

NASA’s Radioisotope Power Systems Program Overview – A Focus on RPS Users

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Abstract—The goal of NASA’s Radioisotope Power Systems (RPS) Program is to make RPS ready and available to support the exploration of the solar system in environments where the use of conventional solar or chemical power generation is impractical or impossible to meet potential future mission needs. To meet this goal, the RPS Program manages investments in RPS technologies and RPS system development, working closely with the Department of Energy. This paper provides an overview of the RPS Program content and status, its collaborations with potential RPS users, and the approach employed to maintain the readiness of RPS to support future NASA mission concepts.

conducts studies of future mission and systems that would benefit from use of RPS, and assesses their potential required capabilities. This is done with heavy participation from the user community and NASA flight centers. This past year, the RPS Program conducted a comprehensive Nuclear Power Assessment Study (NPAS) to consider options for needed technology investments in RPS and potential fission-based power systems, as well as other investment considerations. [1]

TABLE OF CONTENTS

1. INTRODUCTION.....	1
2. PROGRAM SUMMARY	1
3. RPS COLLABORATION AND MISSION INTEGRATION	4
4. DOE RPS ROLES.....	5
5. TECHNOLOGY DEVELOPMENT AND SUSTAINMENT.....	6
6. CONCLUSION.....	10
REFERENCES.....	10
BIOGRAPHY	11

1. INTRODUCTION

NASA’s Radioisotope Power Systems (RPS) Program exists to provide solutions for the deep space power needs of U.S. robotic planetary science spacecraft. The RPS Program’s goal is to make RPS available for the exploration of the solar system in environments where conventional solar or chemical power generation is impractical or impossible to use to meet mission needs. To meet this goal, the RPS Program manages investments in RPS system development and RPS technologies.

To ensure the maximum applicability of the RPS available for use and to guide program investments, the RPS Program

Significant progress and some fundamental changes to the content within the RPS Program occurred in 2014–2015 in response to user needs and mission requirements. The Program content consists of flight system development and capabilities sustainment, as well as research and development activities for advanced energy conversion system technologies. Focus has shifted to address optimum mission performance at its destination, rather than an emphasis on beginning of mission (BOM) power.

To assure the availability of RPS, the RPS Program provides NASA management insight to maintain the core capabilities at the Department of Energy (DOE) needed for space nuclear power system deployment. These capabilities include the re-establishment of a production capability for the RPS heat source isotope, plutonium-238 (Pu-238), as well as the operations and analysis capabilities to process and certify that the heat source is ready for flight use in an RPS. The RPS Program also invests in advancing multi-mission data products in an area known as Launch Approval Engineering, to enable efficient mission implementation once NASA identifies a specific mission with a potential need for RPS.

2. PROGRAM SUMMARY

The RPS Program has three major thrusts; ensuring the availability of RPS flight systems through the sustainment of agency partnerships and industrial sources; the development of new power conversion technologies that are germane to the needs of the planetary science community; and, the support of the nuclear safety launch approval process.

Supporting these primary goals is a Program Planning and Assessment (PP&A) activity, which is the primary engagement vehicle for users and the flight community. PP&A accomplishes this engagement through the formulation and execution of studies, by coordinating systems engineering activities for flight systems, and by assuring that the Program has adequate sustainment activities in place.

Flight Systems

Flight system development activities during the past year have focused on three areas: maintenance of the ability to deploy either, or both, of the previously constructed Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) for mission-specific purposes; transition planning for the potential on-ramp of improved thermoelectric conversion technology for an enhanced MMRTG; and, replanning the development strategy for Stirling energy conversion technologies.

The RPS Program has a Level I requirement to ensure the availability of RPS for mission concepts requiring or benefiting significantly from nuclear power for implementation. Currently, the MMRTG is the only flight qualified RPS available for this purpose. Figure 1 shows an MMRTG attached to the rear of the Curiosity rover on the surface of Mars. The program has funded the completion of two additional MMRTG flight units (known as F2 and F3) up to the point of fueling, final assembly, and testing. These units, built in part to sustain thermoelectric fabrication capability, were placed in bonded storage awaiting assignment to a flight mission. One of the two units is the baseline power system for use on the Mars 2020 rover mission.



Figure 1. MMRTG on the Curiosity rover; after arrival on Mars in August 2012.

Other RPS continue to support planetary exploration missions in flight. The two groundbreaking Voyager spacecraft continue to return valuable scientific data after

more than 35 years of space operations—with Voyager 1 having left the “solar bubble” and entered interstellar space—thanks to the durable capabilities of their Multi-Hundred Watt RTGs. The Cassini spacecraft has achieved over 10 years of extraordinary orbital science operation at Saturn powered by three General Purpose Heat Source RTGs (GPHS-RTGs). In July 2015, the New Horizons spacecraft flew by Pluto nine years after its launch, capturing incredible close-approach images and beginning its year-long transmission of this valuable data using power from a single GPHS-RTG.

Technology Development

The RPS Program has changed its approach to managing its technology investments. The previous Technology Advancement Project (TAP), which encompassed all technologies being managed within the program, was bifurcated into its two remaining elements. These two projects have been formed to increase individual focus on each project and aid their successful implementation. The Thermoelectric Technology Development Project (TTDP) and the Stirling Cycle Technology Development Projects (SCTDP) were formulated and formally allocated to their performing organizations.

