimes, making them a continued viable technology option for NASA missions.

In October 2016, the Department and NASA renewed a memorandum of understanding to work together on future development and deployment of radioisotope power systems. This arrangement updated agency responsibilities to reflect funding authority changes and to provide more emphasis on aligning and integrating work to ensure and enable future space exploration missions.

In the same month, the Office of Nuclear Energy realigned responsibilities to the Office of Nuclear Infrastructure Programs elevating interface with NASA to the Deputy Assistant Secretary level.

Upon approval of the new memorandum of understanding, the agencies initiated discussions to assess current activities and to determine options to support for NASA mission goals. In early 2017, the Department and NASA agreed to transition delivery of radioisotope power systems from a mission-driven approach to constant-rate production strategy. Constant-rate production establishes clear deliverables, as defined by annual average production rates for Plutonium-238 and fueled clads allowing the Department to level-load work, ensuring that the capability is fully exercised, technical proficiency of the workforce is maintained, and opportunities to maintain and refurbish equipment in a systematic approach are available to support NASA mission requirements.

Measurable progress has been made to realign activities to directly address identified risks to achieving plutonium production rates. The Department completed its first campaign of new, domestic Plutonium-238 in 2015, and the new material met NASA mission specification requirements. The Department and NASA agreed to continue efforts to reconstitute the plutonium supply chain by utilizing this material as part of the Mars 2020 mission. I am pleased to report that as of August 2017, the Department successfully fabricated two fueled clads utilizing new plutonium for the Mars 2020 mission. A second campaign of new plutonium is scheduled to complete this fall, taking into account lessons learned from the first campaign.

The Department is actively working to address and mitigate risk to establishing domestic Plutonium-238 production. Additional funding was made available as part of the Fiscal Year 2017 Omnibus. The Department is utilizing those funds to further reduce risk and accelerate the schedule. For example, the Department is accelerating work to expand the capability to ship larger quantities of Plutonium-238 heat source oxide between its sites. The Department is also accelerating research and testing on production target design with a goal of recommending a standard target design for both the advanced test reactor at Idaho National Laboratory and the high flux isotope reactor at Oak Ridge National Laboratory by 2019.

The Department has an existing inventory of Plutonium-238 that is able to meet NASA's current demands through a notional mission in 2025 plus additional plutonium that is currently out of specification.

The Department recognizes there is a need to develop long-range projections of plutonium to support space exploration planning activities beyond 2025 and is initiating several activities to begin this work.

The Department accelerated an experimental campaign to verify an approach for irradiation in underutilized positions in the advanced test reactor that would yield sufficient quantities of very high assay plutonium which can be blended with the existing larger quantities of out-of-specification inventory to support overall heat source production rates while minimizing impact to existing irradiation customers.

The Department is also assessing options to support redesign of the high flux isotope reactor's beryllium reflector to optimize it for Plutonium-238 production with the potential to increase total yield and assay so that it could also be blended with larger amounts of out-of- specification plutonium.

The Department remains committed to partnering with NASA to ensure continued availability of radioisotope power systems for space exploration missions. Thank you for the opportunity to share the Department's progress, and I look forward to addressing any questions you may have in this area.

[The prepared statement of Ms. Bishop follows:]

Statement of Tracey L. Bishop
Deputy Assistant Secretary for Nuclear Infrastructure Programs
Office of Nuclear Energy
U.S. Department of Energy
before the
House Committee on Science, Space and Technology
Subcommittee on Space
U.S. House of Representatives

October 4, 2017

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity today to discuss the Department of Energy's efforts to ensure radioisotope power systems are available for NASA use.

The Department is committed to its partnership with NASA to provide radioisotope power systems for space exploration activities. This successful partnership has extended over 50 years and 22 missions. Radioisotope power systems have a proven track record with no failures and long power lifetimes, making them a continuing viable technology option for NASA missions. My testimony today will focus on how DOE is strengthening our relationship with NASA; ensuring delivery of radioisotope power systems through a transition to a constant-rate production strategy; and aligning planning for long-range production of plutonium for space power applications with NASA for missions beyond the current 2025 timeframe.

Relationship with NASA

In October 2016, the Department and NASA renewed a memorandum of understanding (MOU) to work collaboratively on future development and deployment of radioisotope power systems solutions. This arrangement updated agency responsibilities to reflect funding authority changes and to provide more emphasis on aligning and integrating work to enable future space exploration missions.

In the same month, the Office of Nuclear Energy reorganized and aligned the responsibilities for radioisotope power systems to the Office of Nuclear Infrastructure Programs, elevating the interface with NASA to the Deputy Assistant Secretary level. DOE recognizes the technical challenges in reconstituting nuclear capabilities for plutonium production that were suspended in the late 1980's and made this change to leverage Nuclear Energy's expertise in re-establishing and maintaining nuclear infrastructure capabilities in support of the radioisotope power system missions.

Constant Rate Production

Upon approval of the new MOU, the agencies initiated discussions to assess current activities and determine options to improve support for NASA mission goals. In early 2017, DOE and

NASA agreed to transition the delivery of radioisotope power systems from a mission-driven approach to a constant-rate production strategy. Applying a constant-rate production strategy affords both agencies the ability to improve reliability and predictability to deliver systems in support of NASA space exploration missions. Constant-rate production establishes clear deliverables, as defined by annual average production rates for plutonium-238 and fueled clads. Maintaining a predictable throughput of plutonium-238 and fueled clad manufacturing activities will level-load the work, ensuring that the capability is fully exercised, technical proficiency of the work force is maintained, and opportunities to maintain and refurbish equipment in a systematic approach are available. The agencies agreed to plutonium production targets that are aligned to NASA mission requirements, with a goal of achieving an annual heat-source plutonium oxide production rate of 1.5 kilograms/year by the year 2025 with an interim annual heat-source plutonium oxide production rate of 400 grams/year by 2019.

Specific to the production of plutonium-238, the Department's approach shifted from a project-based management construct to the framework utilized for decades at Oak Ridge National Laboratory to produce isotopes for medical and industrial use. Employing this framework provides NASA and DOE flexibility to align resources and efforts to optimize plutonium production; and identify, evaluate, and implement improvements to maximize NASA investments.

Measurable progress has been made to realign activities to directly address identified risks to achieve plutonium production rates. The Department completed its first campaign of new, domestic plutonium-238 in 2015 and the new plutonium-238 met NASA mission specification requirements. Given the composition of the material, the Department and NASA agreed to continue efforts to demonstrate the nuclear capabilities supply chain by utilizing this material as part of the Mars 2020 mission. I am pleased to report that, as of August 2017, the Department successfully fabricated two fueled clads, in part utilizing a small amount of new plutonium mixed with the existing inventory for the Mars 2020 radioisotope power system. A second campaign of new plutonium is scheduled to be completed this fall, taking into account lessons learned from the first campaign.

The Department is actively working to address and mitigate risks to establishing domestic plutonium-238 production capability. The Fiscal Year (FY) 2017 Omnibus Appropriations bill made additional funding available for domestic production of plutonium-238, and the Department is using those funds to further reduce risk and accelerate the schedule. For example, DOE has made progress to expand the capability to ship plutonium-238 heat source oxide between its sites, focusing efforts on development, design, procurement and certification of shipping containers with the majority of activities scheduled to be completed in FY 2017 for both Idaho National Laboratory (INL) and Los Alamos National Laboratory (LANL). Currently, DOE has limited capacity to load plutonium-238 heat-source oxide at Oak Ridge National Laboratory (ORNL) due to the configuration of equipment and its incompatibility to package material with new packaging containers. DOE was originally scheduled to complete modifications by FY 2020 but has accelerated this schedule by roughly 12 months. This is being achieved by utilizing the additional funding to fast-track the procurement of gloveboxes, welders, and other equipment to modify the current packaging capability by early FY 2019. This revised schedule better aligns with established production goals.

The Department also accelerated research and testing on a production target design with the goal of recommending a final target design for both the Advanced Test Reactor (ATR) at INL and the High Flux Isotope Reactor (HFIR) at ORNL by 2019. DOE is testing a potential process improvement at ORNL to replace the current neptunium oxide/aluminum target with a new target that eliminates the use of aluminum. The new target is estimated to increase the amount and the assay of plutonium-238 produced. The increased yield per target would result in manufacturing fewer targets as well as eliminating a chemical processing step and waste stream, resulting in production cost reductions. DOE is pursuing evaluation of this target design with the goal of completing all testing and providing a recommendation to NASA in 2019 for a standardized target design for both research reactors.

Aligning Plutonium Project to Future NASA Missions

The Department has an existing inventory of approximately 35 kilograms of plutonium-238 that is able to meet NASA's current demands for RPS activities through a notional mission in 2025. Of this inventory, less than half of the plutonium meets the NASA mission specification of roughly 82 percent assay of plutonium-238 isotope with the remaining amount falling outside of this specification. In collaborations with NASA, the Department recognizes that there is a need to develop long-range projections of plutonium to support space exploration planning activities and assure available supplies to meet missions beyond 2025.

DOE is initiating several activities to begin this long-range planning work. Currently, the Department is utilizing the HFIR to produce small campaigns of plutonium-238 to finalize the production process. In April 2017, the Department completed a study to evaluate the use of the ATR, along with the HFIR, to produce plutonium-238 to meet the established heat source production rate of 1.5 kilograms per year by 2025. Based on this study, the Department has identified an approach for irradiation in underutilized positions in the ATR that would yield sufficient quantities of very high assay product, which can be blended with larger quantities of out-of-specification inventory at LANL, to support the overall heat source production rate of 1.5 kilograms per year while minimizing impacts to existing irradiation customers.

With the additional funding provided in the FY 2017 Omnibus, DOE is actively pursuing opportunities to further optimize use of the ATR and HFIR. The Department accelerated activities on ATR to conduct an experimental campaign to verify the results of the recent study, with the goal of obtaining data at least six months earlier than planned to support FY 2019 decisions on ATR target designs. Additional funding was also provided to support redesign of the HFIR beryllium reflector to optimize it for plutonium-238 production, with the potential to increase total yield and assay so that it could also be blended with larger amounts of out-of-specification material at LANL.

Conclusion

The Department remains committed to partnering with NASA to ensure the continued availability of radioisotope power systems for space exploration missions. Thank you for the opportunity to share the Department's progress and I look forward to addressing any questions you may have in this area.

TRACEY BISHOP - DEPUTY ASSISTANT SECRETARY FOR NUCLEAR INFRASTRUCTURE PROGRAMS

As the Deputy Assistant Secretary for Nuclear Infrastructure Programs, Ms. Tracey Bishop is responsible for the management of the Office of Nuclear Energy's infrastructure programs at Idaho National Laboratory. She is also responsible for NE's field operations at the Nuclear Energy Oak Ridge Site Office supporting the lease administration of uranium enrichment capabilities at Oak Ridge Reservation and the Portsmouth Gaseous Diffusion Plant.

In this capacity, Ms. Bishop is responsible for a large portfolio of infrastructure programs, spanning facility management, capital asset planning and construction, safeguards and security, emergency planning, and nuclear materials management. These programs and capabilities enable critical nuclear energy research and development activities by providing and maintaining safe, secure, and compliant facilities for multiple customers within and external to the Department of Energy. She is also responsible for delivering compact, safe radioisotope power systems, heater units, and related technologies to support the National Aeronautics and Space Administration and other agencies in space exploration and national security missions.

Ms. Bishop has over 25 years of experience in facility management and environmental, safety and health oversight experience with DOE. Before joining the Office of Nuclear Energy in 2008, Ms. Bishop served as the Acting Director of the Office of Facilities Operations, Office of Defense Programs, National Nuclear Security Administration. In this capacity, Ms. Bishop managed a multi-site facility operations program that supported the Stockpile Stewardship Program and other national security missions at Kansas City Plant, Pantex Plant, Savannah River Tritium Facilities, Y-12 National Security Complex, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, and Nevada National Security Site.

Ms. Bishop holds a Bachelor of Nuclear Engineering degree from the Georgia Institute of Technology and a Master of Business Administration degree from the University of Maryland. Ms. Bishop is certified as a Project Management Professional with the Project Management Institute.

Chairman BABIN. Thank you, Ms. Bishop. I now recognize Dr. McNutt for five minutes to present his testimony.

TESTIMONY OF DR. RALPH L. MCNUTT, JR., CHIEF SCIENTIST FOR SPACE SCIENCE IN THE SPACE EXPLORATION SECTOR, THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

Dr. MCNUTT. Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for providing this opportunity for me to discuss some of the things that we've been able to do with these radioisotope power supplies over the years and some of the challenges that have been going on in order to be able to actually make a lot of these discoveries. Of course, it's already been remarked that 60 years ago today Sputnik was launched. It was powered by a battery. It was not until the fourth mission, Vanguard I that was launched by the United States, that there were actually solar cells that were used.

Solar cells were a problematic technology at the time. We've come an incredibly long way since then. But at the time there were issues about whether that they would actually be able to be useful. And so the development of radioisotope power supplies was begun early. The first use was on the Transit 4A satellite launched in 1961 as part of the Navy's communications system. And since then, the United States has poured a great deal of effort and money into maturing the radioisotope power system supplies that we've been using until today.

And of course, things like the Pioneer 10 and 11 probes, the first ones beyond the asteroid belt, the Viking 1 and 2 landers, the first landers on Mars, and now even the venerable Voyager 1 and Voyager 2 space probes, which have celebrated more than 40 years in space and are still broadcasting from beyond the edge of the solar system new data about our surroundings, none of these would have been available if it had not been for these power supplies.

It's also been remarked about the Cassini mission, of course, and I think I've got a graphic and that is indeed is up.

[Slide]

Of course, trying to describe everything that's been done with Cassini over the last 13 years in orbit is something that would take considerably more than five minutes. But certainly, our discoveries at Titan, our discoveries about Saturn, its rings, the magnetosphere, how similar and different the magnetic fields of Saturn and the Earth are, as well as looking at Enceladus of course, and the plumes which have already been talked about, is perhaps places where there might actually be life are all things that would not have been possible without those power supplies on board the spacecraft. And if we'd go to the next slide, please?

[Slide]

Of course, also with New Horizons, on the left-hand side is the best Hubble image of Pluto, and in the middle is what we were able to get with New Horizons, after 9–1/2 years of flight. And the final image is actually looking back toward the sun with the New Horizons spacecraft.

[Slide]

And you can see the haze around the edge. This is a movie. This is actually put together from actual data that was gathered by the New Horizons spacecraft showing you what the glaciers look like made out of nitrogen ice, water mountains, very young features, all geologically active. This has also been already remarked about, basically an incredible world out at the edge of the solar system. And again, if it had not been for having these radioisotope power supplies, none of this would have been possible.

Of course, one of the things that has also been noted is that at the time of the Academy report in 2009, it looked like we were into a going-out-of-business sale with being able to actually have plutonium supplies to be able to do these kinds of missions. The good news is that we were able to actually recover from that, as has already been noted by my other colleagues here at the table. We seem to have turned the corner on that.

