NASA's Radioisotope Power Systems Program Status Update and Focus on Commercialization

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Abstract— **Radioisotope Power Systems (RPS) have been safely providing the United States with the power to explore space for almost 65 years. NASA established the RPS Program in 2010 to support specialized science missions and potential future opportunities more effectively and efficiently. The RPS Program ensures the availability of RPS for the exploration of the solar system in environments where conventional solar or chemical power generation is impractical or impossible. NASA missions have utilized space nuclear power to explore planets, moons, and interstellar space, enabling missions to some of the deepest, darkest, and dustiest regions in the solar system and beyond. This scientific exploration has deepened our understanding of the solar system and our role within. The RPS Program, in partnership with the Department of Energy (DOE) Office of Nuclear Energy continues to operate as an interagency partnership to provide robust radioisotope power system solutions to spacecraft that conduct missions to extreme environments for science and exploration. This Program invests in systems and technologies to ensure that NASA maintains this capability well into the future and it manages processes that ensure the safe use and launch of these systems. This paper provides a synopsis of current activities of the RPS Program, and it introduces a focus on the commercialization of RPS to enable a variety of future mission applications.**

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1. PROGRAM CONTENT AND STRUCTURE

The RPS Program is responsible for the acquisition and development of thermal energy conversion technologies and related system technologies as well as acquisition and development of flight RPS for future mission use. It manages activities related to the National Environmental Policy Act (NEPA) and nuclear launch authorization of RPS missions and systems. Additionally, the RPS Program maintains the capability to acquire future RPS through strategic investment in unique competencies that may be needed by future missions. This includes DOE's production of plutonium-238 (Pu-238) and the subsequent processing of the isotope into a useable form (plutonium oxide) as a heat source for thermal energy to support NASA missions. Further, it works to maintain and foster relationships with the broader nuclear community, including other agencies, academia, industry, and international entities.

The NASA RPS Program structure consists of multiple program office elements focused on RPS mission support, in addition to system development projects. These projects mature technologies critical to RPS systems and transition them into flight system designs, ultimately enabling DOE to develop and fuel RPS for NASA missions.

In addition, the DOE manages Constant Rate Production (CRP) for ongoing production of heat source material and subsequent manufacturing into its final flight form. This interagency scope is codified in accordance with a 2016 Memorandum of Understanding and additional lower-tier agreements. [1, 2]

Acquiring Power Flight Systems

The RPS Program's core purpose is to deliver reliable radioisotope power systems to enable science and exploration missions. To that end, the Program coordinates with DOE to ensure there is fuel available to enable missions within NASA's planning set, as well as to power and heat systems. The Program also invests in technology advancements to improve power system capabilities including the production of flight qualified hardware in preparation for future mission needs. NASA's Next Generation Radioisotope Thermoelectric Generator (Next Gen RTG) project is a flight design effort managed in conjunction with DOE to reestablish the ability to produce General Purpose Heat Source-Radioisotope Thermoelectric Generators (GPHS-RTGs), such as those that flew on Cassini and New Horizons, as closely to the original design as possible.

Accommodating both spaceflight and nuclear system requirements demand continual coordination between DOE and NASA. The system acquisition and design processes are conducted using DOE's Federally Funded Research and

Development Centers, to ensure these systems meet all requirements that will allow a future mission to integrate these technologies safely and appropriately. DOE employs the Idaho National Laboratory (INL) contractor as the agent to acquire flight systems that can be fueled and launched on NASA missions.

Flight System Builds

The currently selectable power flight system is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). Supporting activities typically involve procuring, building, fueling, and integrating the "as-designed" system for the mission. As a part of its mandate, the Program ensures these systems are available. For instance, after the launch of flight unit 1 (F-1) onboard the Curiosity Rover for the Mars Science Laboratory mission, the Program, working with the DOE, procured F-2 and F-3 to reduce risk for future planned missions. As an additional risk mitigation maneuver, the NASA and the DOE established CRP and compliance with National Security Presidential Memorandum (NSPM)-20. These activities, in addition to delivering and successfully integrating F-2 on the Perseverance rover for the Mars 2020 mission resulted in RPS mission cost and schedule savings, and a high-performance power system that exceeded the minimum power performance requirement. Perseverance, as shown in Fig. 1, has been exploring the Jezero Crater on Mars for over 4 years and has collected and retrieved 24 sample tubes for return to Earth by the future Mars Sample Return (MSR) mission. The MMRTG unit F-3 is built and in storage and being evaluated for potential use on future mission opportunities.