The TTDP and SCTDP projects are managed by the NASA Jet Propulsion Laboratory (JPL) and NASA Glenn Research Center (GRC), respectively. Each project tracks and reports their resources and progress at regular intervals to the RPS Program. Each benefits from better synergy within their locus of technology within the performing organization.

Thermoelectric research on basic materials and device fabrication, described in more detail below, is ongoing at JPL. The Advanced Thermoelectric Materials (ATOM) effort focuses on work at the low TRL end of the spectrum primarily in the area of materials identification and characterization. The Advanced Thermoelectric Devices (ATEC) effort takes these materials and develops them into prototype components and subsystems toward the goal of integration into flight systems. Skutterudite materials first identified in the low TRL activity have been matured through the ATEC process and have advanced to the point of being a candidate for transition to flight systems. A technology maturation effort is currently underway to develop an enhanced MMRTG (eMMRTG). JPL technologists are working with Teledyne Energy Systems, Inc. (TESI) to integrate these new thermocouples into an MMRTG housing. If successful, the net result would be a device with improved performance in beginning-of-life power due to higher efficiency, but also significantly better end-of-mission (EOM) power output due to reduced device degradation. The RPS program has scheduled decision gates by which to gauge progress and determine whether or not to proceed to flight-ready status.

In the Stirling research area, the Advanced Stirling Radioisotope Generator (ASRG) project was cancelled in 2013 due to NASA Planetary Science budget issues. The

flight convertors were being fabricated, the flight generator housings were in hand, and the controller hardware was ready for production. With the termination of the ASRG flight hardware contract, all work on flight hardware was immediately halted. The assets associated with the contract had to be redistributed to government facilities or scrapped. The RPS Program took custody of these assets and distributed them strategically in the best interests of the federal government. Upon termination of the contract and redistribution of the assets, the DOE decertified the hardware produced for flight due to the end of quality and mission assurance surveillance.

Some of this hardware was delivered to GRC and was integrated into a system, referred to as Engineering Unit 2 (EU2). The EU2 mated a pair of the third-generation Sunpower Advanced Stirling Convertors (ASC-E3) in an aluminum housing in a flight-like configuration. A brassboard controller fabricated by the original flight system integrator and electric heating elements completed the EU2 assembly.

The EU2 was successfully operated as a system and its performance was characterized. The system operated as expected, but testing was eventually halted due to output power fluctuations in one of the ASC-E3 convertors. The cause of the power fluctuation is being investigated to help understand the behavior and the remaining unresolved technical issues to inform any future system development. The system did demonstrate successful startup and operation and detailed results of the testing are detailed in Reference 2. [2]

Multi-Mission Launch Approval Engineering

For any U.S. space mission involving the use of RPS, launch approval must be obtained from the Office of the President. The approval decision is based on an established and proven review process that includes an independent evaluation by an ad hoc Interagency Nuclear Safety Review Panel (INSRP) comprised of representatives from NASA, DOE, the Department of Defense, and the Environmental Protection Agency, with a technical advisor from the Nuclear Regulatory Commission.

DOE uses a launch vehicle-specific databook prepared by NASA to develop a Safety Analysis Report (SAR) for the space mission, which plays a critical role in the launch approval process. This report identifies an array of potential accident conditions along with their associated risks. Additionally, the *ad hoc* INSRP conducts its nuclear safety/risk evaluation, and documents its results in a Safety Evaluation Report (SER). The SER contains an independent evaluation of the proposed mission's radiological risk. DOE uses the SER as its basis for accepting the SAR. If the United States Secretary of Energy formally accepts the SAR-SER package, it is forwarded to the head of the mission-sponsoring agency, e.g., the NASA Administrator, for use in the Presidential launch approval process. NASA distributes the SAR and SER to the other cognizant government agencies

involved in the INSRP, and solicits their opinions of the documents. After receiving responses from these agencies, the agency conducts internal management reviews to address the SAR and SER, and any other nuclear safety information pertinent to the launch. If NASA recommends proceeding with the launch, a formal request for nuclear safety launch approval is sent to the Director of the Office of Science and Technology Policy within the Office of the President; the SAR and SER are included with the request. NASA Headquarters is responsible for implementing this process for NASA missions. DOE supports the process by analyzing the response of power system hardware under different accident scenarios and environments identified in the databook, and prepares a probabilistic risk assessment of the potential radiological consequences and risks to the public and the environment for the launch.

Recent investments made by the RPS Program have helped provide tools and test data (Figure 2) that can be used again in future launches, thereby streamlining launch preparation time and reducing costs.



Figure 2. Images of solid propellant motor drop testing and solid propellant fire testing.

Planned work in this area in the coming years includes support for the Mars 2020 launch, scheduled for July 2020, and continued databook development (specifically for the Falcon 9 v1.1 launch vehicle and the Falcon Heavy vehicle). Also planned are real-time RPS re-entry debris field modeling and Mission Flight Control Officer function activities, and analysis of the environments associated with the October 2014 Antares Orb-3 accident. In later years (FY17-18), the team would make improvements to the DSENDS (Dynamic Simulator for Entry, Descent and Surface landing) model, update fragment models, and conduct a large diameter heat shield re-entry analysis.