At the same time, this is a difficult business, and the converters that NASA has been investing in, DOE has been investing in, these have been technically hard problems. It's been elusive in trying to raise the types of efficiencies that one would like, and indeed the type of radioisotope power systems that are on board Cassini and on board New Horizons right now are technologies that right now we cannot reduplicate. We cannot rebuild those supplies.

It's been a difficult, difficult time trying to come up with a sort of a power supply where that one supply will fit all. And that has particularly remained elusive. Of course, it's limited by the amount of funds that are out there, but nonetheless, there are other steps that perhaps could be taken in order to enable us to keep moving forward. Certainly within the scientific community, a great deal of interest in the decadal surveys with future missions that cannot be done any other way, and I look forward to being able to answer any questions that you might have about some of those missions or any of the other aspects of these supplies and what they've been able to do for us. Thank you.

[The prepared statement of Dr. McNutt follows:]

Testimony of
Ralph L. McNutt, Jr., Ph.D.
Chief Scientist for Space Science
Space Exploration Sector
The Johns Hopkins University Applied Physics Laboratory

Before the
Subcommittee on Space
for the
Committee on Science, Space, and Technology
U.S. House of Representatives

October 4, 2017
"Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini"

We shall not cease from exploration
And the end of all of our exploring
Will be to arrive where we started
And know the place for the first time.

- T.S. Eliot (1942)

Introduction

The world changed 60 years ago today when the Soviet Union launched the artificial satellite Sputnik I into Earth orbit. While plans had been announced in the United States to launch such an object as part of the International Geophysical Year (IGY) of 1957, Sputnik caught the United States off guard. A 23-inch diameter sphere weighing just over 184 lbs (83.6 kg), much of Sputnik's weight was made up of 112 lbs. (51 kg) of three silver-zinc batteries, which regulated the temperature and powered the radio transmitter. The battery power lasted for 22 days and the satellite itself for 3 months before reentering the Earth's atmosphere.

Although it is commonplace now for most satellites to be powered – and very efficiently so – with solar arrays, this was not always the case. The first American satellite, Explorer I, launched at the end of January 1958 was also battery powered. Vanguard I, the fourth artificial satellite, a 6.4-inch diameter sphere weighing 3.2 lbs. was powered by six solar cells producing a watt of electricity, which allowed one of the transmitters to operate until 1964 (a separate transmitter was powered by a battery until 1958). Vanguard remains as the oldest spacecraft still in Earth orbit.

Providing power to satellites was an ongoing technical challenge. Batteries were reliable, but were also heavy and had limited lifetimes. Solar cells showed promise, but were subject to radiation damage in space that also limited their lifetimes. The use of nuclear power supplies for spacecraft, both in the form of radioisotope supplies and fission reactors was a subject of significant study. Such supplies offered lifetimes far in excess of the lifetime that could be expected from the electronics and other subsystems on satellites as well as total independence from both orientation of the spacecraft with respect to the Sun and the radiation environment of space.

The Atomic Energy Commission (AEC), beginning in 1951 and following RAND Corporation studies on the topic from the later 1940's, initiated what became the Systems Nuclear Auxiliary Power (SNAP) program. Following a great deal of development work, the first power unit was tested on the Navy's Transit 4A communications satellite, which was launched on June 29, 1961. The 175-lb satellite (slightly lighter than Sputnik I) was powered mostly by solar cells tied to nickel-cadmium batteries. However, the spacecraft also carried a ~4.5-lb SNAP 3B7 power supply, about 5.5 inches long and 4.5 inches in diameter, producing 2.7 watts of electricity from the heat provided by the radioactive decay of ~7 ounces (~200 grams) of the rare, human-produced isotope plutonium-238 (Pu-238).

Since those early years, many other isotopes have been proposed, produced, investigated, and tested. For spacecraft applications and reasons of moderate power combined with long lifetime, safety in handling, assembly and mounting in spacecraft, and relative ease of production, Pu-238 in the chemical form of plutonium dioxide has always been the best technical choice. While it is radioactive and must be handled with care, and while is it certainly not "cheap" to produce – and never has been – nonetheless it has consistently been, and continues to be, the best choice due to reasons of physics and chemistry that any technologies are subject to.

The Next Steps Taken

While solar arrays have vastly improved with time, both with respect to their efficiency in converting sunlight into electricity and in their tolerance to radiation damage in space, they remain limited in power output by the amount of sunlight available to them. Given the decrease of sunlight intensity with distance from the Sun (the "inverse-square law"), it had already become clear to NASA in the late 1960s that Radioisotope Power Systems (RPS) would be enabling for spacecraft trips past the asteroid belt to Jupiter and beyond. This led to the test of two SNAP 19 units on the Nimbus III satellite in 1969, qualifying them for use on Pioneer 10 and Pioneer 11, the first spacecraft to Jupiter and then to Jupiter and Saturn, respectively.

Such systems proved to be vital for applications closer to the Sun as well in applications for which large solar arrays were out of the question due to other engineering limitations. SNAP 27 systems were used to power the Apollo Lunar Surface Experiments Packages (ALSEPs) left on the lunar surface during the Apollo 12, 14, 15, 16, and 17 missions, and modified SNAP 19s enable the Viking 1 and 2 stations on the surface of Mars.

The twin Voyager 1 and 2 spacecraft followed Pioneer 10 and 11 out of the solar system, employing the Multi-Hundred Watt (MHW) RPSs developed by the U.S. Air Force for the communications satellites Lincoln Experimental Satellite (LES) 8 and 9.

With the then-upcoming Ulysses mission – joint between NASA and the European Space Agency (ESA) – a standardized "building block" for the RPSs, a General Purpose Heat Source (GPHS) was developed to ensure safety standards and cost efficiencies could be more easily realized for future missions. The GPHS modules combined with silicon-germanium converters enabled the Ulysses mission (one unit; with ESA and in an orbit near perpendicular to the orbital plane of the Earth and most of the planets), Galileo (two units; orbital mission to Jupiter), Cassini (three units; orbital mission to Saturn, just ended 15 September 2017), and New Horizons (one unit; had been a flight spare for the other missions; fly through the Pluto system on July 14, 2015 and now en route to the Kuiper Belt Object (KBO) "(486958) 2014 MU_{69}" on January 1, 2019).

None of these missions would have been possible without these RPS power supplies employed on them.

Cassini at Saturn

Describing all of the Cassini results from Saturn is an ongoing process. As the data returned from Cassini continue to be mined, there will be more and more new results. Taking a very broad-brush approach one can summarized some of the findings from the Cassini Huygens mission (*Ten Notable Findings from Cassini Huygens* by JoAnna Wendel, Earth and Space Science News, Vol. 98, No. 9, September 2017) as:

1. Cassini Revealed Enceladus's Potentially Habitable Internal Ocean
2. Huygens Showed Us Titan, a Possibly Primordial Earthlike World
3. Cassini Changed How We Think of "Habitability"
4. Cassini Found Enceladus Ocean Material in the E Ring
5. Cassini Unlocked Mysteries of Saturn's Hexagon
6. Cassini Showed Us One of Saturn's Huge, Infrequent Storms...
7. ...And That Storm Helped Cassini Detect Atmospheric Water
8. Cassini Dazzled Scientists with Saturn's Color-Changing Atmosphere
9. Cassini Spied Saturn's Rings Acting Like a Seismometer
10. Cassini Showed Us Saturn's Other Dynamic Moons

Cassini spent 13 years in orbit about the ringed-planet Saturn (2004 to 2017), acquired 435,000 images, and generated 3,948 scientific papers with 750 of these published in 6 journals of the American Geophysical Union (from Mike Liemohn, Editor-in-Chief, Journal of Geophysical Research: Space Physics).

At Saturn Orbit Insertion (SOI) on 1 July 20014, the three GPHS Radioisotope Thermoelectic Generators (RTGs) provided 744 watts for electricity to run the spacecraft from ~54 pounds of plutonium-238 (a smaller weight than that of the total plutonium dioxide mass in the generator housings).

New Horizons at Pluto

After a journey of 9.5 years (January 19, 2006 to July 14, 2015), the New Horizons spacecraft revealed the Pluto system: Pluto itself, its large moon Charon, and four more satellites (Nix, Hydra, Kerberos, and Styx). Pluto and Charon are entirely different worlds with different and unique landforms and surface compositions. Pluto itself has glaciers of frozen nitrogen, mountains of water ice, a surface that changes with, rather than being frozen by, time. The entire landscape merges with layers of haze and a tenuous atmosphere, reaching outward from the surface itself, showing the Kuiper Belt to be populated with anything but boring balls of ice, rather with distinct systems with personalities of their own.

No Guaranteed Future for RPS

Against the backdrop of the Cassini mission operations at Saturn and the successful flyby of the Jupiter system by New Horizons in the first half of 2007, it had become clear that there would be potential issues for any future missions that required RPSs. With the wind-down of the Cold War and fewer non-NASA users of Pu-238 in the U.S., supplies were more and more focused on purchases of the material from Russia. At the time of the RPS Provisioning Report (aka the "Casani report" of May 8, 2001), a restart of domestic Pu-238 production was still being discussed (it had been shut down when the Savannah River K-reactor was taken off line in 1988), and DOE had issued a record of decision (ROD) to proceed.

With a variety of upcoming requirements from NASA for (1) a 2007 Mars Smart Lander (MSL), (2) Europa Orbiter (EO), (3) Pluto Kuiper Belt (PKB), (4) Solar Probe (SP), and (5) a 2011 Mars Sample Return (MSR) mission, plans were made to develop a dynamic, Stirling RPS and a "new RTG" as a backup. The Stirling converter promised far greater conversion efficiency than existing static, thermoelectric converters, which would help take some of the pressure off of the Pu-238 supply but was seen as offering developmental and consequent programmatic risk. Hence the new RTG was designed to serve as a backup to the Stirling unit in order to alleviate such programmatic risks, if development problems arose. This middle ground eliminated both the risk of an all-Stirling program and the continued high-use rate of Pu-238 in an all-RTG program – the driver was viewed to be the provision of a Stirling system to the MSL mission in time for a 2007 launch.

With the 9/11 attacks in the United States, security for production of Pu-238 and assembly of the RPSs came under renewed scrutiny. One consequence was the removal of the Mound facility in Miamisburg, Ohio to a new facility in Idaho in the midst of the fueling campaign for the GPHS-RTG for New Horizons. The Stirling program suffered technical performance issues and the "new RTG" that was the "backup" now became the primary item. In order to operate in both an atmosphere (on the surface of Mars) and in the vacuum of space, a decision was made to go back to the conductive converter technology that had been used in the SNAP 19 units, in effect abandoning the more efficient and longer-lived, silicon-germanium technology that could operate only in a hard vacuum. The unit was christened the "Multi-Mission RTG" or MMRTG.

MSL, now the Mars Surface Lander, was already slipping to a 2009 launch date (and eventually to a 2011 launch date as the "Curiosity" rover). Mars Sample Return was, in turn, moved even further "to the right," i.e., to a later launch date. Europa Orbiter was cancelled, Pluto Kuiper Belt became the competitive procurement won by the New Horizons team, with the promise of a GPHS-RTG in the form of the Cassini "flight spare," and Solar Probe was reformulated as "Solar Probe Plus" (now Parker Solar Probe) to eliminate its need for an RTG. An Advanced Stirling Radioisotope Generator (ASRG) project was begun, picking up from the Stirling unit originally advocated as the prime development by the RPS Provisioning Team in 2001.

At this time (2008), the Radioisotope Power Systems Committee was stood up by the National Research Council to assess the situation. That committee made 13 findings, 3 recommendations, and 2 high-priority recommendations. While most of the recommendations reiterated many aspects of the then-current situation, the final one was one of the most significant, reflecting upon the lack of progress since the Provisioning report of 2001:

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

The recommendations addressed the MMRTG, Flight Readiness criteria, and the provision of a guiding Technology Plan. The first required monies for maintaining the MMRTG as something that could be used while other approaches continued to be investigated and developed. The Committee found the other two recommendations as vital for providing overall programmatic guidance, while realizing that neither would be easy to implement:

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

> **RECOMMENDATION. Technology Plan.** NASA should develop and implement a comprehensive RPS technology plan that meets NASA's mission requirements for RPSs while minimizing NASA's demand for 238Pu. This plan should include, for example:
> - A prioritized set of program goals.
> - A prioritized list of technologies.
> - A list of critical facilities and skills.

• A plan for documenting and archiving the knowledge base.
• A plan for maturing technology in key areas, such as reliability, power, power degradation, electrical interfaces between the RPS and the spacecraft, thermal interfaces, and verification and validation.
• A plan for assessing and mitigating technical and schedule risk.

The two high-priority recommendations were listed as such to try to stem what the Committee viewed at the time (2009) as negative trends, which, if left to go for too long, might be irreversible:

HIGH-PRIORITY RECOMMENDATION. Plutonium-238 Production. The fiscal year 2010 federal budget should fund the Department of Energy (DOE) to reestablish production of 238Pu.
• As soon as possible, the DOE and the Office of Management and Budget should request—and Congress should provide—adequate funds to produce 5 kg of 238Pu per year.
• NASA should issue annual letters to the DOE defining the future demand for 238Pu.

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

The first high-priority recommendation has been acted upon, and the first new material has been produced at the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL). An updated need for plutonium-238 is included in *Vision and Voyages*, the Planetary decadal survey document, published in 2011. Table 9.5 in that document compares the stated NASA needs as of April 29, 2008 and March 25, 2010. The projected needs decreased with the termination of the Constellation program and its associated pressurized rovers for human use on the lunar surface. Negotiations between NASA and DOE have continued to try to strike the right balance for the production rate, but (to the best of my knowledge) no further requirements letters have changed hands at these two agencies, or, if they have, they have not been easily, publicly accessible.

Subsequent to the issuance of the 2009 RPS report, responsibility for maintenance of the production infrastructure of Pu-238 fuel for the RPSs was transferred to NASA from DOE. An assessment was made of the true cost impacts, and a final report was transmitted from NASA to the Office of Management and Budget (OMB) in the Fall of 2013. I was a member of that study team; to the best of my knowledge, that report has never been made public.

The second high-priority recommendation had also been followed, but technical progress lagged. The need for ASRGs for future missions was reiterated in the *Vision and Voyages* document; however, with costs mounting and technical difficulties continuing, that particular program was cancelled by NASA late in calendar year 2013. There do continue to be ongoing developmental efforts in looking at Stirling technology for RPS converters, however.

It is worth noting that converter technologies for RPSs have long remained technically difficult, expensive, and elusive. The Galileo spacecraft was to originally have used a Selenide Isotope Generator (SIG), which effort was finally stopped due to technical problems and replaced by the GPHS-RTG. Similarly, the use of the alkali-metal thermal to electric converter (AMTEC) for spacecraft use was initially funded as part of NASA's X-2000 technology development program. Technical problems led to its abandonment in the early 2000's with the moves to the Stirling converter and MMRTG as advocated in the 2001 provisioning study.