Fig. 1. Perseverance Rover on Mars with the Second Flight Unit of the Multi-Missions Radioisotope Thermoelectric Generator (MMRTG F-2). (NASA)

The next planned mission to utilize an MMRTG is the New Frontiers 4 mission Dragonfly, which will explore Titan, the largest moon of Saturn. Dragonfly is a unique rotorcraft lander, as depicted in Fig. 2, that will explore the richly organic moon to advance the knowledge of the building blocks of life by studying its prebiotic chemistry in multiple diverse regions and geological contexts. Because of Titan's dense atmosphere and cold temperatures, the heat and electrical power generated by a single MMRTG (F-4) is crucial to enable Dragonfly to conduct this campaign. The fabrication of F-4 is well underway and on schedule. Modifications to the MMRTG design have been made to allow the spacecraft to utilize the MMRTG waste heat, enabling survivability of the spacecraft in the harsh cold of Titan.

Fig. 2. Artist Render of the Dragonfly Rotorcraft on Titan with a Computer Aided Draft of the Multi-Mission Radioisotope Thermoelectric Generator Flight Unit-4 (MMRTG F-4) with True Hardware After Manufacturing. (JHUAPL/DOE/NASA)

Lightweight Radioisotope Heater Unit

For missions requiring solely heat and not power, Lightweight Radioisotope Heater Units (LWRHUs) are available. These provide approximately 1 watt of heat and are used to keep spacecraft components and systems warm so that the equipment can survive the cold environment of space. DOE has an adequate supply of LWRHUs to support current mission planning needs. In addition, the RPS Program, in partnership with DOE, is providing up to 40 LWRHUs to the Rosalind Franklin Mission (RFM). RFM is a robotic rover mission to Mars by the European Space Agency (ESA) that includes several NASA contributions. The ROsalind (Franklin) Support and Augmentation (ROSA) project is NASA's sub-project of the RFM that provides these contributions including the LWRHUs. DOE is re-establishing the LWRHU production, since the last mission to use a significant number of LWRHUs was Cassini. DOE successfully produced several of the LWRHU components, as depicted in Fig. 3, including the cladding hardware, graphitics, fine weave pierced fabric, and it brought a new welding machine online to aide in the manufacturing.

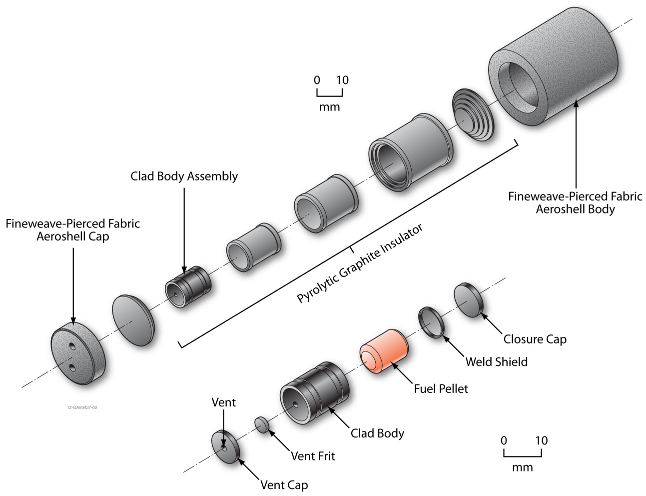

Fig. 3. Exploded view of a LWRHU. (DOE/INL)

Next Generation RTG Development

To meet future mission demand, the RPS Program has been working with the DOE to initiate a project to reestablish the General Purpose Heat Source-RTG (GPHS-RTG). This system has been used with great success by missions such as Galileo to Jupiter, Ulysses to the heliosphere, Cassini to Saturn, and New Horizons to Pluto and the Kuiper Belt.