3. RPS COLLABORATION AND MISSION INTEGRATION

The Program Planning and Assessment (PP&A) element of the RPS Program is responsible for developing and maintaining a comprehensive implementation strategy to meet the stakeholder requirements and expectations of the planetary science community. Entities that are considered to be RPS stakeholders within this text primarily consist of RPS users and mission teams, RPS partners in technology and system development, and the science mission community at large. The flow of RPS research and technology development must be responsive to the needs of potential future NASA science missions. The RPS Program performs this crucial function by conducting mission studies that drive RPS system-level capabilities and mission requirements, and subsequent system studies that drive out generator design requirements. The continuing need for increasingly capable planetary missions that could require RPS has been articulated clearly and repeatedly during the last decade from the National Research Council's 2009 report on RPS [3] through the 2011 Planetary Science Decadal. [4] Implementation of nuclear systems for space flight has never been an easy task. Determining the proper investments, including technology funding, to enable these missions and their scientific discoveries demands a rigorous process that has been refined for decades. In early 2014, on behalf of the NASA Planetary Science Division (PSD), the PP&A group initiated the Nuclear Power Assessment Study (NPAS), which will be discussed in detail throughout the remainder of this section.

Historically, NASA has pursued different approaches for provisioning nuclear power systems. The last Science Mission Directorate (SMD) provisioning study was conducted in 2001 and recommended a dual development strategy that would provide both an SRG and an RTG, for both deep space and Mars surface missions. The MMRTG, currently powering Curiosity, resulted from this recommendation, as did the technology advancement in Stirling RPS through the ASRG project. Given the cancellation of ASRG project and continued technology investments in Fission Power Systems (FPS) by the NASA Space Technology Mission Directorate, NPAS was chartered to examine the provisioning approach for future nuclear power systems, for both radioisotope- and fission-based concepts. [1]

The objective of NPAS was to “discuss a sustainable strategy and present findings for the provisioning of safe, reliable, and affordable nuclear power systems that enable NASA SMD missions and is extensible to Human Exploration and Operations Mission Directorate (HEOMD) needs in the next 20 years.” NASA's PSD sought to understand 1) the potential for commonality between RPS systems for robotic planetary science and the components (and any initial future investments required) in potential fission systems and components, to guide near-term PSD technology investments; and, 2) the opportunities and challenges of a

sustainable, incremental development strategy for nuclear power systems that could be needed to support the efficient development of technology requirements both for SMD needs and future fission capabilities for HEOMD. [1]

NPAS work was performed by the RPS Program in collaboration with NASA centers including GRC, JPL, Goddard Space Flight Center (GSFC), Johnson Space Center (JSC), and Kennedy Space Center (KSC). The DOE and its laboratories, including LANL, INL, SNL, and the Y-12 National Security Complex, also participated. The Johns Hopkins University Applied Physics Laboratory and independent consultants were also contributors. The NPAS was conducted from March through September, 2014. [1]

The NPAS was guided by an Executive Council (EC) and conducted by two primary technical teams: the Mission Study Team (MST) and the Systems Study Team (SST). The two technical teams performed in-depth assessments of mission and systems concepts to address specific considerations provided in the Terms of Reference and answer key questions from the EC. The EC was comprised of stakeholders from the relevant NASA mission directorates and flight centers, the DOE, and nuclear safety experts. The EC assimilated reports from the technical teams and developed the findings contained within the final report. Study participants were selected to span a diverse set of experiences to ensure NPAS encompassed a broad view of technology options, mission concepts, and organizational practices. [1]

Nuclear power system performance, technology readiness, cost, and safety as well as operational flexibility, served as the basis for developing the system options and the Design Reference Missions (DRMs). The Design Reference Systems (DRSs) included conceptual advanced thermoelectrics as well as Stirling convertors, which could be utilized in notional radioisotope and fission system concepts. The technical teams also considered the extensibility of the DRSs to other potential users. The MST evaluated the applicability of the DRSs to smaller NASA Discovery and New Frontiers mission classes. The future needs of NASA HEOMD, as stated in its Mars Design Reference Architecture 5.0, [5] were compared to the potential capabilities of the DRS concepts.

The MST and SST evaluated mission and systems concepts in the context of the entire system development and mission lifecycles. The MST enumerated options for Assembly, Test, and Launch Operations for both RPS and FPS concepts. The technical teams also assessed nuclear safety, launch approval processes, and security implications of the notional systems used by the DRMs. The SST prepared notional flight system development plans and examined the impact of fuel availability, infrastructure, and ground-test activities on the proposed system concepts. Both technical teams developed cost estimates for the power system development and implementation on the DRMs. The detailed technical work performed by the MST and SST was provided to the EC for review. The EC distilled the technical data from the teams into the findings and observation that were presented to PSD for consideration. The NPAS team prepared and delivered a

detailed final report to PSD with all of the study details, findings and observations.

A key finding of NPAS was that nuclear power systems will continue to be a vital option to enable many high-priority SMD mission concepts recommended by the 2011 planetary science decadal survey, and beyond. The power level required for such missions will likely be less than 1 kW_e and therefore would be best met by radioisotope-based solutions. Sustaining this capability requires new plutonium production and funding of the maintenance of the associated DOE infrastructure by NASA. NPAS found that FPS does not represent a good fit for the currently envisioned set of future SMD mission concepts. Due to the size of foreseen FPS concepts, such systems would not likely enable non-orbiting missions such as landers or rovers, and, therefore would not likely address the breadth and depth of the science goals discussed in the current decadal survey. As with several previous studies, NPAS found that FPS has strong promise—and would likely be required—for HEOMD surface missions. [1]

To meet SMD science needs across all flight mission-cost classes, a combination of both thermoelectric and Stirling convertors appear to be most advantageous mix for the foreseeable future. Advancement of these convertor technologies (both static and dynamic) to achieve increased efficiency would have direct benefit to future SMD science mission concepts (including flyby spacecraft, orbiters, landers, and rovers). Continued investments are being pursued to support this advancement and determine the best implementation strategies based on mission-informed system requirements at key decision points in the development. Once successful, these technologies could enable compelling science output by achieving higher power output for longer operational time, balancing plutonium fuel usage and production in support of an increased flight rate. From a NASA perspective, such developments could also help missions remain within budget constraints (via more cost-effective implementations), and help retire mission risk (thanks to more reliable implementations). In any case, it was concluded the outcome resulting from a mix of these two investments would be of significant benefit to the future space science program.