Overall, a lesson, which should be learned and acknowledged as such, is that while the various converter technologies discussed over the years have shown promise, the actual development of these techniques into usable flight hardware has proven to be a very, very difficult task. This is perhaps best reflected in the fact that no other country in the world to date has developed, much yet used, comparable power systems for deep space use.

Current Status and Perceived Needs

An examination of the *Vision and Voyages* survey reveals that the view of the scientific space community is that the need for such RPS supplies has not gone away. While developments with the solar arrays have now pushed the technology into use in the Jupiter system (notably on the current Juno mission, and the future ESA JUpiter ICy moons Explorer (JUICE) mission and the NASA Europa Clipper mission), such developments have had their own challenges. The notable difficulty was with the low-intensity, low-temperature (LILT) effect that makes for less efficiency (than would have been ascribed to the simple decrease in solar intensity with distance to the Sun alone).

Future missions to the outer solar system, e.g., a return in-depth study of Saturn's moon Titan or to the Icy Giant worlds of Uranus and Neptune and/or Neptune's large moon Triton (perhaps a captured KBO), will all be hard pressed to be flyable without an RPS. As with the MMRTG on Curiosity and Mars 2020 (now being built), other pieces of a successful Mars Sample Return campaign will likely need an RPS. Similarly, future landers on Mercury or landers with rovers into the permanently shadowed regions of the Moon will be problematic without RPSs. Any mission to other large KBOs such as Quaoar, Makemake, Haumea, or others or an Interstellar Probe mission to the far reaches of the interstellar medium beyond, well past the reach of Voyagers 1 and 2, will also have the same needs. These needs will require the capabilities of the long-lived, high-efficiency systems possessed by the MHW and GPHS-RTG systems with their silicon-germanium converters, a capability which we no longer possess (Pioneer 10 and 11, with converters similar to those used in the MMRTGs, finally succumbed to the decay of their power supply outputs. Voyager 1 and 2, now at their 40-year marks, will not outlast the 2020s, and, if supported for operations until then, New Horizons will not outlast the 2030s; even the Pu-238 fueled RPS generators based upon silicon-germanium converter technology will not last forever; even longer-lived supplies are another story).

The Nuclear Power Assessment Study (NPAS) of 2014 to 2015 was conducted with many participants both from the DOE and NASA to examine the objective of discussing "a sustainable strategy and present findings for the provisioning of safe, reliable, and affordable nuclear power systems that enable NASA Science Mission Directorate (SMD) missions and is extensible to Human Exploration and Operations Mission Directorate (HEOMD) needs in the next 20 years." That group of people looked in depth at various future possibilities, again using *Vision and Voyages* as a guide. They came to ten, broad conclusions:

1) NASA will need appropriately sized nuclear power systems to support robotic space missions for the period covered by the decadal surveys currently in force.
2) This need for nuclear power systems is expected to extend for at least one more decade past that covered by the current decadal surveys.
3) Without significant budget increases in mission cost caps, projected, single-mission power requirements are unlikely to exceed ~600 W_e [i.e., watts of electrical power, rather than thermal power].
4) Radioisotope Power Systems (RPS) with projected Pu-238 production rates and current technology may suffice to fulfill currently projected SMD needs.
5) Significantly increased capability in the rate of RPS electrical power available for missions is possible only with increased Pu-238 production rates and/or flight qualification of a dynamic [e.g., Stirling] converter.
6) Converter technologies are independent of the nature of the nuclear heat source.

7) SMD has a continuing requirement to maintain and advance RPS for the next two decades and to plan for increased Pu-238 production rate over time.
8) A space-based fission power system (FPS) could potentially enable higher power SMD missions, but only if the future need arises and sufficient new funds to develop an FPS flight unit are provided.
9) FPS could be used on, but are not currently required for, SMD missions and would present technical challenges.
10) SMD has no current requirements for a mission power system at the 1-kW_e [1,000 watts of electricity] level or higher, and so no current requirement for an FPS exists.

A Road Forward

With a great expenditure of funds (literally billions of inflation-adjusted dollars from the late 1940s forward), effort, and time (over six decades) the United States has developed a technology for powering spacecraft to regions of space not otherwise reachable. The spectacular results from the Cassini mission to Saturn, the New Horizons mission to the Pluto system, and the Curiosity mission carrying out its in-depth investigations of Mars would not have been possible without this means, a means duplicated by no other country or entity on this planet. The road forward remains clouded, not because we do not know the way, but because we do not like its cost. Time and again, we have attempted other roads with the promise of a less-expensive way out, only to run into new technological dead-ends after an additional great expenditure of time and money.

Operating on the edge of the scientifically and technologically possible will never be cheap, yet the realities of resources mean that we must plan prudently as we move ahead. Production of Pu-238 fuel and converters to use it is a complicated undertaking, most efficiently carried out with decades of upfront planning and carefully planned stewardship of the required infrastructure. The spacecraft missions that make use of these materials come and go on much shorter times scales, with starts and stops, and turns and twist that resist the type of planning needed to produce the power supplies. This dichotomy has led to the continuing managements challenges between the DOE and NASA, which has become even more difficult as NASA has emerged as the "primary customer" for RPS.

This activity is one that requires active joint management by both the DOE and NASA. The years following the original 2009 RPS study have shown that formal and public yearly assessments of needs by NASA and DOE can help to maintain a solid operative plan and that a corresponding and regularly updated, public technology plan attached to consensus-based, flight-readiness requirements, all items called for in the 2009 RPS report, could provide beneficial tools for all of the stakeholders in tracking and managing the progress needed in implementing Decadal missions in the future. Such an effort is not trivial, nor should it be. The unfortunate debacle presented by the cancelled ASRG effort is yet another example in the line following the selenide and AMTEC converter dead ends, not of a management failure but of how technically difficult these efforts are. It also helps drive home the point that the GPHS-RTG technology was a technical result that should be seriously reconsidered for reestablishment as the backup to missions that do not need to operate in an atmosphere, yet cannot be carried out without RPS power. At the same time, the MMRTG remains vital for the exploration of Mars and the search for life there. Perhaps the lesson is that despite our best attempts, there is no "one size fits all" RPS converter technology, nor is there one on the horizon.

As President Kennedy said in unveiling the manned lunar program, as explorers and as Americans, we choose to do things not because they are easy but rather "because they are hard, because that goal will serve to organize and measure the best of our energies and skills, ..." These sentiments are no less true of our endeavors in space today.

No one, either at the launch site of Sputnik I in Kazakhstan or in Washington, D.C. learning of that event sixty years ago today would have predicted the incredible results, which we have all now witnessed, to be returned by robotic satellites operating throughout our solar system and along our first faltering steps to the stars. But making a thing look easy does not mean it is easy or that the effort was not worth it. Rather that apparent "easiness" is the reflection of the determination of the woman and men who have made it look so. We can continue on this path with new wonders to be beheld sixty years from now, or we can stop. It is an active choice, and that choice is ours, as we make the history for future generations to look back at. In the end, it really is all about us.

Summary

1. **Introduction**
   Launch of Sputnik 60 years ago
   Vanguard and solar cells
   Batteries – robust but limited lifetime
   SNAP development
   Selection of Pu-238 isotope

2. **The Next Steps Taken**
   Limitations of solar arrays with Sun distance
   SNAP 19 units on Nimbus III satellite to qualify for use on Pioneer 10 and Pioneer 11
   Applications closer to the Sun as well in other applications
   SNAP 27 for ALSEPs - Apollo 12, 14, 15, 16, and 17
   Modified SNAP 19s enabled the Viking 1 and 2 landers
   Voyager 1 and 2 followed Pioneer 10 and 11
   Multi-Hundred Watt (MHW) RPSs developed for LES 8 and 9
   GPHS modules with silicon-germanium converters enabled Ulysses, Galileo, Cassini, New Horizons
   None possible without these RPS power supplies

3. **Cassini at Saturn (graphics)**

4. **New Horizons at Pluto (graphics)**

5. **No Guaranteed Future for RPS**
   Issues for any future missions that required RPSs
   "Casani report" May 8, 2001
   Restart of domestic Pu-238 discussed
   Requirements from NASA: 2007 Mars Smart Lander (MSL), Europa Orbiter (EO), Pluto Kuiper Belt (PKB), Solar Probe, and 2011 Mars Sample Return (MSR) mission
   Stirling RPS and "new RTG" as a backup
   Eliminate risk of an all-Stirling program and continued high-use rate of Pu-238 in an all-RTG
   9/11 attacks - removal of the Mound facility in Miamisburg, Ohio to a new facility in Idaho
   "new RTG" that was the "backup" now became the primary item
   Conductive converter technology used in the SNAP 19 units used for "Multi-Mission RTG" or MMRTG.
   NRC RPS Committee: 13 findings, 3 recommendations, and 2 high-priority recommendations
      RECOMMENDATIONs. Flight Readiness and Technology Plan
      HIGH-PRIORITY. Plutonium-238 Production and ASRG Development
   Projected needs decreased with the termination of the Constellation program
   Responsibility for maintenance of the production infrastructure of Pu-238 transferred to NASA
   Need for ASRGs for future missions reiterated in *Vision and Voyages* document
   Converter technologies for RPSs have long remained technically difficult, expensive, and elusive: Selenide Isotope Generator (SIG) for Galileo, and Alkali-metal thermal to electric converter (AMTEC) for NASA's X-2000 program
   Lesson: development into usable flight hardware has proven to be a very, very difficult task

6. **Current Status and Perceived Needs**
   Scientific space community need for such RPS supplies has not gone away.

Missions to the outer solar system, Mars Sample Return campaign, landers on Mercury, rovers into the permanently shadowed regions of the Moon, missions to large KBOs, and Interstellar Probe also will require long-lived, high-efficiency systems
Voyager 1 and 2, now at their 40-year marks, will not outlast the 2020s
New Horizons will not outlast the 2030s;
The Nuclear Power Assessment Study (NPAS) of 2014 to 2015 reached ten, broad conclusions

7. **A Road Forward**
U.S. has developed a technology for powering spacecraft to regions of space not otherwise reachable.
Operating on the edge will never be cheap
Requires active joint management by both the DOE and NASA; not trivial, nor should it be.
President Kennedy: "because they are hard, because that goal will serve to organize and measure the best of our energies and skills, …."
Making a thing look easy does not mean it is easy or that the effort was not worth it
The choice is ours, as we make the history for future generations to look back at
It really is all about us.

RALPH L. McNUTT, JR. is a Physicist, member of the Principal Professional Staff, and Chief Scientist for Space Science in the Space Exploration Sector of The Johns Hopkins University Applied Physics Laboratory (APL). He received his B.S. in Physics (summa cum laude) at Texas A&M University in 1975 and his Ph.D. in Physics at the Massachusetts Institute of Technology in 1980. He has been at APL since 1992.

Dr. McNutt is Co-Investigator on NASA's Parker Solar Probe, Europa Clipper, New Horizons, Voyager Interstellar Mission, Member of the Ion Neutral Mass Spectrometer Team on Cassini, and Project Scientist and Co-Investigator on NASA's MESSENGER mission to Mercury.

From 2008 to 2009, he Co-Chaired (with General William Hoover) the Committee on Radioisotope Power Supplies, which produced the National Research Council (NRC) report "Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration," and in 2014 to 2015 he chaired a committee consisting of NASA and Department of Energy personnel that wrote the "Nuclear Power Assessment Study."

He has served on various other NASA and Academy panels as well.

He is a Member of International Academy of Astronautics (IAA) and elected Trustee Chair of its Basic Sciences Section (2017-2019 term), Associate Fellow of the American Institute of Aeronautics and Astronautics, Member of the American Astronomical Society, American Geophysical Union, Sigma Xi, The Planetary Society, and the American Nuclear Society.

Chairman BABIN. Thank you, Dr. McNutt. I recognize Ms. Oakley for five minutes to present her testimony.

TESTIMONY OF MS. SHELBY OAKLEY, DIRECTOR, ACQUISITION AND SOURCING MANAGEMENT, GOVERNMENT ACCOUNTABILITY OFFICE

Ms. OAKLEY. Good morning, Chairman Babin, Ranking Members Johnson and Bera, and Members of the Subcommittee. I am pleased to be here today as the simple analyst on the panel to discuss the current status of radioisotope production to enable future exploration.

As you know, radioisotope power systems, or RPS, have enabled many of our most ambitious exploration missions such as Curiosity and of course, Cassini. DOE has been providing RPS to NASA for over five decades. However, our continued capability to produce RPS is dependent on a ready supply of Pu-238, the highly radioactive isotope used to power RPS.

From the late '80s until recently we haven't produced any Pu-238 in the U.S., and our national stockpile that can be used in RPS is about 17.5 kilograms, about half of what was used in Cassini.

With one mission expected to use RPS, Mars 2020, and one that may potentially use RPS, New Frontiers 4, the Pu-238 stockpile could be exhausted as early as 2025.

In 2011, NASA began funding DOE's efforts to develop new Pu-238 through its Supply Project. Timeframes and costs for the Supply Project have shifted and increased since 2011, and it will be 2025 at the earliest until DOE expects it can reach its full production goal of 1.5 kilograms per year. Until it does, questions will remain about NASA's ability to plan for and execute scientific missions that rely on RPS as an enabling technology.

With this information as a backdrop, today I will discuss our recent work looking at how NASA selects RPS-powered missions, what factors affect such demand, and the progress and challenges DOE faces in meeting NASA's demand. Regarding mission selection, NASA officials acknowledge that the availability of Pu-238 has been a limiting factor for selecting missions that require RPS, particularly prior to the establishment of the Supply Project in 2011. For example, NASA did not offer RPS up for New Frontiers #3. Based on DOE's progress, NASA has now indicated that it is currently not a limiting factor but one of several factors it considers in mission selection. These other factors include scientific priorities and objectives, costs and timeframes, and policy direction.

NASA officials indicated they prioritize mission selection based on the decadal survey which represents the highest priorities of the scientific community and includes many missions that may require RPS.

According to NASA, it can only do two to three RPS missions using RPS per decade. Traditionally, RPS have been used on what NASA refers to as flagship missions. Flagships typically cost $2 billion or more and as our previous work has shown frequently experience cost overruns and schedule delays. As a result, the projected rate of these kinds of missions, due to their high cost, has allowed the demand for RPS to be met, at least in the near term. For other less expensive missions, the cost and time it takes to produce RPS makes their use a little more challenging. Finally, it is important to note that consistent with National Space Policy, NASA uses RPS for missions when it enables or significantly enhances the mission or when alternative power sources would compromise mission objectives. Sometimes it's evident that RPS is the only option, but other times more work is needed to determine if there's an alternative source available, such as solar, as was the case with the Europa Clipper mission.

Regarding supply, DOE is making progress toward producing new Plutonium-238. So far DOE has produced approximately 100 grams of new Pu-238 and has initiated efforts to ensure it has sufficient equipment and facilities to meet NASA's demand. However, DOE faces challenges in hiring and training the necessary workforce, perfecting and scaling up chemical processing, and ensuring the availability of reactors. That must be addressed or its ability to meet NASA's needs could be jeopardized.