Known as the Next Generation RTG Mod 1, this power system builds upon the successful technical heritage of the GPHS-RTG. The Next Gen RTG is designed for operation in the vacuum of space and will employ the heritage Silicon Germanium (SiGe) unicouple design as the thermoelectric energy conversion technology. This unicouple was successfully used in the Multi Hundred Watt-RTGs (MHW-RTGs) that have operated for more than 47 years aboard Voyager 1 and 2, as well as in the GPHS-RTGs as previously mentioned.

The Next Gen RTG Mod 1 will be designed as a build-to-print reproduction of the GPHS-RTG with minimal modifications required for the use of Step-2 GPHS modules, and replacement of any obsolete components. The Next Gen Mod 1 system will require the re-establishment of a new SiGe unicouple production line. Additionally, the manufacturing capability to produce the Multi-Layer Insulation (MLI) package together with the overall system assembly will need to be re-established.

By building upon the historic design heritage and demonstrated performance of the GPHS-RTG, the Next Gen RTG will continue to provide NASA with the power to explore for decades more to come. This Mod 1 unit is planned to be completed in 2030.

Flight Unit-5 Refurbishment (F-5R)

The F-5 GPHS-RTG, as shown in Fig. 4, was originally built for the Cassini mission and was fueled in 1984 as a flight spare. In 2005, it was defueled and put in storage. Under a task within the RPS Program, the DOE is refurbishing the F-5 unit to make it flight worthy and available to support a Planetary Science mission in the event a mission requires such a unit before the Next Gen RTG is available. After refurbishment, the unit will undergo testing with an electric heat source. This unit is known as F-5R (formerly Mod 0). The F-5R unit will utilize Step-1 GPHS modules and is planned to be complete in 2025 and put in storage in an unfueled state.

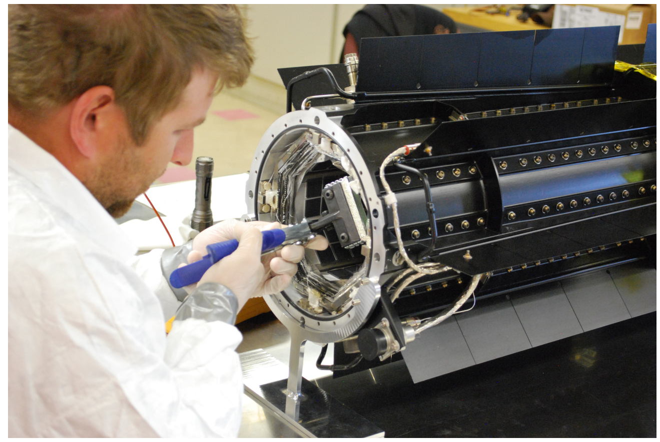

Fig. 4. Flight Unit-5 Refurbishment. (DOE/INL)

Constant Rate Production (CRP)

The management of production capabilities and nuclear facilities requires specialized processes, skills, and security which are well understood and provided by the DOE. In 2017, DOE and NASA agreed to transition the delivery of RPS from a mission-driven approach to a CRP approach. Under the CRP program, components, materials, facilities, and expertise across the plutonium production supply chain are managed to produce a steady flow of heat sources, instead of individual mission needs. The outcome of CRP is an underlying base of shelf-ready, flight-quality components readily available for NASA mission use. This strategy helps reduce the overall mission schedule and risks. The goals of CRP are to produce an average of 1.5 kg of heat source Pu-238 oxide annually by 2026 and to manufacture an average of 10–15 fuel clads (FCs) a year.

Since the demonstrated success of the CRP program for the Mars 2020 mission, the focus of CRP is on scaling up production, optimizing processes, and maintaining, modernizing, and replacing equipment and infrastructure.

National Environmental Policy Act (NEPA) and Launch Authorization

The Program is responsible for facilitating NEPA and launch authorization compliance for missions and programmatic policy infrastructure. The RPS Program follows a documented process for NEPA and launch authorization management which involves working with NASA, DOE, and other organizations. This highly involved process to achieve nuclear launch authorization ensures nuclear safety and environmental protection, while optimizing available data and resources.