4. DOE RPS ROLES

DOE Operations and Analysis Program

The DOE Operations and Analysis (O & A) Program maintains the personnel skills, mission-supporting capabilities, safety and mission assurance expertise, and physical infrastructure needed to support NASA's future RPS requirements. This sustainment effort is necessary for continued RPS assembly, testing, and analysis to support potential radioisotope-powered missions. These capabilities are dispersed predominantly between four DOE laboratories: Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL). The

laboratories also work closely with each other to achieve mission success.

LANL maintains the capability for fuel processing and fuel clad fabrication. Fuel clads, ceramic Pu-238 pellets in their protective casing of iridium cladding, are encased into a GPHS module. GPHS modules serve as the essential building block for the radioisotope generators and they protect the Pu-238 fuel that gives off heat for producing electricity. Newly produced plutonium dioxide is intended to be added to the existing fuel inventory. Details associated with the production of new fuel will be discussed later within the Plutonium-238 Supply Project section. An expanded view of a fueled clad assembly is shown in Figure 3. LANL also specializes in the purification, pelletization and encapsulation of Pu-238. Additional essential abilities include impact testing, metallography, chemical analysis, nuclear material storage and security, and waste handling and disposal. The associated facilities are housed in a highly secure area.

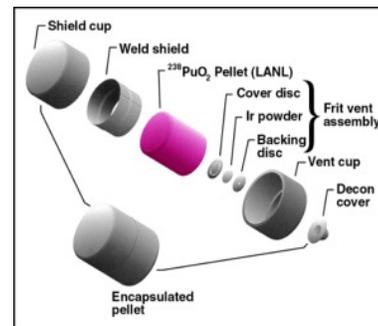


Figure 3. Fueled Clad Assembly.

INL maintains the capability for RPS assembly, storage, testing, and delivery of RPS for NASA, and serves as the Technical Integration Office with respect to the other DOE RPS laboratories and as the Lead Laboratory for quality assurance. Leading up to the assembly of an RPS, INL also develops and procures specialized components/materials, assembles heat source modules, and delivers RPS to the launch site using specialized transportation systems.

ORNL is the lead materials development laboratory for RPS. Their specific capabilities include the manufacture of Carbon-Bonded Carbon Fiber insulation and Light-Weight Radioisotope Heater Unit (LWRHU) components. LWRHU are small heat sources that are typically used to heat critical components and subsystems for spacecraft. ORNL also produces iridium alloy encapsulation hardware for the fuel clads and maintains unique material testing capabilities.

SNL is the lead lab for safety analysis and safety testing capabilities. SNL maintains critical skills and computational tools to assist in evaluating the safety and performance of RPS on NASA missions. In support of mission-specific Environmental Impact Statements (EISs) that are prepared by

NASA, SNL conduct RPS mission risk assessments. In addition, SNL performs nuclear safety analyses, and prepares safety analysis reports to characterize nuclear risks and support mission launch approval.

The keys steps in RPS production are shown in Figure 4.

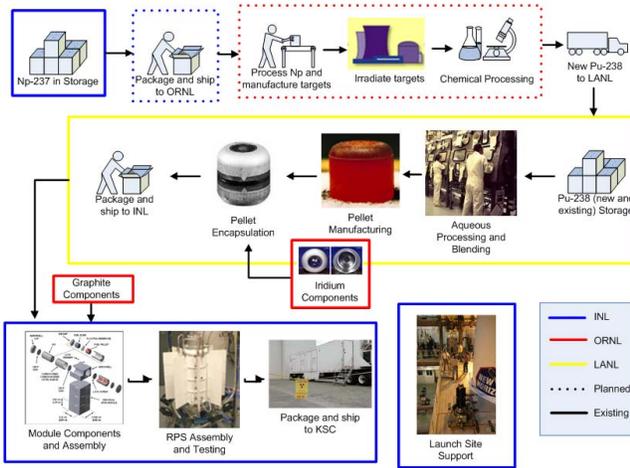


Figure 4. Key Steps in RPS Production

Significant O&A tasks for FY16 include initiating the cold testing of a new hot press and replacing high-priority glovebox windows in Pu-238 laboratories at LANL to provide future redundancy for fueled clad production. Additionally, INL is working to update their safety analysis report for packaging plutonium dioxide to ensure efficient transportation, and LANL is planning to receive and analyze the first sample of newly produced Pu-238 from ORNL. At SNL, the Mars 2020 launch safety analysis for the upcoming mission is being conducted, and the effects of the recent Antares Orb-3 launch accident are being investigated to enhance blast- and impact-modeling capabilities.