Addressing these challenges will take careful planning and coordination. However, we've found that DOE and NASA could do more in this regard. For example, we found that DOE doesn't have a long-term plan in place that identifies interim steps and milestones to allow it to show progress in meeting production goals or how risks are being mitigated. We also found that DOE's prior approach to managing the work doesn't allow it to adequately communicate systematic risks to NASA and their potential on programmatic goals. Having such information would allow DOE and NASA to make adjustments to the program, if necessary, and better plan for future missions.

We made recommendations to DOE aimed at better planning and communicating risk. DOE concurred and has identified actions it's taking.

Chairman Babin, Ranking Member Bera, and members of the Subcommittee, this concludes my remarks. I'm happy to answer any questions that you have.

[The prepared statement of Ms. Oakley follows:]

United States Government Accountability Office

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Testimony
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SPACE EXPLORATION

Improved Planning and Communication Needed for Plutonium-238 and Radioisotope Power Systems Production

Statement of Shelby S. Oakley, Director,
Acquisition and Sourcing Management

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee:

I am pleased to be here today to discuss our recent work on radioisotope power systems. The National Aeronautics and Space Administration (NASA) has long used radioisotope power systems (RPS) to generate reliable electrical power and heat energy for long-duration space missions. RPS can operate where solar panels or batteries would be ineffective or impossible to use, such as in deep space or in shadowed craters, by converting heat from the natural radioactive decay of plutonium-238 (Pu-238) into electricity.[1] The Department of Energy (DOE) and its predecessor agencies have been providing Pu-238 and fabricating RPS for NASA and other federal agencies for more than 5 decades.[2]

In 2011, with funding provided by NASA, DOE initiated the Pu-238 Supply Project (Supply Project) to reestablish the capability to domestically produce Pu-238.[3] According to DOE documents and agency officials, DOE currently maintains about 35 kilograms (kg) of Pu-238 isotope designated for NASA missions, about half of which currently meets the power specifications for spaceflight. However, given NASA's current plans for solar system exploration, this supply could be exhausted within the next decade. Specifically, NASA plans to use about 3.5 kg of Pu-238 isotope for one RPS to power the Mars 2020 mission. NASA may also use an additional 10.5 kg of Pu-238 isotope for its New Frontiers #4 mission if three RPS are used.[4] If DOE's existing Pu-238 supply is used for these two missions, NASA would be forced to eliminate or delay future missions requiring RPS until DOE produces or acquires more Pu-238.

[1]Pu-238 is defined as Pu-238 oxide, also known as "heat source" plutonium oxide or "bulk-oxide", and is the form used to power RPS. Pu-238 isotope is a precursor to Pu-238 oxide.

[2]The Atomic Energy Act of 1954 authorizes DOE to provide systems that meet the special nuclear material needs of other federal agencies. Under a 1991 agreement with NASA, which was revised in 2016, DOE is responsible for maintaining our nation's capability to support the development, production, and safety of NASA's space exploration missions that use RPS.

[3]Historically, Pu-238 was produced domestically or was purchased from Russia. Domestic Pu-238 production ended in 1988, and DOE has not purchased material from Russia since 2009.

[4]NASA has offered up to 3 RPS for the New Frontiers Mission and plans to make a mission selection in July 2019.

My remarks today are based on our recent report on NASA's use of radioisotope power systems that are powered by plutonium 238,[5] which we are releasing today. Our report examined (1) how NASA selects RPS for missions and what factors affect NASA's demand for RPS and Pu-238; and (2) DOE's progress in meeting NASA's RPS and Pu-238 demand, and what, if any, challenges DOE faces in meeting the demand. Today, I will discuss the key findings and recommendations from that report.

For our report, we reviewed documentation on how NASA considered mission requirements during the agency's planning for recent missions that considered or used RPS as a power source. We also interviewed officials from the Planetary Science Division (PSD) of NASA's Science Mission Directorate and from the Human Exploration and Operations Mission Directorate. In addition, we reviewed documentation related to DOE's efforts to develop the Supply Project and DOE's RPS production process. We also interviewed officials from DOE's Office of Nuclear Energy as well as officials involved in RPS work at three DOE national laboratories—Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), and Oak Ridge National Laboratory (ORNL)—and conducted site visits to ORNL and INL. More detailed information on the objectives, scope, and methodology of our work can be found in the September report. The work upon which this statement is based was conducted in accordance with generally accepted government auditing standards.

In summary, we found that NASA selects RPS for missions based primarily on scientific objectives and that several factors may affect NASA's demand for RPS and Pu-238. For example, RPS have been typically used on NASA's most expensive and highest priority missions. Based on expected funding levels, NASA can only support two or three of these missions per decade. We also found that DOE has made progress meeting NASA's demand for RPS and Pu-238, but the agency faces some challenges in reaching full production goals. For example, DOE does not maintain a comprehensive system for tracking RPS production risks. In addition, DOE's management approach does not allow for the agency to adequately communicate long-term production challenges to NASA. We made several recommendations to DOE to address these

[5] GAO, *Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges,* GAO-17-673 (Washington, D.C.; Sept. 8, 2017).

issues. DOE agreed with our recommendations and outlined actions it planned to take to address them.

Background

RPS are long-lived sources of spacecraft electrical power and heating that are rugged, compact, highly reliable, and relatively insensitive to radiation and other effects of the space environment, according to NASA documentation. Such systems can provide spacecraft power for more than a decade and can do so billions of miles from the sun. Twenty-seven U.S. missions have used RPS over the past 5 decades. The current RPS design, the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), converts heat given off by Pu-238 into about 120 watts of electrical power at the beginning of its life—a 6 percent power conversion efficiency. One MMRTG contains 32 general purpose heat source (GPHS) fuel clads in the form of pressed Pu-238 pellets encapsulated in iridium.

NASA's PSD science portfolio includes a wide array of missions that seek to address a variety of scientific objectives and answer many questions about the solar system, from how life began to how the solar system is evolving. Scientific and mission objectives influence the types of equipment needed for the mission, including the mission's power source. According to NASA officials we interviewed, missions in NASA's PSD portfolio are generally classified in three ways:

- **Flagship.** Flagship missions are the largest and most expensive class of NASA's missions, costing $2 billion or more, and are given the highest priority for resources, including funding, infrastructure, and launch support. Past Flagship missions that have used RPS include the Galileo, Cassini, and Curiosity missions. NASA's Mars 2020 mission is a planned Flagship mission using RPS.
- **New Frontiers.** New Frontiers missions focus on enhancing our understanding of the solar system and have a development cost cap of $850 million.[6] To date, there has been one New Frontiers mission using RPS (New Horizons).
- **Discovery.** Missions in the Discovery program have a development cost cap of $450 million to $500 million and have shorter development

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

time frames, according to NASA officials and documentation. No Discovery mission has been powered by RPS.

DOE oversees the design, development, fabrication, testing, and delivery of RPS to meet NASA's overall systems requirements, specifications, and schedules. DOE's goal under its Supply Project is to reach a full Pu-238 production rate of 1.5 kg per year by 2023, at the earliest, with a late completion date of 2026. DOE also established an interim production rate of 300 to 500 grams per year by 2019, to ensure an adequate supply of Pu-238 for NASA's near-term missions, before the full production rate goal is achieved. The Supply Project involves a number of steps across several DOE national laboratories, including the use of two DOE research reactors—the High Flux Isotope Reactor at ORNL, and the Advanced Test Reactor at INL.

NASA began fully funding DOE's Supply Project in 2011, and since 2014, has been responsible for funding all aspects of RPS production operations, according to NASA documents.[7] NASA funds DOE's efforts to build, test, and fuel RPS, as well as to update equipment and sustain staffing levels associated with RPS production between missions. Since 2014 NASA has provided, on average, approximately $50 million per year to support DOE's ongoing operations and maintenance of RPS production equipment. Since its inception until early 2017, DOE has used a short-term and incremental segmented management approach to manage the Supply Project.[8]

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

[8]Under this management approach, DOE established short-term segments of Supply Project work to be connected to time frames over which DOE could more reliably predict funding from NASA.

NASA Selects RPS for Missions Based Primarily on Scientific Objectives, and Several Factors May Affect NASA's Demand for RPS and Pu-238

NASA selects RPS to power its missions primarily based on scientific objectives and mission destinations. According to NASA officials we interviewed, the need for RPS is usually apparent based on the mission's scientific objectives and destination. For instance, an RPS is more likely to be needed for a mission to a distant planet, where minimal sunlight reduces the effectiveness of solar power. NASA officials we interviewed stated that, consistent with the National Space Policy, the agency uses RPS when they enable or significantly enhance a mission, or when alternative power sources, such as solar power, might significantly compromise mission objectives.[9] NASA prioritizes mission selection based on missions identified in the National Academy of Sciences' decadal survey report, which represents the highest priorities of the scientific community and includes many missions that require the use of RPS.[10]

Prior to the establishment of DOE's Supply Project in fiscal year 2011, NASA officials we interviewed stated that mission selections were influenced by the limited amount of available Pu-238. These same officials told us that missions are now selected independently from decisions about how they will be powered. However, projected availability of Pu-238 is factored into whether an RPS is available for a specific mission opportunity.

In addition to the scientific objectives of planned and potential space exploration missions, several other factors may affect NASA's demand for RPS and Pu-238:

- **Costs associated with missions that typically require RPS.** According to NASA officials, RPS have typically been used on Flagship missions that cost $2 billion or more. NASA can support no more than one mission using RPS about every 4 years—or two to three missions per decade—based on expected agency funding levels.

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

[10]The National Academy of Sciences' decadal survey report presents a 10-year program of science and exploration with the potential to yield revolutionary new discoveries. The National Aeronautics and Space Administration Transition Authorization Act of 2017 states that the NASA Administrator should set science priorities by following guidance provided in this decadal survey report.

- **Cost of RPS relative to mission costs.** According to NASA officials, New Frontiers missions may be good candidates to use RPS; however, given the cost cap for this mission class, one RPS would account for about 9 percent of the mission's budget, while three RPS would account for almost 14 percent. For Discovery missions, for which the cost of using RPS would represent a large portion of a Discovery mission budget, a single RPS would represent more than 17 percent of a mission's development cap.
- **DOE's production capability.** According to DOE officials we interviewed, it can take up to 6 years to acquire, fuel, test, and deliver a new RPS for a NASA mission. According to DOE and NASA officials we interviewed, given the current floor space dedicated to RPS development at INL and limits on staff exposure to radiation at LANL, DOE only has the capacity to produce three to four RPS at one time. To accommodate DOE's current RPS production capability, NASA officials we interviewed said they will not select two consecutive missions requiring RPS.

Technological advances may reduce the demand for Pu-238 and thus RPS. For example, according to NASA officials, advances in solar power technology have realistically expanded the ability to use solar power for missions for which it would not have been considered before, and these advances could help address low levels of light intensity for deep space missions. NASA also is developing new RPS technologies that may reduce its demand for Pu-238 and thus RPS. For example, NASA officials told us that they plan to invest in dynamic RPS technology that could increase RPS efficiency and require less RPS to achieve mission power. NASA research indicates that dynamic RPS designs could be more than four times as efficient as the current MMRTG design.[11]

The Supply Project goal of producing 1.5 kg of Pu-238 per year was established to support two to three PSD missions using RPS each decade, and NASA does not anticipate other potential users to affect demand for RPS or Pu-238, according to NASA and DOE officials and documentation we reviewed. DOE planning documents and NASA officials we interviewed stated that current RPS and Pu-238 production levels expected from the Supply Project are intended to only meet PSD's

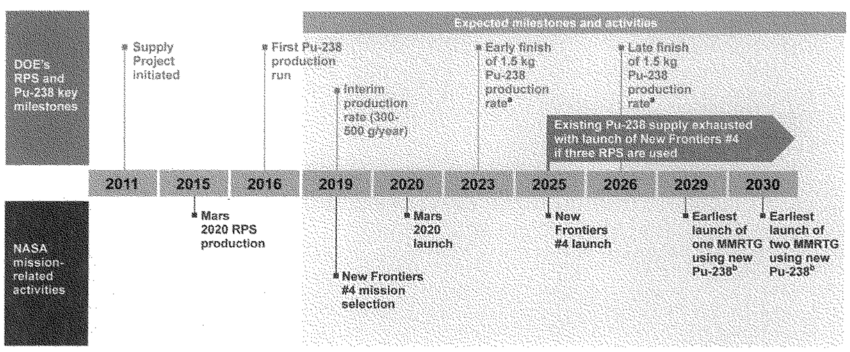
[11]In addition, new thermoelectric materials being researched by NASA may lead to increased RPS efficiency. One such material, skutterudite, could result in an RPS with a 25 percent beginning-of-life efficiency improvement and a 50 percent increase of end-of-life power output when compared to the current MMRTG.

demand. NASA officials said that they did not account for potential demand from other potential users within NASA, the national security community, or commercial sectors when establishing current Pu-238 production goals.

DOE Has Made Progress Meeting NASA's RPS and Pu-238 Demand, but Faces Challenges Reaching Full Production Goals

DOE has made progress meeting NASA's future demand for Pu-238 to fuel RPS. A chronology of key DOE planned RPS and Pu-238 production activities, and NASA's mission-related activities, are shown in figure 1.

Figure 1: Chronology of Key Department of Energy and National Aeronautics and Space Administration Radioisotope Power Systems and Plutonium-238 Production Activities



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

Source: GAO analysis of DOE and NASA information. | GAO-18-161T

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

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

DOE demonstrated a proof of concept for new Pu-238 production, and has made approximately 100 grams of new Pu-238 isotope under its Supply Project, since the project's inception in 2011. However, given DOE's Supply Project and RPS production schedule, and NASA's current space exploration plans to use up to four RPS for its Mars 2020 and New Frontiers #4 missions, DOE's existing Pu-238 supply will be exhausted by 2025.

Moreover, DOE officials we interviewed from INL, LANL, and ORNL identified several challenges, including perfecting and scaling up chemical processing and the availability of reactors, that need to be overcome for DOE to meet its projected Supply Project goal of producing 1.5 kg per year of Pu-238 by 2026, at the latest. If these challenges are not overcome, DOE could experience delays in producing Pu-238 to fuel RPS for future NASA missions.

DOE's ability to meet its production goal and support future NASA missions is at risk if certain steps for chemical processing necessary for the production of Pu-238 are not improved and scaled up. According to DOE officials we interviewed, DOE is still in the experimental stage and has not perfected certain chemical processing measures required to extract new Pu-238 isotope from irradiated targets, creating a bottleneck in the Supply Project and putting production goals at risk.