As with the hardware support provided to missions, the RPS Program seeks to ensure the NEPA and launch authorization processes are as efficient as possible, without sacrificing safety. There are several parallel efforts underway to streamline and improve both the NEPA and nuclear launch authorization processes. [3] These include:

- Revisions to the Center of Environmental Quality (CE-Q) NASA NEPA Rule to maximize NASA's administrative efficiency in ensuring appropriate NEPA compliance [4],
- Environmental Management Division (EMD) publication of a Programmatic Environmental Assessment (PEA) to provide NEPA coverage for future LWRHU-only missions [5],
- EMD, RPS Program and DOE development of a GPHS System PEA,
- DOE development of a Documented Safety Analysis (DSA) for both LWRHU and GPHS modules,
- Office of Safety and Mission Assurance (OSMA) revision of the NASA Nuclear Flight Safety NASA Procedural Requirement (NPR) and similar internal and external policy documents, and
- Revisions to the Interagency Nuclear Standing Review Board (INSRB) Playbook to provide more guidance and clarity in the process.

Specific to the ROSA project in support of the RFM, the RPS Program completed the NEPA Compliance Plan and has drafted the Nuclear Launch Authorization Plan, which outlines the ROSA's support for ensuring the U.S. Government Nuclear Flight Safety and Launch Authorization Process proceeds smoothly and is completed prior to the launch date for the mission. This plan serves to codify NASA-managed milestones and deliverables associated with the launch authorization process.

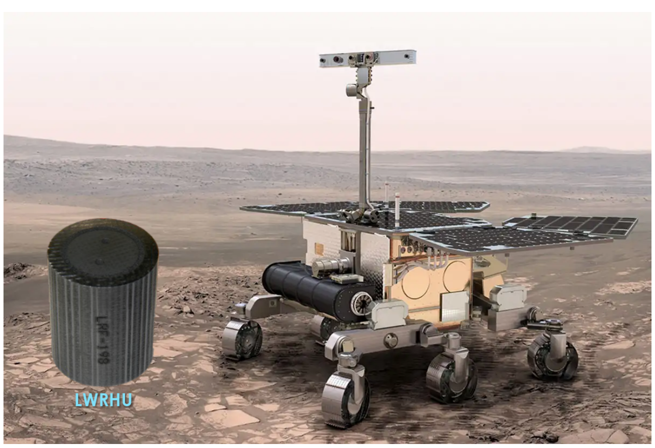

Fig. 5. Rosalind Franklin Mission with an oversized Lightweight Radioisotope Heater Unit to Illustrate the Heat Source Used on this Rover. (ESA/DOE/NASA)

Additionally, the RPS Program is executing an array of liquid natural gas liquid oxygen (LNG/LOX) testing in support of databook development. Specifically, the methane-oxygen vertical impact (MOVI) testing campaign results will be incorporated into United Launch Alliance's (ULA) *Vulcan* and Blue Origin's *New Glenn* multi-mission databooks in support of the launch authorization processes for future missions. The RPS Program also works in coordination with the U.S. Space Force, and NASA Space Operations Mission Directorate (SOMD) to realize efficiencies resulting from shared testing tasks.

Systems Engineering and Integration

The Systems Engineering and Integration (SE&I) Element ensures compliance with NASA's SE&I processes and requirements and supports RPS products from requirement definition through a transition hand-off to the RPS Program's Mission Integration Element. This Element provides these key functions to the RPS Program; systems engineering support, RPS technical studies, a Surrogate Mission Team (SMT), and independent review management.

The systems engineering support function provides the fundamental SE&I processes such as requirement management and verification and validation. It supports the development and maintenance of the program level requirements that guides RPS high-level design and expected performance. Verification and validation of those requirements ensures the RPS meets its customer expectations. RPS technical studies are performed under the SE&I Element to investigate potential future RPS enabled missions or other RPS trades that drive RPS requirements.

The SMT is an integral part of the requirement development process by providing insight from a mission perspective to new RPS designs or existing builds that do not have a mission assigned to them. The SMT helps the RPS Program assess the details associated with its requirements, content that should be modified, along with the respective rationales. To ensure end user mission guidance is fully represented, the SMT is comprised of team members from key organizations and centers that possess RPS-Mission experience.