Plutonium-238 Supply Project

DOE has initiated a project consistent with NASA’s assessment of its mission needs. The Plutonium-238 Supply Project (PSP) is using existing facilities at the Oak Ridge National Laboratory (ORNL) and the Idaho National Laboratory (INL) to reestablish the capability to produce Pu-238. DOE and NASA agreed on this production rate, as a means to meet projected mission needs on the shortest schedule and within budget constraints. The PSP was initiated with NASA funding in FY12.

The PSP originally intended to reach the full production rate of 1.5 kg/yr in 2021. Based on current projections of available funding, the project now intends to phase in production to better support potential nearer-term missions within the projected budget. This would allow lower rate production earlier than originally planned, possibly as early as 2019, but would slow the scale-up to the full rate as funds allow. To date, the four major production processes shown

in Figure 5 are proceeding well. The Neptunium transfer capability at INL is in place and operational. Targets for the High Flux Isotope Reactor (HFIR) have been qualified, but their production rate will need to increase for ongoing operations. Chemical processing steps have all been demonstrated individually, and are in the process of being demonstrated in sequence. The first end-to-end production demonstration began in the summer of 2015 and will conclude with delivery of a small production sample to LANL for verification testing in FY16. This will be followed by a second demonstration to refine the processes and then a scale-up to production levels over several years.

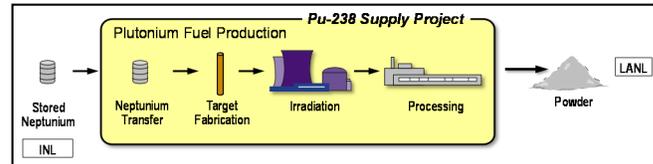


Figure 5. General Process of Plutonium Fuel Production

While NASA has budgeted funding for the cost of reestablishing this Pu-238 production capability for U.S. civil space exploration, DOE retains responsibility for operating a national capability if deemed necessary for a range of federal users and for managing efforts related to the safe and secure production of special nuclear material. The cost of sustaining the production capability for NASA, once established at completion of this project, would transfer and integrate with the NASA-provided funding of the related DOE O&A Program.

5. TECHNOLOGY DEVELOPMENT AND SUSTAINMENT

Thermoelectric Technology Development Project

The TTDP is formulated into three distinct tasks: Advanced Thermoelectric Materials (ATOM), Advanced Thermoelectric Devices (ATEC), and Technology Maturation (TM). These three tasks are scoped for full life cycle development of a given technology. The technology flow and decision gates for these tasks are illustrated in Figure 6 and further described in [6].

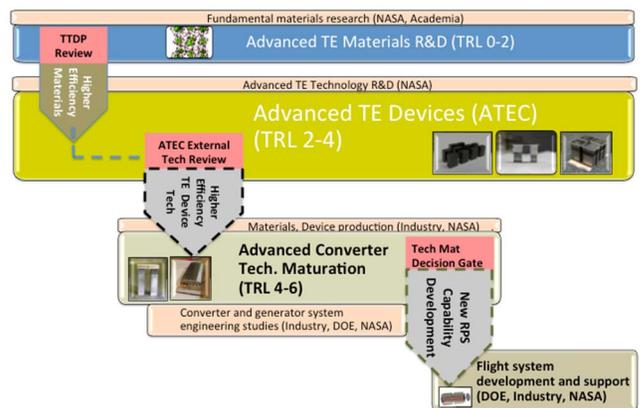


Figure 6. Workflow in the RPS Thermoelectric Technology Development Project.

The ATOM task investigates new thermoelectric materials for performance and manufacturability into a flight-like thermocouple. Initial performance parameter predictions are made, and the materials are fabricated and characterized via test protocols. Specific material performance goals have been established. A long-range goal includes development of a next-generation couple having an efficiency of greater than 18%, nearly three times better than the couples in the MMRTG.

The ATOM task is currently working on materials for segmented thermocouples, which utilize Rare Earth, Skutterudites, and Zintl. These devices are segmented to take best advantage of their properties at a given temperature, leveraging the temperature gradient over the length of the couple. A candidate “next generation” couple is illustrated in Figure 7.

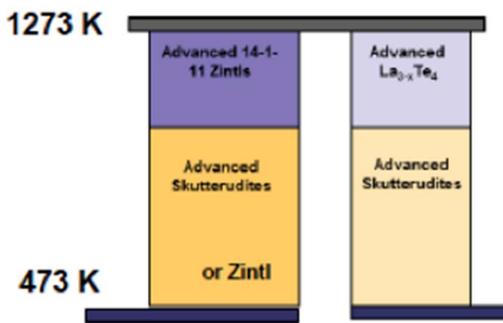


Figure 7. Segmented thermocouple utilizing advanced materials.

In addition to the basic materials work, ATOM also investigates materials issues related to the metallization and bonding of the semiconductor material for electrical contacts. The high temperatures at which these devices operate can drive sublimation of the semiconductors to occur, resulting in

a loss of mass from the thermocouple. This results in a performance loss over time, and can result in the plating of this sublimated material on cooler surfaces within the generator. Anti-sublimation coatings are being developed to mitigate this process. These coatings must survive the high temperature of operation and not react chemically with the devices that they are protecting.

The ATEC task further develops the most promising materials identified by the ATOM task into flight-like devices and modules as candidates for infusion into flight designs. The task investigates and resolves issues concerning materials strength and stability, develops fabrication processes and procedures, fully characterizes device degradation over time, and evaluates possible performance improvements.