In addition, reactor availability will be necessary for DOE to achieve its Pu-238 production goals. Officials we interviewed at INL and ORNL said that achieving 1.5 kg of Pu-238 per year is contingent on the availability of positions within both the High Flux Isotope Reactor (HFIR) and the Advanced Test Reactor (ATR) to irradiate neptunium targets for conversion to Pu-238 isotope.[12] DOE officials said HFIR can produce approximately 600 grams of Pu-238 isotope and they plan to use

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

positions within ATR to achieve full production goals; however, ATR has not been qualified for Supply Project work. In addition, DOE officials said that ATR's availability for the Supply Project may be limited due to competition from other users. DOE officials said that they will be unable to meet full Pu-238 production goals if positions in ATR, which are already over-utilized, are not available for Pu-238 isotope production and that they do not have a plan to address this challenge.

These and other challenges identified in our September 2017 report may place DOE's RPS and Pu-238 production goals at risk, in part, because of the short-term and incremental segmented management approach DOE had used to manage the Supply Project since its inception in 2011 through early 2017. In March 2017, DOE officials we interviewed said that the agency anticipated moving to a constant GPHS production rate approach to help provide funding flexibility and stabilize RPS production staffing levels between NASA missions. In June 2017, DOE officials we interviewed said that implementing a constant GPHS production rate approach would also address other previously identified challenges associated with RPS production and the Supply Project and therefore decided to discontinue its short-term and incremental segmented management approach.

However, DOE officials we interviewed did not describe how the new constant GPHS production rate approach would help them address some of the longer-term challenges previously identified by the agency, such as scaling up and perfecting chemical processing. We found that DOE has yet to develop an implementation plan for the new approach, with defined tasks and milestones, that can be used to show progress toward assessing challenges, demonstrate how risks are being addressed, or assist in making adjustments to its efforts when necessary. Our previous work has shown that without defined tasks and milestones, it is difficult for agencies to set priorities, use resources efficiently, and monitor progress toward achieving program objectives.[13]

In our September 2017 report, we recommended that DOE develop a plan that outlined interim steps and milestones that would allow the

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

agency to monitor and assess the implementation of its new approach for managing Pu-238 and RPS production. DOE agreed with our recommendation and noted it was in the process of implementing an approach for the RPS supply chain that was more responsive to NASA's needs, among other things. DOE also noted that it was developing an integrated program plan to implement and document the agency's new approach and expected this to be completed in September 2018. We believe that the development of an integrated program plan is an important step and that any such plan should include defined tasks and milestones, so that DOE can demonstrate progress toward achieving its RPS supply chain goals.

In addition, in our September 2017 report we identified another factor that could undermine DOE's ability to inform NASA about previously identified challenges to reach its full Pu-238 production goal. We found that DOE does not maintain a comprehensive system for tracking RPS production risks and, instead, relies on individual laboratories to track and manage risks specific to their laboratories. *Standards for Internal Control in the Federal Government* call for agency management to identify, analyze, and respond to risks related to achieving defined objectives.[14] We recommended that DOE develop a more comprehensive system to track systemic risks, beyond the specific technical risks identified by individual laboratories. Doing so would better position DOE to assess the long-term effects of the challenges associated with its Pu-238 and RPS production objectives. DOE agreed with our recommendation and stated that the agency would include steps to ensure that its risk assessment system would include comprehensive programmatic risks.

Finally, in our September 2017 report we found that DOE's new approach to managing RPS and Pu-238 production does not allow for DOE to adequately communicate long-term challenges to NASA. It is also unclear how DOE will use its new management approach to communicate to NASA challenges related to Pu-238 production. As a result, NASA may not have adequate information to plan for future missions using RPS. *Standards for Internal Control in the Federal Government* call for agency management to use quality information to achieve agency objectives and communicate quality information externally through reporting lines so that external parties can help achieve agency objectives and address related

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

risks. In our September 2017 report, we recommended that DOE assess the long-term effects that known challenges may have on Pu-238 production quantities, time frames, and required funding, and communicate these potential effects to NASA. DOE stated that it agreed with our recommendation and would work with NASA to identify, assess, and develop plans to address known challenges. DOE also stated that the agency expected to complete this effort in September 2019.

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, this concludes my prepared statement. I would be pleased to respond to any questions that you may have at this time.

GAO Contact and Staff Acknowledgments

If you or your staff have any questions about this statement, please contact Shelby Oakley at (202) 512-3841 or OakleyS@gao.gov. In addition, contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this statement. Individuals who made key contributions to the report on which this testimony is based are Jonathan Gill (Assistant Director); Samuel Blake, Kevin Bray, John Delicath, Jennifer Echard, Cindy Gilbert, Timothy Guinane, John Hocker, Michael Kaeser, Jason Lee, Tim Persons, Danny Royer, Aaron Shiffrin, Kiki Theodoropoulos, Kristin VanWychen, and John Warren.

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Shelby S. Oakley

Ms. Oakley is currently serving as a Director in GAO's Acquisition and Sourcing Management (ASM) team where she has responsibility for GAO's work on Navy Shipbuilding, VA procurement, whistleblower protections, and GAO's annual review of major weapon systems (a.k.a. Quicklook). Prior to returning to ASM, Ms. Oakley served as an Acting Director in GAO's Natural Resources and Environment (NRE) team for two years. While in NRE, she led teams reviewing a range of nuclear related issues. From 2004 to 2015, Ms. Oakley led reviews of the activities of NASA with a focus on helping NASA improve its acquisition management practices. Her reviews have covered key aspects of NASA's operations, such as Space Shuttle workforce transition and sustainment of the International Space Station, as well as reviews of all major NASA systems including in depth reviews of NASA's human spaceflight programs and the James Webb Space Telescope. Ms. Oakley has been with GAO for 16 years. She earned a Master's Degree in Public Administration from the University of Pittsburgh's Graduate School of Public and International Affairs and received her Bachelor of Arts Degree in both Psychology and Sociology from Washington and Jefferson College.

Chairman BABIN. Thank you, Ms. Oakley. I thank the witness for your testimony and all of the witnesses. The Chair recognizes himself for five minutes, and I'm going to ask a question of Mr. Schurr. But I would like to—answer it as briefly as you possibly can but cogently, of course, and then I want to try to get in as much as I possibly can from some of the rest of you folks.

Mr. Schurr, your testimony states that NASA has approximately 35 kilograms of plutonium dioxide. You also stated that NASA expects DOE to begin initial operations of Pu-238 production in 2019 with a goal of producing 400 grams of plutonium dioxide annually and ramping up to 1.5 kilograms per year by 2025. Finally, you stated that this production rate would satisfy expected NASA Planetary Science mission requirements through 2030. Of the 35 kilograms of Pu-238 allocated to NASA, how much of that is viable for use in an RPS system for spaceflight?

Mr. SCHURR. Currently about 17 kilograms of the 35 meets the specifications for our use for spaceflight. So what's valuable to us is as we start ramping up the initial production of the new plutonium which will be at a higher assay, a hotter material, we'll be able to blend that with the remaining 18 kilograms or so that is not to specification.

So in the short term, the missions that we've got with Mars 2020 and a potential mission in 2025, we have all the materials that we need for a mission in the 2030 timeframe when we'll rely upon the new production to blend with the rest of the material that's in inventory that's not up to specification.

Chairman BABIN. Okay. Thank you. Does your assessment that planned production will meet NASA requirements assume the use of multi-mission radioisotope thermoelectric generator technology or advanced sterling radioisotope generators technology?

Mr. SCHURR. At the moment, we're assuming the MMRTG is the baseline since the ASRG does not exist and it's not in our inventory. But we are looking at alternatives and improvements to the basic MMRTG technology. But right now we assume that's our baseline.

Chairman BABIN. Okay. Thank you. How much Pu-238 does an MMRTG require versus an ASRG?

Mr. SCHURR. The MMRTG uses 4.8 kilograms of plutonium dioxide, and the ASRG is 1/4 as much for the same amount of power.

Chairman BABIN. Okay. Just wondering if we need more Pu-238 than we're thinking. Does your assessment that planned production will meet NASA requirements also factor in the potential needs of the human exploration community?

Mr. SCHURR. At this point, we're not making any assumptions about needs for human exploration, Mars or elsewhere. If for human spaceflight we determine that there's a value for Pu-238 in their activities, it would likely require an increase in production. And that's part of what we're working with DOE, what are our options to do a higher rate of production if needed.

Chairman BABIN. Okay. Thank you. And lastly, if some portion of NASA's existing stockpile of 35 kilograms of Pu-238 is not currently flight worthy and NASA's assessed need for future missions is based on systems that are more efficient than we currently produce, does NASA only need 1–1/2 kilograms per year for Pu-238 from DOE to meet its existing demands or could it use more? And also, what are we losing by not employing RPS for human missions?

Mr. SCHURR. There's a lot in there. We certainly could do more missions at a higher rate, but the number of missions that we can go do in, you know, a decade for instance, is also constrained by how much budget we have for the missions of that scale as well as the other activities that we're doing in the Planetary Science.

So what we've been trying to do is get a balance right between what we think is a reasonable forecast in making sure that we've got the capability and the plutonium available to meet that forecast.

Chairman BABIN. Okay. Thank you. Ms. Tracey, based on the National Nuclear Security Administration's Global Threat Reduction Initiative, DOE committed in 2012 to convert all research reactors to a low-enrichment fuel for non-proliferation concerns. The high flux isotope reactor at Oak Ridge National Laboratories is approaching 60 years of age and uses highly enriched fuel. What is the certainty of continued use and availability of HIFR, H–I–F–R?

Ms. BISHOP. Thank you for the question. The mission for HIFR is continuing on within the Department. My organization, along with other elements in the Department, continue to work with the National Nuclear Security Administration regarding efforts to convert the research reactors from highly enriched uranium to low-enriched uranium fuel. At this time I do not have any indications regarding impact to future missions or the ability to impact NASA's goal to produce Plutonium-238.

Chairman BABIN. Okay. Thank you. I have a lot more, but my time has expired. So we will go to the gentleman from California, Mr. Bera.

Mr. BERA. Thank you, Mr. Chairman. We currently have 35 kilograms of Pu-238. Is that our current stockpile, Mr. Schurr?

Mr. SCHURR. That's correct.

Mr. BERA. And there was a time where we were purchasing Pu-238 from Russia, but Russia has now indicated they either don't have the supplies or is it that they don't want to sell us supplies, Mr. Schurr?

Mr. SCHURR. I have to admit, all those activities pre-dated me and have been closed down for a while.

Mr. BERA. Okay.

Mr. SCHURR. I don't know if Tracey, if you've got anything to add to that.

Ms. BISHOP. Those discussions also pre-dated my involvement.

Mr. BERA. Okay. So regardless, they may have supplies but they don't want to sell them to us or they no longer have supplies.

Mr. SCHURR. We currently have no negotiations or discussion going on with the Russians regarding Pu-238.

Mr. BERA. And it's reasonable to assume that there are no other countries currently capable of producing Pu-238 that we know about?

Mr. SCHURR. That's correct.

Mr. BERA. In thinking about what our needs are by 2025, we've got the 35 kilograms. What would you say our needs are between now and 2025, Mr. Schurr?

Mr. SCHURR. The most that we can envision that we would use between now and 2025 is about the 17 kilograms that's within specification. Through 2030, we could possibly use that full 35, but we would have to bring the rest of it up within specification. And that's where the new production is required.

Mr. BERA. Okay. And we would—I think the chairman asked questions if there are missions we'd consider without the RPS? But it wouldn't make sense I think if we're going to deeper space not to have that ability to collect and communicate.

Mr. SCHURR. That's correct. We have now demonstrated we can do missions as far away from the sun as Jupiter. The Juno mission is currently there, the Europa Clipper mission will be going there. I've seen proposals that can go as far as Saturn for fairly limited missions, but beyond that, solar power is not really going to be useful and we need an alternative source, such as RPS.

Mr. BERA. Okay, and we'd certainly want to have some certainty that we're not, you know, sending a mission pretty far out and not certain whether solar power—

Mr. SCHURR. Correct. And we have high-priority missions that are out to Uranus and Neptune that are part of our decadal survey that we want to maintain the ability to service.

Mr. BERA. Great. Is there any science going into other alternative fuel sources or is it Pu-238 that is the source that we have to be using? And is all the science on improving conversion, blending it, making it a bit more efficient?

Mr. SCHURR. There's been a lot of work historically looking at what are the best isotopes to use for power conversion. Pu-238 tends to come up on top for many reasons as one of the best. And the infrastructure is in place today. So as far as isotopes go, we wouldn't really look at a different radioisotope. There's possibility that fission might be developed in the future, and we'll look at what missions a fission system could possibly support. But likely it's not everything we're trying to do with planetary exploration. We're also looking at what are the different power conversion technologies. How can we advance thermocouples to be more efficient than what we've got right now? We have a technology project underway today to improve thermocouple efficiency, and we're also continuing to explore dynamic power which is the basis for the ASRG to see if we can come up with a more efficient system there.

Mr. BERA. Dr. McNutt, would you have some thoughts on this as well?

Dr. MCNUTT. Well, I think that David put the case fairly well. Certainly the idea of being able to have a dynamic converter is something that we've been talking about for a long, long time. And the problem is these have always fallen short. There are technical reasons. There's a lot of concern about whether that if one had a dynamic power system, is that something that you really want to rely upon, having the moving parts? And there's a great deal of debate back and forth in the community about that.

So as I mentioned, certainly the GPHS, RTGs, these are the ones that were used on Cassini, Galileo, Ulysses, New Horizons. Those were sort of the top-level power supplies we were able to put together which will work in a hard vacuum. They won't work on the surface of Mars for technical reasons. And again, they're the sort of thing that we've sort of backed away from, partially because we were looking for the one-size-fits-all kind of a unit.

With respect to other isotopes, David is actually absolutely right. That sort of thing has been examined over and over and over again, a great deal in the 1950s, the 1960s especially, and for all sorts of technical reasons, Plutonium-238 in the dioxide form is the only thing that really makes any sense.

Mr. BERA. So if we're projecting into the future past 2025 and further, we know more of the international community is getting involved and thinking about space exploration as we go into deeper and deeper space. It is my perspective that we will be doing that in partnership with the international community. You know, if we do more human space exploration, whether it's human exploration of Mars, et cetera, we'll also need reliable energy sources, et cetera. It's not easy to produce Pu-238 obviously. We potentially become the only supplier of Pu-238 with missions that are beyond what we're just thinking about within NASA and our own scope. And I'm not sure we want other countries producing Pu-238 or encouraging that. That wouldn't necessarily be a good thing.

So one thing that I would urge us to also think about as we're ramping up production beyond 2025 is how do we meet the international community's needs potentially as well? Am I thinking about this correctly? Because again, I don't think we want other countries exploring Pu-238 production.

Dr. MCNUTT. Well, certainly one of the things that's happened in the United States, if you look at inflation-adjusted dollars, there's been about $6 billion that went into developing these supplies. And of course, we've already had that kind of an international partnership because the Ulysses spacecraft was actually built by the European Space Agency but we provided the GPHS–RTG that actually enabled that mission. And there have been other discussions with other space agencies, notably with—VESA, about trying to duplicate that or replicate that, having similar things go ahead in the future.