The independent review management portion of the SE&I Element provides technical expertise from around the country in various areas for the formation of boards to support RPS projects. The boards attend formal milestone reviews, as appropriate, to provide their independent review of the RPS. This helps to ensure and give confidence that the RPS is on track to be successful before moving onto the next lifecycle phase of development.

Stakeholder Engagement

The Stakeholder Engagement (SE) element positively and strategically influences the overall nuclear community, with a special focus on scope of the RPS Program. This involves leading media communication training events to ensure that nuclear stakeholders throughout NASA are prepared to support public engagement forums, inspiring the next generation of science, technology, engineering, and mathematics (STEM) explorers, driving cohesiveness throughout the mission planning community by educating stakeholders on the status of power systems development and potential for strategic alignment, and supporting interagency and international relations.

The SE team consists of a diverse group of communications specialists including public affairs, strategic communications, internal communications, contingency communications, stakeholder engagement, visual communication, public engagement, workforce development, and educational outreach. It reports up to the Office of Communications at NASA's Science Mission Directorate, under the Planetary Science Division, and across to NASA Glenn Research Center's Office of Communications. Members are seated at NASA Glenn, NASA's Jet Propulsion Laboratory, and Johns Hopkins Applied Physics Laboratory. SE cross-coordinates with communications specialists within the NASA Space Technology Mission Directorate to develop common talking points to increase the public trust and elevate the understanding of positive uses and potential for all forms of nuclear power and propulsion in space.

The SE element works closely with the NEPA and Launch Authorization element and the Mission Integration element to develop concise, accurate, and clear talking points, responses to queries, and a suite of information products for the public, the media, and contingency planning representatives within the agency and associated agencies. SE is reviewing and influencing processes to ensure that the appropriate official representatives understand their roles and responsibilities for information dissemination during future nuclear launches [6]

Fig. 6. Pre-launch Media Event Interview of a DOE Subject Matter Expert, Greg Hula. (NASA/DOE)

2. COMMERCIALIZATION APPROACH

To address emerging needs within the spaceflight mission community, the use of non-Pu-238 isotopes is being evaluated by commercial entities to enable near-term mission opportunities. In response to this need, the RPS Program is expanding its role in managing agency Pu-238-based RPS NEPA, launch authorization, and mission integration processes to include coordination with commercial vendors, international partners, and other federal agencies to incorporate the use of alternative isotopes. This also encompasses initiating the evaluation of launch authorization processes using commercially sourced RPS for NASA missions thus, enabling a significant increase in discoveries via RPS-enabled planetary and exploration missions.

3. OUTLOOK

The RPS Program and DOE are continually looking to ensure mission success while reducing cost and improving technology capabilities. The interagency activities to develop and utilize RPS will continue to enable and enhance space exploration at destinations where conventional use of solar power and batteries would be infeasible or impossible. The current decadal survey, *Origins, Worlds, and Life, A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* [7], identifies the most important questions facing planetary science and missions. Many of the missions needed to answer these questions are enabled or significantly enhanced through the use of RPS. Missions conducted in the past using RPS have conducted extended operations of four or more times than that which would have been possible using solar power. [8] It is important to provide these missions with systems that are available, affordable, and reliable.

The current NASA investments made across agency boundaries ensure fuel inventory is available and ready for NASA mission use; RPS Program's operational processes improvement activities drive mission savings; the development and production of flight systems continue giving missions the power to explore. These investments enable the continued use of RPS for decades to come.

4. CONCLUSIONS

The NASA RPS Program was established to ensure the availability of RPS for the exploration of the solar system in environments where conventional solar or chemical power generation is impractical or impossible. The strong NASA and DOE partnership on the RPS Program has yielded significant achievements: establishing continuous production of heat-source plutonium oxide, the successful MMRTG-powered Perseverance rover, and the streamlining of the NEPA and launch approval processes. Continuing to utilize the strengths of each agency, NASA is leading RPS-related technology maturation and flight systems development. DOE continues to manage nuclear power system development and deployment, and constant rate production processes enable exploration for the NASA mission community.