Like the ATOM task, ATEC has established performance criteria and deliverables for the objective evaluation of the devices to determine their suitability for eventual integration into flight hardware. These criteria are accompanied by set standards for accelerated life tests and other tests, with clear success definitions that are designed to extensively characterize the materials and devices and inform any decision to proceed to flight. Tests are performed on both single devices and modules to develop an extensive performance database for the configurations planned. [7]

Skutterudite-based couples are currently the most mature couple developed under ATEC. JPL is transferring this technology to TESI for further technology maturation and potential integration into the current MMRTG housing under the STM task. This development model, illustrated in Figure 8, allows for the direct interaction of the technologists who developed the couples with the flight hardware vendor. The insertion of these advanced couples into an MMRTG could result in an enhanced MMRTG (eMMRTG).

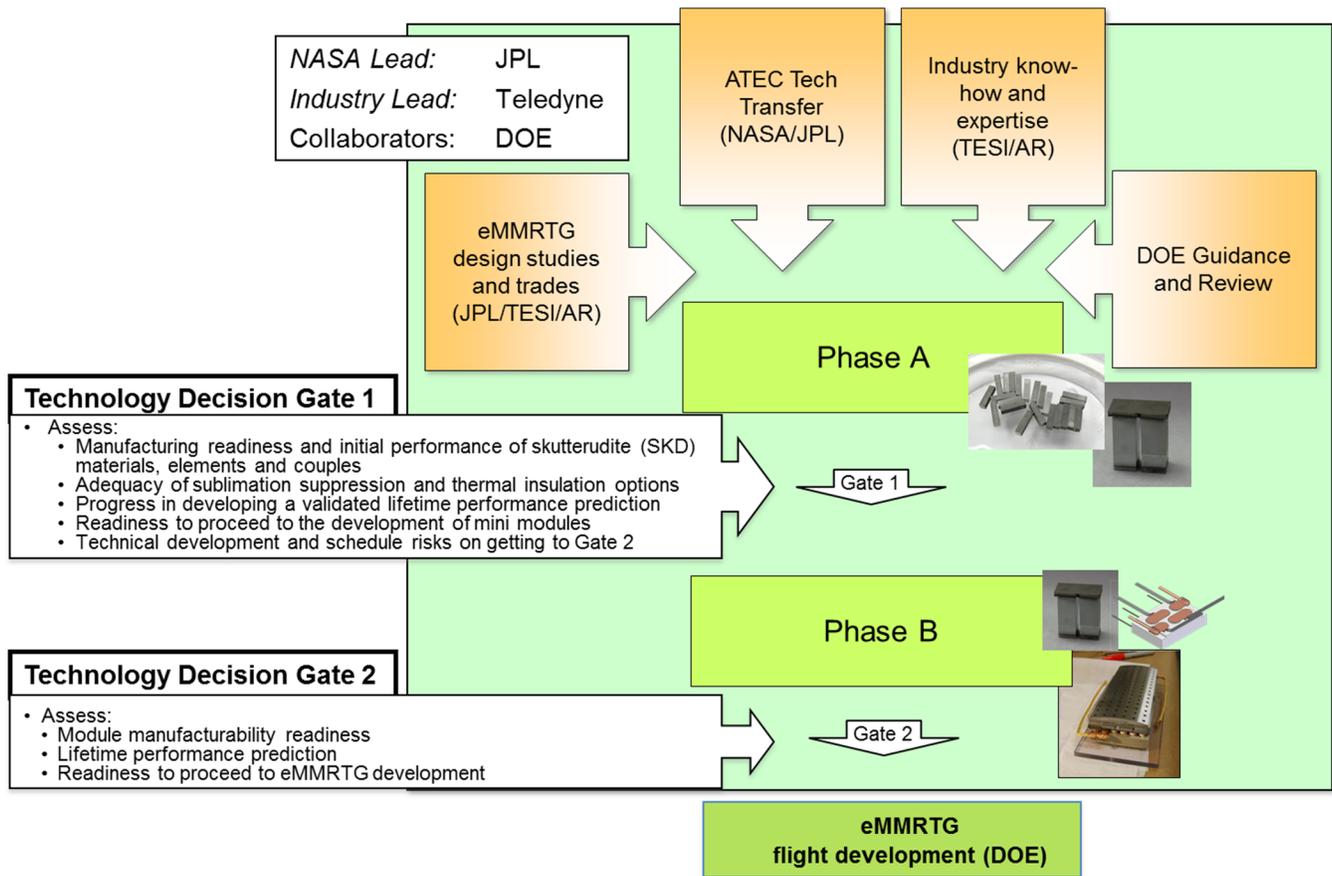


Figure 8. Technology Maturation Model as Currently Utilized for the eMMRTG.

Upon successfully meeting criteria for the second Gate review, the RPS Program may work with the DOE to initiate a flight system development that would use the SKD technology, along with minor system modification, to develop an eMMRTG. Installing the couples into the MMRTG with minimum design accommodations should result in a cost savings in qualifying this new generator design. The eMMRTG would provide higher conversion efficiency, leading to greater initial power; however, the greater return on investment would be the reduced degradation over time predicted for the Skutterudite couples, resulting in end-of-design-life (EODL) power being significantly higher than the existing MMRTG EODL power. As a result, this should enhance end-of-mission (EOM) power when compared to the MMRTG currently on Curiosity. Such an improvement would be highly significant for mission concepts with long cruise and operational timelines, as is the case for many current RPS-powered missions, since the power system must be sized for EOM power requirements. This performance improvement could potentially result in fewer RTGs being needed to support a given mission concept, saving cost and complexity, and preserving fuel for future missions.