But the bottom line is as David was saying is that once you get beyond Jupiter and especially with some of the things you'd still like to do with Jupiter, you just simply cannot do them without this. And the United States is the premier developer of the technology, the owner of the technology, the owner of all of the intellectual property. We're the ones that know how to do this. It's been a very hard-fought battle getting to that point, and it's something that I think most members of the Science Committee would hope that we don't lose.

Mr. BERA. I would hope so as well. Thank you, sir.

Chairman BABIN. Yes, sir. The gentleman's time has expired. Now let's go to the gentleman for California, Mr. Knight.

Mr. KNIGHT. Thank you, Mr. Chair. I'm going to go in a little bit different direction, probably to Mr. Schurr or Dr. McNutt. Are ASRGs, are they already assumed in deep space explanation, NASA is already taking them into effect or into account?

Mr. SCHURR. The ASRG project itself, the flight project was cancelled back in 2013. So right now we don't build it into any of our forecasts for future needs as a system that would be available to us. We're still investing in the technology to see if we can develop the technology from that. But we don't build it into any of our forecasts.

Mr. KNIGHT. Okay. So if we go down the road of going to Mars in the next 16 or 17 years as the bumper sticker says—if my good friend from Colorado would be here, Ed Purlmutter, he would have his bumper sticker out there. If we assume we're going to make it there in the next 16 years, a lot of these efforts have got to be or a lot of these problems have got to be fixed. One of them is the propulsion. Obviously the number one is the radiation, to make sure that our astronauts get there and they get back safely. That's always the number one mission.

If we are going to get there a little faster to make sure that the radiation impact is lessened because of less travel time, is that going to be a part of a new propulsion system or is that going to be a propulsion system that might be nuclear powered?

Mr. SCHURR. I don't believe there's a relationship between the Stirling power conversion and the NTP, Nuclear Thermal Propulsion. So you see, the sterling gets involved when you want to convert the heat that comes out——

Mr. KNIGHT. Right.

Mr. SCHURR. —of the reactor into electricity.

Mr. KNIGHT. Right. Okay. But again, if I just follow that question or that line of thinking, we're going to need that kind of propulsion system to get us there quicker, is that correct?

Mr. SCHURR. I actually have to admit that's not my field of expertise. So in the Planetary Science, our focus is on the power conversion. And I know we have folks in our space technology organization that are working on NTP.

Mr. KNIGHT. Okay. And now I'm going to go back to what the Chairman said, about the 35 kilograms. If we have enough to make sure that we're going through 2025 or 2030 and the conversion of this 35 kilograms is proper, we have enough, wouldn't the ASRGs be a part of that at some point to make sure that we have the burn rate or the conversion rate or some other technology? It could be something else.

Mr. SCHURR. If we're able to develop a dynamic technology that is four times more efficient, we'd be able to stretch the supply to conduct four times more missions or larger missions. So it is something we are investing in to see if we can make it work.

It is technology that would also be applicable to any human-based usage with a fission-based system, if one were developed. So the technology has multiple uses, any heat source conversion to electricity. So it is an area that we're going to continue to invest in. Whether it makes sense for planetary missions or not, we have to solve some of the issues that Dr. McNutt was referring to. A dynamic power system with moving parts that can't be maintained for 20 years, you have to make sure there's enough reliability in the system. But those are the things that we're investigating.

Mr. KNIGHT. Okay. Very good. I yield back the balance of my time.

Chairman BABIN. Okay. Nobody down there. The gentleman from Florida, Mr. Posey.

Mr. POSEY. Thank you very much, Mr. Chairman. Questions for each member of the panel. Are you aware of any destruction of the United States' supply of Pu-238 in the past?

Mr. SCHURR. I'm going to defer to my colleague from the Department of Energy.

Ms. BISHOP. Sir, I'm not aware of any destruction of Pu-238.

Mr. POSEY. Anyone else hear any rumors of it at all? Okay. In 2004 we had Dr. Jim Green, Director of NASA's Planetary Science Division here, and he indicated there was absolutely no problem whatsoever with future supplies of Pu-238. And Mr. Schurr, you've kind of indicated the same thing, but the Inspector General leads me to believe there might be a problem with it. What's the deal here?

Ms. OAKLEY. I think what we were trying to convey in our report was more that there was a limiting factor, the Pu-238 was a limiting factor in the early part of this decade. That coupled with a lot of really significant overruns on Planetary Science missions I think limited even the number of missions that Planetary Science could undertake, let alone the ones that would need Pu-238.

Right now based on the development of new Pu-238 blended with the old, the needs are met in the near term. Our report tries to convey the fact that if this new supply of Pu-238 isn't established and the goals aren't met by DOE, then it could become a limiting factor again in the future.

Mr. POSEY. Well, I would think, and it's common sense, that if we know we're going to need more in the future, we would have some plan, some coordination between NASA and DOE to furnish a supply or produce a supply. And the information that I seem to be getting is there really is no firm coordination or agreements or efforts to do that at this point.

Mr. SCHURR. I think I'd say it a little bit differently. In 2012 we kicked off with the Department of Energy a restart of the plutonium production project. So we've been investing since 2012.

Mr. POSEY. Okay. Now, bring me up to date on that. Where's that progressed to? At what point are you in now?

Mr. SCHURR. We've now produced up to 200 grams?

Ms. BISHOP. We've produced 100 grams——

Mr. SCHURR. 100 grams.

Ms. BISHOP. —of new material. We have a second campaign underway that should end this fall that's going to produce approximately the same amount of material. And we are continuing our efforts to reestablish our infrastructure and our pipeline to produce the rates that NASA requires to support their mission activities.

Mr. POSEY. And does NASA's request take into consideration maybe a loss of a launch and might need to replace that?

Mr. SCHURR. Not specifically, but since the only firm mission that's on our books right now is the Mars 2020 mission, we clearly would have the ability to replace one MMRTGs' worth of fuel if we were asked to do so.

Mr. POSEY. Well, I've heard the 35 that we have now potentially being utilized by 2025, is that correct?

Mr. SCHURR. About half of that could be used by 2025. The other half needs the blending of the new material and would cover our needs through at least 2030.

Mr. POSEY. And beyond 2030?

Mr. SCHURR. We would need the new production that's coming on line which should be to full operational capability by 2025. And at that point, we're already starting the discussions about whether we want to raise the rates if we need it for future forecasts.

Mr. POSEY. Okay. Thank you, Mr. Chairman.

Chairman BABIN. Yes, sir. Thank you. I'd like to call on the gentleman from Florida, Mr. Dunn.

Mr. DUNN. Thank you very much, Mr. Chairman. Let me start if I may with Mr. Schurr and Ms. Bishop. How does NASA communicate their needs regarding the RPS for Pu-238? How do you communicate with each other, and do you feel like you've got enough lead time on that?

Mr. SCHURR. I mean, we have regular processes. We have a monthly management review where we sit down and look at all of the progress in their activities as well as talk about any changes in our activities. Then we have a formal process. It's part of the annual budget cycle where——

Mr. DUNN. You feel like you're interconnecting well, both of you?

Mr. SCHURR. Yes, I would say so.

Ms. BISHOP. Yes, I would agree.

Mr. DUNN. Okay. For Ms. Oakley, does DOE have an assessment of the total cost requirements to upgrade the facilities to undertake the Plutonium-238 production? And who pays for that?

Ms. OAKLEY. Well, the bottom line is that NASA will bear the cost, most of the cost, to upgrade the facilities and prepare all of the——

Mr. DUNN. That's not spread over any of the other users of 238?

Ms. OAKLEY. No.

Mr. DUNN. Pu-238.

Ms. OAKLEY. Not that I understand. No, and NASA is the primary user right now, and NASA is responsible for reestablishing the capability for the United States. So they've been providing the funding to DOE through the Supply Project since 2011.

And so I think that if you want to talk about costs, this is one of the criticisms in our report that we had is that prior to recent changes that Ms. Bishop discussed, the Supply Project was being managed in a very segmented, short-term approach because of uncertainties about funding that would be available in any given year. So it was really difficult to project how much this was going to cost overall.

So in the beginning we were being told it was about $85 to $125 million to reconstitute this effort. Now it's looking like it's going to take a little bit longer and be more upwards of about $235 million. That being said because of the way the project was being managed before, we don't know exactly if this is a realistic accounting of risks that are involved in reestablishing that project.

Mr. DUNN. Do I misunderstand, does DOE—you're producing this Pu-238 also or 239 for weapons?

Ms. BISHOP. That's not my area of——

Mr. DUNN. Not yours but DOE is the one doing it, right?

Ms. BISHOP. The Department of Energy is producing Plutonium-238 to support the mission requirements.

Mr. DUNN. So are those two parts of DOE talking to each other? I mean, we're making the stuff, so maybe they can get some—NASA doesn't have to start all over?

Ms. BISHOP. No, we coordinate very closely with NASA regarding mission needs as well as their requirements for plutonium. Also with our arrangement with NASA, the Department employs full-cost recovery. So we go forth and look at the infrastructure that NASA needs. If it is shared infrastructure, for example at Los Alamos National Laboratory where the infrastructure is shared with other national security customers, there is a cost-sharing arrangement. So the——

Mr. DUNN. Have you now reprocessed all of the Russian plutonium we got from the warheads at the end of the Cold War?

Ms. BISHOP. No. The Russian material is still part of the stockpile that we currently have available.

Mr. DUNN. That 17.5 or 35 whatever——

Ms. BISHOP. The 35 kilograms, yes.

Mr. DUNN. Okay. So that's the last of it?

Ms. BISHOP. Yes.

Mr. DUNN. That's it? Okay. Just turn for a moment there. I think this is a Mr. Schurr question. Please compare the relative development levels. Which is ready first, the MMRTG, the ASRG, and the kilopower fission system? Which one can we expect to be on line first?

Mr. SCHURR. Well, the MMRTG is active today on the Mars Science Lab that's on Mars. So we started developing that one back around 2001 or so, and it's operational. We've got two more copies of that that were built at the same time. One of those will go on the Mars 2020 mission that will launch in 2020. So that's the system that we have in hand. It's ready to go. We can build more copies of that, and DOE builds those for us. We are making technology investments in potential enhancement——

Mr. DUNN. I understand you're stalling the ASRG, right?

Mr. SCHURR. The ASRG, we are just looking at the technology——

Mr. DUNN. Okay.

Mr. SCHURR. —basic conversion technology itself right now.

Mr. DUNN. How about the kilopower?

Mr. SCHURR. Kilopower is investigation that other parts of the agency are looking at for potential fission systems.

Mr. DUNN. Purely investigational at this point?

Mr. SCHURR. It's still technology development.

Mr. DUNN. So I'm going to try to squeeze one more question in here if I may, Mr. Chairman. So is there any chance that we can make this plutonium power available to commercial partners, the commercial sector? And is that legal, going for other missions——

Mr. SCHURR. We haven't spent any time working on that.

Ms. BISHOP. Yeah, I don't have information.

Mr. DUNN. So that's a novel idea to you?

Mr. SCHURR. We certainly haven't had any asks for it.

Mr. DUNN. Okay. Thank you very much, Mr. Chairman. I yield back.

Chairman BABIN. Yes, sir. I now recognize the gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman, and we get a great education here. You know, this is a—I feel like I'm talking to the greatest experts in the world, and for us to have hired people like this individually would be just impossible. So thank you very much for your testimony.

And with that said, I sort of look at myself as a student that hasn't done his lessons yet on this particular issue. So let me ask this. Solar power is one way of promoting and actually providing the energy that we need at least for closer in space exploration missions but solar power will not work further out in space, is that correct?

Mr. SCHURR. Correct. The further away you get from the sun, the less power you can get off the same solar panels. So if you go to Jupiter, it's only four percent of what you can get from Earth from the same solar panels.

Mr. ROHRABACHER. Okay. So we are going to—with anything that goes beyond Mars—this will not affect any calculations as far as for a Mars mission, is that correct?

Mr. SCHURR. Mostly correct. There are uses where the environment is—if you look at the rovers on Mars, they're not always in the sunlight because of the way the sun changes as Mars goes through its seasons. So on MSL and Mars 2020 actually having the RTG makes it operational year round as opposed to having to stop during the winter.

Mr. ROHRABACHER. How about on the far side of the Moon?

Mr. SCHURR. The far side of the Moon? One of the problems you have with the Moon is you get two weeks of darkness no matter what part of the moon you're going to be on. And these can enable missions, possibly rovers or landers, to survive that lunar night at well.

Mr. ROHRABACHER. Okay, so this does have some application other than just deep space?

Mr. SCHURR. That's correct. It's not just distance. It's also any place that may be dark or dusty and not have enough sunlight.

Mr. ROHRABACHER. Okay, and I understand Japan has a large, how do you say, storage? Not storage but they possess a large amount of plutonium left over from their reactors?

Mr. SCHURR. I'm not familiar with that at all.

Mr. ROHRABACHER. Okay. Is anyone familiar with that and the possibility that that could be used to produce the Plutonium-238 that we need?

Ms. BISHOP. Congressman, I'm not aware of any inventory.

Mr. ROHRABACHER. All right. Now what about Russia? Is Russia—I understand they actually produced this at one point, is that right?

Ms. BISHOP. Yes, that's correct, and previously the United States purchased material from Russia. And that's what we have in our current inventory. But there's no plans at this point to purchase additional material.

Mr. ROHRABACHER. So is it possible that we could, if we could get our relations back together again as they were a few years ago, we might have—this could be some area of cooperation between Russia and the United States in providing this material and perhaps joint deep space projects?

Dr. McNUTT. Can I——

Ms. BISHOP. Yes.

Dr. McNUTT. So I was actually the co-chair of the 2009 report, and we looked at the situation with Russia at the time. And apparently, from what we could tell, they pretty much had sold or were planning to sell to the United States everything that they had left. There were discussions that they brought up suggesting that if we wanted to fund a plant in Russia, that they would be interested in taking our money and producing plutonium for us. It was not going to be cheap, and at least at the time talking with the people that were at DOE, they did not think that that would be an appropriate thing to do, nor were really the funds there in place to do that.

So there are—of course, the Chang'e 3 lander that the Chinese landed on the moon not too many years ago did have radioisotope power supplies on board. They're very small. From what one can tell from the open literature, those probably did come from the Russians, perhaps some leftovers of what they had. But as far as there's anything out there that is available in open literature, the majority of this material that's left in the world is in the United States, and it's that 35 kilograms.

Mr. ROHRABACHER. And it has to be produced. This is something—you have leftover plutonium from nuclear power plants but that plutonium needs to be worked on and produced through another process.

Dr. McNUTT. So that's actually a different kind of plutonium. That's the same thing that one uses in weapons. It's Plutonium-239.

Mr. ROHRABACHER. Right.

Dr. McNUTT. The power supply is 238. That one difference makes all the difference in the world. It turns out that Plutonium-238 gives off power by actually decaying. Half of it goes away after about 87 years, and that's the reason that the Voyagers will be going off-line sometime in the mid-2020s because their nuclear batteries effectively are winding down.