Radioisotope power systems developed through this partnership ensure future missions will have access to the most extreme environments in the solar system; probing the sunless depths of lunar craters, flying across the surface of Saturn's moon Titan to search for the building blocks of life, or touring the rings and moons of the ice giant planet Uranus. Expanding coordination with commercial vendors, international partners and other federal agencies on the use of alternative isotopes and commercial RPS will provide additional opportunities for exploration. With this vital technological capability, the possibilities for exploration and discovery are limited only by our imaginations.

ACKNOWLEDGEMENTS

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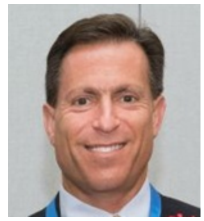
Biography

Mr. Carl E. Sandifer II currently serves as the Program Manager and Division Chief for the Radioisotope Power Systems Program at the NASA Glenn Research Center. In this role, he leads the development of power systems to enable NASA missions given a high priority by the scientific community to visit some of the harshest, darkest, and coldest locations in the solar system. Prior to this role, he served as the Deputy Chief of the Space Science Project Office at Glenn, and managed the science portfolio at the Center, which includes the development of new technologies, instruments, and systems to enable planetary science missions. Mr. Sandifer has a wealth of program and project management experience, along with a background in space mission design and systems analysis.

Carl graduated with a Bachelor of Science in Applied Mathematics degree from Bowling Green State University, studied Aerospace Engineering at Case Western Reserve University and earned his Master of Business Administration from Indiana Wesleyan University.

Lauren Clayman *received her B.S. (2005) in mechanical engineering from the University of Toledo. She has worked at the NASA Glenn Research Center (GRC) for over 20 years. She spent her first decade of service as a thermal design and test engineer and analyst working various projects and programs including Orion (known as Constellation at the time) and the first three Spacecraft Fire Safety flight experiments. She then transitioned to working as the Chief Safety and Mission Assurance Officer (CSO) for the GRC Space Communications and Navigation project office and now works as the CSO for the Radioisotope Power Systems Program.*

Ryan Edwards *is the Acting Mission Integration Manager and Acting NEPA and Launch Authorization Manager for NASA's Radioisotope Power Systems Program (RPS). Edwards is responsible for leading the planning, support, execution, integration, and management of all RPS aspects of an RPS-powered mission for the RPS Program. Additionally, Edwards collaborates with missions to ensure the safe launch of nuclear payloads. Prior to this position, Mr. Edwards was a thermal systems engineer and represented the NASA Glenn Research Center's Passive Thermal Discipline team as part of the NASA Engineering and Safety Center Passive Thermal Technical Discipline Team, working on projects such as Fission Surface Power, Orion, and Human Landing Systems.*



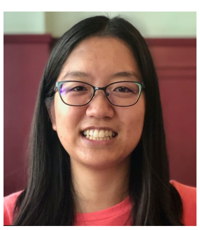
David Frate *currently serves as the Radioisotope Power Systems Deputy Program Manager. Mr. Frate has worked at the NASA Glenn Research Center (GRC) for 39 years. During that time, he has served as a Project Manager for a multitude of space flight projects including microgravity combustion experiments, thrust vector control systems, refurbishment of space shuttle Orbital Manuevering System engines for use on the Orion European Service Module, and the Power and Propulsion Element for Gateway. Mr. Frate received a Bachelor of Science in Chemical Engineerig from the University of Dayton and a Master of Science in Material Science Engineering from Case Western Reserve University.*

Allen Guzik *is the RPS Program Systems Engineering and Integration Element Lead. Mr. Guzik has worked for the NASA Glenn Research Center since 2010. During this time, he has supported the Orion project as the subsystem manager for three mechanisms; the Launch Abort System Retention and Release mechanism, the Spacecraft Separation Mechanism, and the Vent mechanisms. He has worked as a systems engineer since 2020 supporting a variety of projects including cryogenic fluid transfer, research and technology projects mitigating lunar dust and magnetic motors for extremely cold environments on the Moon, dynamic RPS using Stirling engines. He has earned a Bachelor of Science degree in Astronautical and Aeronautical Engineering from Purdue University and a Master of Science degree in Mechanical Engineering from Cleveland State University.*