Stirling Cycle Technology Development Project (SCTDP)

The Nuclear Power Assessment Study (NPAS) [1] and the current Planetary Science Decadal Survey [4] have affirmed

the long-term need for high-efficiency power conversion technology for future planetary missions. Stirling cycle technology, like that of the former ASRG project, would provide a factor of four reduction in plutonium-dioxide fuel needed to produce a given power level when compared to RTGs.

Under the SCTDP, work continues at GRC and Sunpower on Stirling convertor, thermal management and controller tasks. While lagging somewhat behind the TTDP, this effort will eventually follow the same model, with low- and mid-TRL work followed by a technology maturation effort. The details of this organization will emerge following the final close out of the ASRG flight project, which has just been completed. Performance criteria and deliverables are under development.

Low-TRL work currently underway involves generator component-level testing, in materials and subsystems. [8][9] In the area of improved thermal control, work on multi-layer insulation (MLI) continues toward the goal of reduced mass and improved heat transfer when compared to the current insulation. Preparation for thermal-vacuum testing is shown in Figure 10.



Figure 10. Twenty-five layers of MLI applied and installed into vacuum chamber.

Additional component research that could benefit a potential future Stirling system is being performed. A Radial Core Heat Spreader (RCHS) has undergone testing in progressively more flight-like environments. The RCHS uses radial heat pipe technology to improve low temperature heat rejection for the cold side of a Stirling engine. This concept has been validated in the laboratory and has been successfully flight tested on a zero-g aircraft and sounding rocket. [9]

The Applied Physics Laboratory developed a Dual Convertor Controller (DCC) as a technology demonstration under the TAP. The controller is capable of operating two ASCs as an opposing pair, as was planned for the flight configuration of ASRG and is single-fault tolerant. Work to characterize the dynamic response of the controller and its interaction with ASCs continues.

To improve the environmental operational envelope for future systems, tests are characterizing magnets and organic compounds capable of operation at higher ambient temperatures. A potential deficiency identified in the ASRG was operation in high-albedo environments such as certain Venus flyby trajectories. The higher heat rejection temperatures increase the operating temperatures of the alternator magnets and the organic compounds used in the linear alternator. Margin is required against the Curie temperature of the magnets, and alternative magnets have been identified and are in the qualification process.

The mid-TRL content of the project is focused around the components developed under the ASRG project. ASC-E3s represent the most advanced development within the project, of free-piston convertors prior to the flight units. An ASC-E3 pair was installed into an aluminum Generator Housing Assembly with flight-like insulation and electric heating elements to simulate GPHS modules. A Lockheed Martin prototype controller based on the flight design was integrated with these components to complete an electrically heated demonstration system. This system, known as EU2, was successfully operated, demonstrating startup, steady-state

operation, and limited fault recovery. Following these checkout tests, the system was placed on long-term operation, shown in Figure 11. Power fluctuations in the convertors were observed after a relatively short period. The root cause of these is under investigation.



Figure 11. EU2 long-term operations configuration with command and data rack.

The maturation plan for SRG technology is currently under development. Following the cancellation of the ASRG project, PSD made the commitment to continue to invest in SRG technology. The RPS Program has begun plans with DOE for a reformulated flight hardware development project.

A Request for Information to establish whether the industrial base for Stirling convertors may be applicable to a flight system was released in June of 2015. [9] Requirements are being written for a Stirling technology application. A cross-organizational team that includes members from the DOE and NASA, including mission and system engineers as well as technology experts, has been formed to review the RFI data and recommend a plan forward. The team should understand this plan by the end of 2015. The goal of the Stirling development remains to deploy a highly fuel efficient, robust power system for potential space mission use.

Sustainment

NASA works in close collaboration with DOE to maintain and improve the systems and capabilities necessary to produce RPS for future NASA missions. Since FY14, NASA has provided funding to DOE for infrastructure funding to maintain RPS capabilities. This method, directed to NASA by the Office of Management and Budget and Congress, seeks to transition to a full-cost recovery approach for activities benefitting NASA, yet performed by DOE and their operational laboratories, staff, and other facilities. The details of this effort were previously detailed herein.

Construction of the thermocouples that convert the heat of decay of Pu-238 into electricity is a critical technology that must be sustained to ensure availability of RPS for future missions. In order to maintain this capability, the RPS program funds a sustainment activity wherein thermocouples of the design used in MMRTG are fabricated for test, storage, or integration into a flight capable system for future mission integration. The quantities produced strike a balance between maintaining the capability without creating a hardware surplus, thus maintaining an effective availability.

The RPS Program must also sustain the technology base within the agency for power conversion. NASA is committed to maintaining a cadre of expert technologists in the areas of static and dynamic power conversion technologies to support the application of these devices to future missions. Some of these resources are allocated to low-maturity technologies that target performance improvements with the eventual goal of flight hardware implementation. The TTDP project maintains this capability at JPL, wherein critical skills in materials and device fabrication reside. As the Skutterudite technology previously described is transferred to industry, work will continue on the next generation of devices.

NASA's PSD has also decided to sustain a level of Stirling technical support at GRC and convertor manufacturing at Sunpower as a part of the RPS program's baseline. High-efficiency Stirling power generation remains a critical technology for the future of Solar System exploration, and could be enabling for missions where the MMRTG or eMMRTG may not meet requirements. In addition, Stirling systems would extend the utility of the nation's limited supply of plutonium dioxide fuel for civil space RPS.