So you do indeed have to make it. You make it out of Neptunium-237——

Mr. ROHRABACHER. And that comes from where?

Dr. McNUTT. Well, the Neptunium-237 was left over from the United States weapons program. There's about 300 kilograms of the material that's left under storage at Idaho National Laboratories in Idaho, and the United States no longer has the capability of making that.

Mr. ROHRABACHER. Okay, but none of that comes directly from leftover material from nuclear power plants?

Dr. McNUTT. Not in the United States, sir, no.

Mr. ROHRABACHER. But over in perhaps in Russia——

Dr. McNUTT. There are some processes that one can use, but again, one has to do a lot of processing of material. And of course, we haven't been reprocessing material for the commercial world in the United States since the Ford Administration. It's been a security issue.

Mr. ROHRABACHER. I understand that, but we're looking at just reprocessing for this specific 238. That will come from plutonium that is not in any way related to what's left over from a nuclear power plant. Is that correct?

Dr. MCNUTT. Right.

Mr. ROHRABACHER. Okay.

Dr. MCNUTT. It is the——

Mr. ROHRABACHER. This is not reprocessed plutonium——

Dr. MCNUTT. Right.

Mr. ROHRABACHER. —from a nuclear power plant?

Dr. MCNUTT. No, it is not.

Mr. ROHRABACHER. And where does that plutonium come from that the 238 comes from? It's just processed.

Dr. MCNUTT. So again, the Plutonium-238 is material that we actually made out of the neptunium that we've had as heritage material that's been left over from other programs in the United States. Again, once you make it, half of it goes away in about 87 years. And so that's one of the reasons that part of that 35 kilogram inventory is not currently up to specs because it's old enough that it has decayed away. And so that's the reason for needing to up-blend it with new material in order for it to be used in future missions.

Mr. ROHRABACHER. And for long term, any long-term strategy that would have us in deep space, this is an issue that we must deal with because some day we're just going to reach a brick wall and can't go any further. I hope by then perhaps we will have not just Russia but other international partners that could work with us on this so the total cost isn't the American taxpayer. But who knows? We'll see. But in the meantime, I'm pleased that you are alerting us to this long-term need that should be there on one of our considerations as we're looking through our budget. So thank you very much for your testimony today.

Chairman BABIN. Thank you, Mr. Rohrabacher. There was just a couple other issues that I wanted to address. Dr. McNutt, NASA indicates that a production rate of 1.5 kilograms per year is sufficient to meet its needs, and that is based on the use of MMRTGs. The 2009 National Academy of Science Report that you chaired included an attachment which was a letter from NASA to DOE expressing Pu-238 production needs, and it states the Mars Science Lab and the Outer Planet Flagship 1 are designed to use the multimission radioisotope thermoelectric generator technology. The rest of the missions assume the use of advanced sterling radioisotope generator technology, significantly reducing the quantity of Pu-238 required to meet the power requirement. Is there a more recent letter from NASA to DOE that might clear some of the seemingly incongruencies or whatever you'd want to call it here?

Dr. MCNUTT. Right. So to the best of my knowledge, there's only been one letter that at least has been made public since then, and that was issued in 2010. I was on the Planetary Decadal Survey that came out in 2011. We had access to that. That was the letter that had reduced the need to the 1.5 kilogram per year level. The reason for that reduction from the 5 kilogram per year level that had been issued in the previous letter in 2008 by Administrator Griffin was because that included elements of the Constellation Program that required pressurized rovers for human excursions on the surface of the Moon. Once the Constellation was cancelled, that need went away. And that was reflected in the letter of 2010.

To the best of my knowledge, there has been no series of letters that has been interchanged between NASA and the Department of Energy since then. And one of the items that we flagged in the 2009 report is that having a publically available assessment of need on a yearly basis or so was actually something that perhaps should be reinstated.

Chairman BABIN. One other thing. Now that SLS and Orion are back on line so to speak, is it a possibility that we might need more than 1.5?

Dr. MCNUTT. Yes, there could be. So one of the exercises that we went through in the 2014/2015 timeframe was putting together of what's called the Nuclear Power Assessment Study. We had a variety of people from all of the DOE labs from a lot of the NASA centers as well trying to look, again look forward at what sort of needs there might be, look forward at what sort of a role fission might play, and also look forward at what sort of needs that there might be for human exploration missions. We had representatives from HEOMD, from NASA, on the panel that did the work. Their words to us as we were putting that report together was that there were no current requirements within human mission exploration for NASA and that there really wasn't any way of coming up with a number because those requirements did not exist and it's something that would be studied in the future.

And so that's one of the reasons why that all of this discussion is really hinged on the 1.5 kilograms per year, and as Mr. Schurr said, a lot of this is also reflected in the actual cost of the individual missions. And it's sort of a delicate balance of how much money you have for the missions that would need the material, and then you don't want to overproduce this stuff because it does start decaying away once you've produced it.

Chairman BABIN. Right. Okay. Thank you very much.

Dr. MCNUTT. Certainly.

Chairman BABIN. And then I'm taking a chair's privilege here. I want to ask another question of Ms. Bishop. How will projected production rates be affected when the advanced test reactor at the Idaho National Laboratory undergoes the year-long scheduled maintenance shutdown beginning in 2020? And has the ATR been qualified for Supply Project work?

Ms. BISHOP. Thank you for the question.

Chairman BABIN. Okay.

Ms. BISHOP. Currently, our activities supporting the advanced test reactor, we are doing a lot of planning activities right now to ensure that we are ready to produce Pu-238 in the reactor when we finish the core internal change-out activities in 2020. Currently we have completed a trade study with the advanced test reactor to identify optimum positions within the reactor and develop that initial plan for how we would go about producing the material with some additional funding that was provided in Fiscal Year 2017. We are accelerating an experimental campaign to verify those calculations regarding our projected output of material.

Chairman BABIN. Okay.

Ms. BISHOP. And with that, we're also focused on developing and finalizing a standard target design that we would utilize for both the advanced test reactor and the high flux isotope reactor by 2019 with the goal when ATR is completed its core internal change-out, we would be ready in 2021 to insert targets and start producing Plutonium-238.

Chairman BABIN. Great. Okay. Thank you very much. And I have a request of you, Mr. Schurr. Dr. McNutt's testimony states an assessment was made of the true cost impacts, and a final report was transmitted from NASA to the Office of Management and Budget in the fall of 2013. Would you please provide a copy of the report that Dr. McNutt referenced in his testimony, from NASA?

Dr. MCNUTT. You were on the panel with me. It was the zero-based review——

Mr. SCHURR. Okay.

Dr. MCNUTT. —study.

Mr. SCHURR. We'll take that action.

Chairman BABIN. Okay. Great. Well, this concludes our Subcommittee hearing this morning. I want to thank every one of you witnesses and all the members, although I'm the only one left standing up here and those of you who came to listen. We really appreciate it. Very interesting. And I'd like to adjourn the meeting.

[Whereupon, at 11:22 a.m., the Subcommittee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Mr. David Schurr

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini"

Mr. David Schurr, Deputy Director, Planetary Science Division, NASA

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. The Government Accountability Office (GAO), in its report, "*Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges*", notes that NASA had earlier planned to use a dynamic RPS design, such as the Advanced Stirling Radioisotope Generator (ASRG), for future missions and was funding ASRG development work until 2013. The report also indicates that NASA plans to investigate in 2018 dynamic power conversion systems once again.

    a. What, specifically, are NASA's plans for work on power conversion systems?

       Answer: NASA conducts basic and applied energy conversion research and development to advance state-of-the-art performance in heat to electrical energy conversion. Both static and dynamic energy conversion technology development projects are underway at this time to support potential future power systems.

    b. Did NASA conduct a cost benefit analysis to inform its previous decision on the benefits of continuing ASRG development versus the long-term costs of not continuing that work?

       Answer: No, the decision was made as a result of projected cost increases for the ASRG development project at a time when the NASA Planetary Science budget was being significantly reduced. The budget could not support continuing the work, and sufficient technology issues remained to be resolved, with potential future cost increases.

2. The GAO report referenced above breaks-down NASA's current, annual funding to DOE for Pu-238 production, Radioisotope Power System (RPS) fabrication, and RPS infrastructure sustainment. Does NASA anticipate sustaining all of these activities at the current funding levels over the next budget horizon (FY19-24)?

   Answer: Yes - Since FY 2011, NASA has funded the costs of reestablishing the Pu-238 production capability. In addition, beginning with NASA's FY 2014 appropriation, the responsibility for funding DOE's existing RPS infrastructure maintenance and production operations is allocated to NASA. The budget for all of these activities is sustained in the latest President's budget.

a. What is DOE currently funding for each of these efforts?

Answer: As mentioned in answer 2, NASA has funded the costs of reestablishing the Pu-238 production capability since FY 2011, and funding the production operations.

3. When do you estimate DOE will be able to meet NASA's annual production requirement of 1.5 kilograms of Pu-238 per year and what is the confidence level of that projection?

Answer: The current plan calls for full-rate production of 1.5 kg of heat source plutonium dioxide (HS-PuO2) per year (on average) by 2025. As processes are scaled up from the initial demonstrations (now completed), an interim production rate of 400 grams per year of HS-PuO2 is expected to occur beginning in 2019. While no specific confidence level is specified, this progressive demonstration and ramping up of capacity provide a high degree of confidence early-on that the 2025 goal can be met.

a. What is the basis for the confidence level?

Answer: As mentioned in question 3, no specific confidence level is specified; however, progress to date provides a high degree of confidence that the goals can be met. For example, the end-to-end production process has been demonstrated, culminating in some new fuel being included in two of the flight fueled clads for the upcoming Mars 2020 RPS. In addition, plutonium production scale up efforts are on track. Automation equipment to manufacture more targets more expeditiously has been delivered and is being installed for use in 2018. Target irradiations, using the proven capabilities of the High Flux Isotope Reactor (HFIR) continue, and will increase as more targets are manufactured.

b. How does the fact that DOE will not have an implementation plan for the Department's management approach for Pu-238 and RPS production until September 2018 and an assessment of challenges to Pu-238 production until 2019 affect NASA's confidence level?

Answer: NASA and DOE meet monthly to review progress in the Pu-238 project, to stay aware of progress while DOE finishes developing their implementation plan. Maintaining open and regular communications allows NASA to remain confident of DOE's ability to meet our objectives.

DOE priority for NASA is focused on executing the Mars 2020 fabrication and fueling campaign in 2018. After this critical objective is completed, DOE and NASA have agreed to transition the delivery of RPS fueled clads from a mission-driven approach to a constant-rate production (CRP) strategy. Applying the CRP strategy affords both agencies the ability to improve the reliability and predictability to deliver RPS solutions in support of NASA exploration missions. CRP establishes clear deliverables for the annual average production rates for new HS-PuO_2 and heat sources manufactured into their fueled clads across the DOE supply chain.

The 2018 implementation plan is an integration of the total supply chain, bringing together both the plutonium supply and the subsequent fueled clad production capabilities of DOE into a single approach, rather than them being separately managed. In addition to completing the Mars 2020 fueling, the HS-PuO_2 interim production scale-up will have matured sufficiently to enable CRP with confidence.

This combination of approaches increases NASA's confidence of DOE supplying the future heat sources for NASA's envisioned planetary exploration missions into the 2030s.

Responses by Ms. Tracey Bishop

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini"

Ms. Tracey Bishop, Deputy Assistant Secretary for Nuclear Infrastructure Programs, Office of Nuclear Energy, Department of Energy

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. The Government Accountability Office (GAO) report, "*Space Exploration: DOE Could Improve Planning and Communication Related to Plutonium-238 and Radioisotope Power Systems Production Challenges*" includes a chart on page 13 indicating that DOE funding for RPS infrastructure and operations ceased in Fiscal Year 2014. What was the basis for this decision and who made that policy decision?

   Answer: The National Aeronautics and Space Administration (NASA) holds the programmatic requirement for developing and deploying radioisotope power systems (RPS) for space exploration. As such, the President's fiscal year (FY) 2014 budget proposal recommended consolidating funding responsibility for RPS within NASA, including RPS infrastructure and operations. Congress agreed with this proposal and has funded RPS infrastructure and operations within the NASA budget since FY 2014.

2. When do you estimate that DOE will be able to meet NASA's annual production requirement of 1.5 kilograms per year and what is the confidence level of that projection?

   Answer: The Department has high confidence in its ability to sustain the annual production requirement of 1.5 kilograms of heat source plutonium oxide by end of fiscal year 2025.

   a. What is the basis for that confidence level?

      Answer: The Department's position is based on the results from the first campaign at Oak Ridge National Laboratory to produce new plutonium-238, which met NASA mission specification requirements. A sample of this new plutonium-238 was utilized for the Mars 2020 mission to demonstrate the Department's capability to produce material for NASA missions.

b. How does that confidence level take into account the fact that DOE will not have an implementation plan for the Department's management approach for Pu-238 and RPS production until September 2018 and an assessment of challenges to Pu-238 production until 2019?

Answer: The Department of Energy and NASA have an approved Interagency Agreement that outlines priorities and deliverables related to plutonium-238 production, based on identified challenges. The status of the deliverables is actively monitored and progress is formally communicated in monthly status reports and management meetings. Once complete, the implementation plan and assessment of challenges will serve as additional documentation to support the Interagency Agreement.

3. In the report referenced above, GAO indicates that some of the Pu-238 supply that DOE maintains does not meet NASA specifications but could be blended with new Pu-238 to produce useful material for NASA's purposes. Please describe what is involved in blending.

Answer: DOE has reestablished processes to produce heat source plutonium oxide. Newly produced material is higher in Pu-238 content than the spaceflight standard requires. This provides an opportunity to blend below-specification material, otherwise unusable for flight, with this newly-produced material, thereby increasing available amount of net-usable material for NASA missions. This blending should result in making the full civil space allocation usable as heat-source material. The act of blending out-of-specification and new material requires processing of the feed material through aqueous purification operations. During aqueous operations, the blended feed oxide is dissolved in acid to create a liquid solution, which is then processed to purify and precipitate the solid form of plutonium-238. The solid product is converted into heat source plutonium oxide. This process is required to remove impurities, including any uranium-234 present from the decay of Pu-238 and to ensure a uniform, or homogeneous, heat source plutonium oxide product.

a. What is the relative ratio between old and new Pu-238 to make it useful for space missions?

Answer: The blending ratio of out of specification and newly produced material depends on the assay, or percentage, of plutoniun-238. It is currently projected that the blending ratio of out of specification material to new material will be in the 1:1 range (one part out of specification to one part new material). The Department is conducting experiments in fiscal year 2018 at the Advanced Test Reactor to verify the estimated assay of new plutonium-238 that would be produced in that reactor, which may adjust the blending ratio to assure the end product meets NASA mission specifications.

b. Which DOE facilities would be used for blending and what is the amount of time needed to produce the blended material?