Kristin Jansen *is a public affairs specialist of the Office of Communications at NASA Glenn Research Center and a Stakeholder Engagement Lead for the Radioisotope Power Systems Program. Ms. Jansen has over 24 years of experience at NASA's Glenn Research Center. The Stakeholder Engagement Element is responsible for the effective,* *positive, communications of radioisotope power systems, nuclear power and propulsion for space exploration, and energy conversion technologies. These communications specialist are the translators between the technical professionals and everyone else. She holds a Master of Business Administration degree in Marketing from Walsh University and a Bachelor of Fine Arts degree in Graphic Design with a minor in Computer Art from Bowling Green State University.*

Leah Sopko *received her B.S. (2000) in aerospace engineering from the University of Cincinnati. She has worked at the NASA Glenn Research Center (GRC) for over 20 years. She spent her first 6 years working the Fluids and Combustion Facility (FCF) flying hardware on the International Space Station. She transitioned to systems engineer working various projects and programs including Orion (known as Constellation at the time), the Space Launch System (SLS) rocket and the Power and Propulsion Element (PPE) as part of Gateway. Ms. Sopko now is working as the Chief Engineer for the Radioisotope Power Systems Program.*

Colleen Van Lear *is Program Integration Manager for NASA's Radioisotope Power Systems Program (RPS); Program integration ensures integration and control of the RPS Program cost, schedule, risk, and technical performance. Colleen has worked for the NASA Glenn Research Center since 2018 in the Space Science Project Office and Radioisotope Power Systems Program Office. Prior to joining NASA, she served as a Manufacturing Engineer and Production Control Manager in the steel fabrication industry, as well as, a Process Engineering within the Automotive Industry. Ms. Van Lear holds a Bachelor of Science in Manufacturing Engineering and a Bachelor of Science in Engineering Management from Miami University.*



Dr. Emily Hsu *is a program manager for Nuclear Infrastructure Programs in the Office of Nuclear Energy at the Department of Energy. She is responsible for the space nuclear power and propulsion activities, which includes the delivery of radioisotope power systems to support the National Aeronautics and Space Administration missions. Prior to joining the Office of Nuclear Energy, she worked as an engineering consultant in the Materials and Corrosion Engineering practice at Exponent, where she led technical projects on material compatibility and characterization, failure analysis, and corrosion prevention. Dr. Hsu holds a Ph.D. in Chemical Engineering from Columbia University and a B.S. in Chemical Engineering from Cornell University.*

Dr. Sujita Pierpoint *is the Associate Deputy Assistant Secretary of Nuclear Infrastructure Programs in the Office of Nuclear Energy. In this capacity, Dr. Pierpoint is responsible for overseeing infrastructure portfolio, nuclear materials management, safeguards and security and emergency management. She is also responsible for delivering radioisotope power systems, heater units, and related technologies to support the National Aeronautics and Space Administration missions. She has over 25 years of experience with a comprehensive background in nuclear engineering, systems engineering, nuclear safety, and program management. Before this role, Dr. Pierpoint served in several leadership positions at National Nuclear Security Administration and Department of Energy, as the Director of Nuclear Facilities Management overseeing $300M portfolio; and acting Director of the Office of Infrastructure and Resource Management overseeing a $1.5B facilities and infrastructure portfolio. She led consolidation of Special Nuclear Materials for the Complex Transformation initiative to improve the hazard and security posture at the national laboratories; implementation of Defense Nuclear Facilities Safety Board recommendations; and development of Asset Management Program. In 2003, she helped launch the Project on Nuclear Issues at NNSA to develop and nurture the next generation of nuclear weapons policy, technical and operational experts. Prior to joining the Office of Nuclear Energy, she worked as a Systems Engineer at TechSource, Inc., where she led requirements management, technical reviews and production capacity analysis for NNSA weapons complex. Dr. Pierpoint holds a Ph.D. and a master's degree in nuclear engineering and a bachelor's degree in mathematics from the University of Maryland.*