The program is currently considering development of a new Stirling Radioisotope Generator (SRG) system for potential flight opportunities in the next decade. Plans are being made with the DOE to assess the state of the art in dynamic power conversion and to develop the requirements for a generator in the 100-500W_e output class. Following development of the requirements set, a technology maturation effort modeled after the current eMMRTG project would develop the conceptual system to the qualification unit level. Following this, flight hardware could be fabricated. The technology maturation phase would begin in FY16.

6. CONCLUSION

With substantial participation from the user community, NASA centers, and the DOE, the RPS Program continues to provide power for planetary science spacecraft. Together we are paving a path for future space exploration through conducting mission and system studies, tests and analyses, technology development and sustainment of capabilities. RPS continues to fulfill mission needs while strategically managing the resources required to enable and enhance ambitious solar system exploration in this decade and beyond.

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BIOGRAPHY



John Hamley is the Manager of the Radioisotope Power Systems (RPS) Program. The RPS Program Office works with the Department of Energy to ensure the availability of RPS for NASA's planetary science missions where more traditional power systems cannot enable the mission, or where the RPS will significantly enhance the mission capability.

Hamley joined NASA in 1985 developing digital data acquisition and control systems for space flight experiments. He has held positions of increasing responsibility including leading development of flight power and control avionics for electric propulsion and space plasma devices. He has held Branch Chief positions in space test engineering and flight project offices and was the Chief of the Science Division. He was also the Chief of the GRC Constellation Office and center point of contact for the Constellation Program.

Most recently he was the Acting Deputy Director of the Space Flight Systems Directorate. In this position, he supported the Space Flight Systems Directorate Office in center-level planning, organizing, and directing of activities required to develop flight and ground systems in support of NASA's exploration and science objectives.

Hamley received his bachelor's degree in electrical engineering from the Youngstown State University in 1985. He also received master's degrees in electrical engineering and business administration from Cleveland State University in 1990 and 2003.



Name: **Peter W. McCallum**
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Office: Glenn Research Center
Years of Experience: 36
Biography: From 2009 to 2015 Peter was the Program Control Manager for the Radioisotope Power Systems (RPS)

Program. He managed all business aspects of the RPS Program, including procurement, configuration management, schedules, and financial controls and reporting. The RPS Program has averaged approximately \$75M/year and works with a variety of partners, including the Department of Energy, to produce spacecraft power systems. His past experience includes 8 years as the Chief of Glenn Research Center's Office of Environmental Programs.

This involved developing programs and oversight to ensure compliance with regulatory requirements of the Nuclear Regulatory Commission (NRC), the Occupational Safety and Health Administration (OSHA), and the Environmental Protection Agency (EPA). Prior to that, Peter was the environmental compliance manager for BP Chemicals in Lima, OH and for Kennecott Utah Copper in

Salt Lake City. He has a Bachelor's Degree in Chemical Engineering and a Juris Doctorate.



Carl E. Sandifer II has over 10 years of aerospace and project management experience with concentration in mission design and analysis, trajectory optimization, risk management, and requirements development. Currently, Carl serves as the Acting Program Control Manager within the NASA Radioisotope Power Systems (RPS) Program Office and as a liaison and partner to the Infrastructure Capabilities Program within the Office of Space and Defense Power Systems of the Department of Energy to maintain the personnel skills, mission-supporting capabilities, safety and mission assurance expertise, and physical infrastructure needed to support NASA's future RPS requirements. Carl earned a Bachelor's degree in Applied Mathematics at Bowling Green State University, continued postgraduate aerospace studies at Case Western Reserve University, and will earn a Masters in Business Administration at Indiana Wesleyan University during the summer of 2016.



Thomas Sutliff has been employed at the NASA Glenn Research Center in Cleveland, Ohio for over 30 years. Mr. Sutliff currently is Deputy Program Manager of the Radioisotope Power Systems Program, supporting NASA's Science Mission Directorate. He has extensive experience in program and project management at NASA, including flight system leadership for space station and shuttle microgravity science payloads.

Prior to his project management roles, Tom managed Glenn's Structural Dynamics Laboratory, conducting vibration tests and data analyses in that lab, as well as performing structural analyses and mechanical system designs.

Mr. Sutliff's educational background includes a Bachelor's degree in Mechanical Engineering from Rose-Hulman Institute of Technology, and a Master's degree in Mechanical Engineering, with a focus on structural dynamics, from the University of Toledo. Mr. Sutliff is certified as a Project Management Professional by the Project Management Institute.



June F. Zakrajsek has over 20 years of aerospace systems development, research and project management experience. She has led internal discipline teams for space systems health management, ISS power systems analysis, and Biotechnology. She has worked as a project manager in the areas of health management, systems engineering and analysis, propulsion system development, Orion Crew Module and Test & Verification, and Radioisotope Power Systems. Currently June serves as the Program Planning and Assessment Manager for NASA's Radioisotope Power Systems Program. This area is responsible to develop and maintain the implementation strategy for the Program by managing mission and systems analysis functions, integration of new technology into generators, and interfaces with potential missions considering utilizing Radioisotope Power Systems. She holds a Masters in Biomedical Engineering from Case Western Reserve University and Masters and Bachelors in Mechanical Engineering.