Answer: Blending will be accomplished in the Technical Area 55, Plutonium Facility 4 Building at Los Alamos National Laboratory. On average, the time to complete a blending activity in support of constant rate production levels of 10 to 15 fueled clads annually is approximately three to four months.

4. GAO's report notes that perfecting and scaling chemical processing is one of the challenges your department faces in producing Pu-238. Please explain, in layman's terms, what is involved in perfecting the chemical process and what challenges are involved.

Answer: Currently, there are no technical challenges with extracting plutonium-238 from irradiated targets. The Department's efforts in current plutonium production campaign are focused on optimizing the chemical process to reduce impurities, minimize waste streams, to identify opportunities to increase batch size, and recover neptunium that can be reused in targets. Optimizing this process can lead to increased operational efficiencies, reduced waste costs, and lower radiation fields.

a. What is DOE's plan for addressing such challenges?

Answer: DOE will complete four irradiation campaigns of plutonium-238 to refine the current separations process. A campaign is currently underway and scheduled to complete in the spring of 2018. The final campaign before shifting to constant rate production will start in the latter part of fiscal year 2018.

b. What are the implications for meeting NASA's Pu-238 production requirements if DOE does not perfect the capability for chemical processing?

Answer: DOE's efforts are focused on process optimization, which would not impact the ability to meet plutonium-238 production requirements.

Responses by Dr. Ralph L. McNutt, Jr.
HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Powering Exploration: An Update on Radioisotope Production and Lessons Learned from Cassini"

Dr. Ralph L. McNutt, Jr., Chief Scientist for Space Science in the, Space Exploration Sector, The Johns Hopkins University Applied Physics Laboratory

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. Mr. Schurr's prepared statement notes that the initial operations of Pu-238 production have the goal of producing 400 grams of Pu-238 annually and that production would scale-up to 1.5 kilograms per year on average by 2025. Will the initial production level of 400 grams per year be sufficient to enable future planetary science missions beyond the late 2020s?

   Answer: The issue of how much Pu-238 is required by NASA as a function of time has been both a critical and difficult problem. To respond to the question, some background is required.

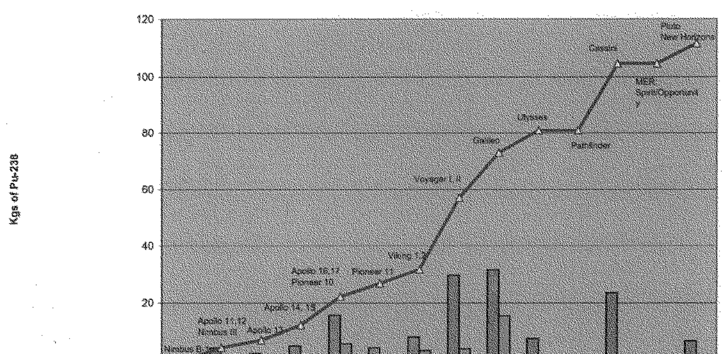
   NASA has an Agency Mission Planning Model (AMPM) which has a 20-year horizon for planned missions (see, e.g. https://www.nasa.gov/sites/default/files/files/FY15_AMPM.pdf). However, this document typically does not include projections of need for radioisotope power supplies (RPS). The last public projection was contained within the NASA Administrator's letter of 25 March 2010, which was made available to the Planetary Decadal Survey's Steering Group and is included in Table 9.5 of the Planetary Decadal report *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Per that plan, the requirement would have been 37.4 kg for launches from 2011 through 2027, a rate of 2.3 kg per year. Those estimates were based upon the successful implementation of the Advanced Stirling Radioisotope Generator (ASRG) and the use of RPS on Outer Planets Flagship 1, which can be mapped to the Europa Clipper. The ASRG program was terminated, Europa Clipper is being implemented with large solar arrays (current design is ~81 m^2 or ~870 square feet), and Mars 2020 is being implemented with the same Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) design currently powering the Curiosity rover on Mars.

   A similar estimate attempt was made during the conduct of the Nuclear Power Assessment Study (NPAS) for NASA (https://solarsystem.nasa.gov/docs/NPAS_Final_Report.pdf). In Table ES-1 of that report are listed all the mission concepts studied in the course of preparing the aforementioned Planetary Decadal Survey report. The ~$35 B in missions, of which ~$22 B used RPS, required a total of 37.8 kg of Pu-238 isotope. That is, for roughly

~$1B per year spent on mission implementation, one might estimate a need of ~1.1 kg of Pu-238 isotope. This is the amount of isotopic Pu-238 in ~1.5 kg of Pu "fuel product," which is the number cited in the production rate (the difference of 400 g here is accounted for by the mass of the oxygen and non-Pu-238 isotopes in the "fuel product" – the technical details are all documented in open literature, but it is a complicated story). Given current spending on the type of mission portfolio present over several decades within the NASA Planetary Science Division (PSD), this rough calculation suggests that an annual fuel product production rate of ~1.5 kg/yr is a reasonable number, assuming there are no significant plus ups or decreases in NASA's budget, nor significant changes in the current mission portfolio across the agency.

The question of historical usage, as a guide to informing future projections, was asked of the DOE by the Radioisotope Power Systems Committee of the National Academies in the course of their work in the 2008-2009 period. The following graphic was provided to the Committee by DOE on October 6, 2008 during the course of their work. The net use of Pu-238 isotope from NASA's Nimbus satellite in 1968 through the launch of New Horizons in 2006 was ~3.1 kg/yr. Including the MMRTG on Curiosity and updating the graph to the present brings the average to just under 3 kg/yr. It is also worth noting that in addition to NASA's robotic program the amounts also include those left on the Moon by the Apollo astronauts in the Apollo Lunar Experiments Packages (ALSEPs). (These account for ~15 kg of Pu-238. The RPS on Apollo 13 returned to Earth with the Lunar Module and is in the Tonga Trench in the Pacific Ocean at an estimated depth of ~7,000 feet; no released Pu-238 has ever been detected).

Historic Pu-238 Usage (kilograms)



	1968	1969	1970	1971	1972	1973	1975	1977	1989	1990	1996	1997	2003	2006
Yearly Pu-238 Usage	1.975	4.637	2.609	5.218	15.843	4.590	8.417	29.651	31.579	7.897	0.006	23.624	0.028	6.978
Recycled	1.975				6.035		3.607	4.231	15.668					
Total Usage	0.000	4.637	7.246	12.464	22.272	26.862	31.672	57.092	73.003	80.900	80.906	104.53	104.55	111.53

Years are shown only if there was a launch with Pu-238 during that year. Including the Curiosity and Mars 2020 rovers, NASA's usage will be just under 120 kg in 2020. Removing ~15 kg for Apollo would leave an average historical use rate of ~105 kg / 52 years = ~2 kg/yr.

Based upon all of these estimates, a usage rate estimate of ~1.5 kg/yr is likely a good one if there is no significant change in NASA's budget or mission portfolio mix (robotic/human). With an initial capability of 400 g/yr and the 35 kg of fuel Pu-238 currently available to NASA (see answer to next question), the current plan should be good into the 2040's. If the initial 400 g/yr were maintained, but the increase to ~1.5 kg/yr were *not* carried out, then how well the 400 g/yr could be leveraged against the current 35 kg allocation depends upon the details of the age distribution of that allocation, and it will also change with the details of when the material is used. As details of the age distribution track back to the production history, which is not publicly available information, DOE would have to provide the analysis to answer that question, based upon a specific usage scenario. For example, while ~17 kg of Pu-238 in the current allocation is within specifications for use (again, see the answer to the next question), the usable amount may be less in, e.g. 5 years from now, depending upon the age distribution in that 17 kg.

Significant changes in needs for the human program for exploration of the Moon, Mars, or both during this period would, of course, change such an assessment (public sources indicate that the DOE and its precursor agencies produced ~300 kg of Pu-238 up through 1988, so NASA has used just over a third of the material).

All of these complications are why reassessment of the predicted requirements on an annual basis is prudent.

2. What are your views on the use of blending as a means to stretch our Pu-238 supply? To the best of your knowledge, does DOE have a blending process with validated results in place?

   Answer: During the course of the NASA's Zero-Based Review (ZBR) study of DOE infrastructure (in 2013), the DOE announced "an allocation in the amount of 35 kilograms (kg) of plutonium-238 isotope for civil space applications. Of that amount, approximately 17 kg complies with the Pu-238 content specified for the General Purpose Heat Source. The balance may be used as blend stock to increase the net amount of usable material for flight system." (DOE Memorandum to NE-75 dated July 19, 2013; reproduced as Appendix E of the NPAS report).

To the best of my knowledge, such an approach should be straightforward and would be an appropriate way to maximize the use of the existing inventory. The implication is that the balance of approximately 18 kg is out of spec due to age, but not so old that blending with new material is not possible (if the energy content is too low due to age of the initial Pu-238, then my understanding is the ductility properties of the iridium clads, as well as other properties of other parts of the General Purpose Heat Sources may not meet required safety standards for various launch accident scenarios).

All of that said, I know of no publicly available information on a blending process with validated results, nor do I have any other knowledge of such a process. Given all of the work with Pu-238 over the years I would be surprised if the means were not in place. Whether this has actually been verified with NASA as the customer is a different question. Whether DOE has such a process, and it is validated, and ready for, or in, use, is a question best put to DOE.

3. GAO reports that NASA is investigating the next generation of Radioisotope Power Systems (RPS), including a modular RPS design. This would allow NASA to use small power increments for missions, have more precision in its use of RPSs, and therefore require less Pu-238 to provide that power. What are your thoughts on moving to new RPS designs? In particular, what testing will be needed to ensure their flight capability?

   Answer: There has always been a problem in moving to new RPS designs. It is always – and ultimately – a question of having a budget sufficient to carry the work to completion. This was the problem with the Selenide Isotope Generator (SIG), originally baselined for NASA's Galileo Jupiter Orbiter, the alkali metal thermal-to-electric converter (AMTEC), originally baselined for the common spacecraft bus for the Europa Orbiter, Pluto Kuiper Express, and Solar Probe missions, and, most recently for the ASRG. A Modular-RTG design was under development in the early 1990's, but the effort never resulted in a flight unit, and the overall effort appears to have been terminated before the year 2000. A historical problem has been that the technical details implicit in new convertor designs have been underestimated consistently, resulting in abandoned technical efforts and a continued "fallback" to older solutions (the MMRTG being the most recent case in point). The GPHS heat source was originally designed as a "standard" in the late 1970's in order to save costs. Minor structural modifications driven by safety calculations, led to the "Step 1" design (used on New Horizons) and the "Step 2" design used with the MMRTG. Further changes to the GPHS would, in my opinion, be unwarranted and totally wasteful of the limited funds available. Significant changes would also likely invalidate decades of safety testing, some of which may no longer be reproducible due to current safety concerns and whether the facilities still exist.

Any modular design even contemplated should be based upon the current, existing GPHS design(s). The argument that "This would allow NASA to use small power increments for missions, have more precision in its use of RPSs, and therefore require less Pu-238 to provide that power" is faulty. The implication is that one could fly "small" missions using RPS, but the reality is that the current cost incurred with the use of *any size* of RPS is so large that their use on small missions is prohibitive due to those costs.

The significant use of less Pu-238 will only occur if a flight-certified, dynamic convertor system can be produced. Such a convertor should also "automatically" solve the power degradation-with-time issue that afflicts the current MMRTG converters, for which no successful substitute has yet been found. Pursuing a modular design might be warranted in the future, but only once NASA and DOE have concluded that all work on dynamic convertors should be stopped, and no further development attempts made.

In any case, prudent testing will require a full-up manufactured flight unit under test in a thermal vacuum system for some agreed-upon (by NASA and DOE) period of time. Protocols for static, thermos-electric systems, are well established. A similar test protocol for a dynamic system has been, and remains, a subject of debate (this was one of the recommendations in the 2009 National Academies Committee Report). A dynamic conversion unit will need to demonstrate continuous, uninterrupted operation in a thermal vacuum chamber for some extended period of time. The appropriate amount of test time required to validate for flight will need to be agreed to by both NASA and DOE, and will likely be at least ~one full year (10,000 hours; this was the ground test time run on a SNAP-10 test reactor in 1965-66. The flight unit ran for only 43 days due to an electrical fault in a non-reactor part of the spacecraft. This remains the only fission reactor the U.S. has ever operated in space). Ground testing for a full mission time of a decade or more before flight is, of course, not practical; it has also been the source of much disagreement by some as to whether a dynamic convertor system can ever be qualified for flight.

4. What are your most significant concerns, if any, regarding the United States' ability to produce Pu-238 and fabricate and use RPSs to enable future space exploration?

   Answer: With respect to Pu-238 production, despite a "rocky start", the current plans, including schedule, for ramping up to a production rate of ~1.5 kg/yr of plutonium product is a good one. Processes appear to be going well, and the current budget appears to support the timely upgrades in needed facilities at Los Alamos National Laboratory (LANL) required to produce the fuel clads for use in the GPHS assemblies. At the time of the National Academies Committee study in 2008-2009, none of this was assured. That said, my most significant concern is that the current plan remain funded and executed as planned. Cost efficient production cannot be carried out in "fits and starts." Not only must infrastructure and a trained workforce be maintained and exercised, but preservation of corporate memory of how we have gotten to this place is also essential.

With respect to use of RPSs to enable future exploration, the whole situation with respect to the thermal-to-electric energy convertors is of significant concern to me. At the time of the "RPS Provisioning Study" in 2001, it was assumed that the Stirling convertor effort would be successful, and the MMRTG was seen as a backup to enable use both in deep space and on the surface of Mars. The highly successful use of silicon-germanium convertors, which require use in a hard vacuum, was abandoned. With the failure to date of any flight worthy dynamic convertor scheme, the MMRTGs with their low conversion efficiency and relatively rapid degradation rates, have left us "frozen" in 1970's technology, close to the state of the SNAP-19 units used on Pioneer 10 and 11 and the Viking 1 and 2 landers. We can no longer duplicate the Multi-hundred Watt (MHW) RTGs that enabled Voyager 1 and 2 or the GPHS RTGs that have brought us the spectacular scientific results from Jupiter and Europa (with Galileo), deep-space over the poles of the Sun (Ulysses – with the European Space Agency, ESA), Saturn, Titan, and Enceladus (with Cassini and the ESA Huygens probe), and the Pluto system and beyond (with New Horizons). Due to the times and mass limitations involved, *these missions could not have been carried out with MMRTGs.*

In looking forward to potential missions to land on Europa, reach the ice giant systems of Uranus and Neptune, and probe the nearby interstellar medium past the Voyagers (which are not expected to last more than about another decade, as their efficient, but still limited, power system outputs decay), it is imperative that the capabilities of the GPHS RTGs be brought back. Given our current state of knowledge, the only known way to do this is with the silicon-germanium converters used in the GPHS RTGs. My biggest concern is that this technology be re-established to a flight basis before all the knowledge of how to do that is lost. This technology has its own difficulties and costs, but until there is a better technology ready to fly, this additional "backup" capability needs to be reestablished.