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Constant Rate Production: DOE Approach to Meeting NASA Needs for Radioisotope Power Systems for Nuclear-Enabled Launches

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Abstract: The use of radioisotope power systems (RPSs) for nuclear-enabled National Aeronautics and Space Administration (NASA) missions is made possible through a long-standing arrangement between the Department of Energy (DOE) and NASA. The requirements for the power system come from NASA, but DOE performs the procurement, fueling, testing, and delivery. A challenge has been interplay between the schedule for RPS availability from DOE versus the schedule for competitively selected missions. By mutual agreement, the actual operations to procure an RPS and prepare it for fueling have always been delayed until the final selection of a mission. The timeline for a New Frontiers–class mission leaves approximately 5 to 6 years from the time of final mission selection to the actual launch date. The number of RPSs used for a New Frontiers–class mission can be one to three units. If one or two units are needed, the timeline from the decision point to the launch date is a challenge, but it is achievable. The activities taking place include manufacturing the power system, producing the fuel, and performing the assembly/testing and delivery operations. If the mission selected requires three RPSs, the logistics of accomplishing all activities during the 5–6 years is problematic. The challenge involves obtaining the necessary resources for plutonium production, heat source production, and assembly/testing operations. Typically, the time between RPS-enabled missions requires staffing reduction down to 65%–75% of peak staffing levels to reduce costs. Coupling the ~2 year duration needed for hiring, training, and obtaining the appropriate security clearances for the required staff with the requirement for the RPS to arrive at Kennedy Space Center 6 months before the launch erodes much of the 5–6 years available to comfortably support the use of three RPSs. To provide better support for NASA RPS missions, a different approach for the production of heat sources was devised—constant rate production. This involves a higher level of base capability at DOE national laboratories to provide a stabilized workforce. This will enable 10–15 heat sources to be produced annually and placed into a stable intermediate form to enable storage for up to several years leading to quick production of general purpose heat source modules when a mission is selected. The upfront production of ^{238}Pu is maintained so material is constantly in the pipeline. Production of key specialized components is also maintained using this model.

Keywords: Plutonium-238 Production, Radioisotope Power Supply, Deep Space Mission

1. Introduction

The production of the radioisotope power systems (RPSs) for use by the National Aeronautics and Space Administration (NASA) is the duty of the Department of Energy (DOE) [1]. This relationship has existed since the late 1960s. It has primarily operated in a mission-oriented fashion with periodic staffing fluctuations based on NASA's needs. The most dramatic example of this occurred in the mid-1980s with the shipment of the final batch of heat sources for the Galileo and Ulysses missions in early 1984. After shipment, funding was reduced immediately from >100 full-time employees to <5 full-time employees [2] at the heat source production facility at the Savannah River Site. The equipment was quickly placed into standby, and promises of additional funding did not come to fruition until roughly 1990 because of a variety of factors. When power systems were desired for the upcoming Cassini and Comet Rendezvous Asteroid Flyby (CRAF) missions starting in 1991, the program moved to Los Alamos National Laboratory (LANL) because of the expense of staffing Savannah River to support the missions. At the end of the 1980's DOE shut down the nuclear reactor used to produce new ^{238}Pu. In 2001, DOE decided to restart domestic production of ^{238}Pu [3, 4, 5]. The existing supply of ^{238}Pu is limited and new domestic production will be needed to support NASA missions during the next decade [6, 7]

The use of a constant rate production plan generates a specified amount of ^{238}Pu each year at Oak Ridge National Laboratory (ORNL). The ^{238}Pu is then shipped to LANL to be made into heat sources, and then the heat sources are shipped to the Idaho National Laboratory (INL), where they are placed into a stable storage state and remain ready to be made into general purpose heat source (GPHS) modules. This approach is intended to create a stable workforce situation for the RPS infrastructure. It also has the advantage of lessening the cost to individual NASA missions. The implementation of this approach will be explained in this paper with an emphasis on the program participants.

2. Plutonium Production

A block flow diagram of the ^{238}Pu supply process is shown in Figure 1 [8, 9]. Neptunium dioxide (NpO_2), previously recovered at the Savannah River Site and currently stored at INL, is packaged and shipped to ORNL as needed. ORNL dissolves the NpO_2 in nitric acid and removes the ^{233}Pa daughter (which emits 300 keV gamma radiation) to enable target fabrication in lightly shielded glove box facilities. ORNL will fabricate targets for the INL Advanced Test Reactor and the ORNL High Flux Isotope Reactor (HFIR) from the makeup neptunium (~15%) and recycled neptunium (85%) recovered from the irradiated targets. The targets are then shipped to each reactor as production and irradiation schedules demand and are irradiated in each reactor to convert ^{237}Np into ^{238}Pu.

The irradiated targets are returned to ORNL for chemical processing to recover ^{238}Pu as product and ^{237}Np for recycle. After separation, the unconverted ^{237}Np is fabricated into recycle targets. The ^{238}Pu separated from the irradiated targets is converted into heat source PuO_2 powder and is packaged and shipped to LANL, where PuO_2 pellets are manufactured for RPSs. All process work for the production project will be performed in existing facilities.

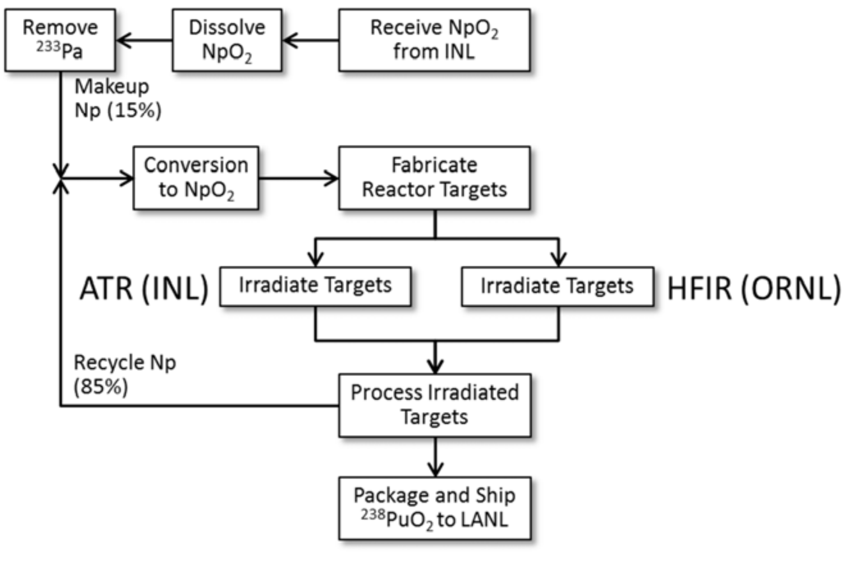

Figure 1. *High-level block flow diagram of ^{238}Pu supply process.*

Chemical process steps are being developed using targets irradiated in the ORNL HFIR [10]. As additional irradiated targets become available, they will be used in further process improvement tests, and the ^{238}Pu recovered from these tests will be used in future NASA missions.

Figure 2 illustrates the planned timeline for constant rate production. During fiscal years 2017–2019, ORNL will

(1) install and operate automated equipment for target fabrication;
(2) design, procure, and install equipment to package the newly produced ^{238}Pu for shipment to LANL [11];
(3) fabricate targets for irradiation in HFIR;
(4) initiate target design work for the Advanced Test Reactor and conduct scoping tests; and
(5) run chemical processing campaigns to recover Np for recycle and Pu as product.

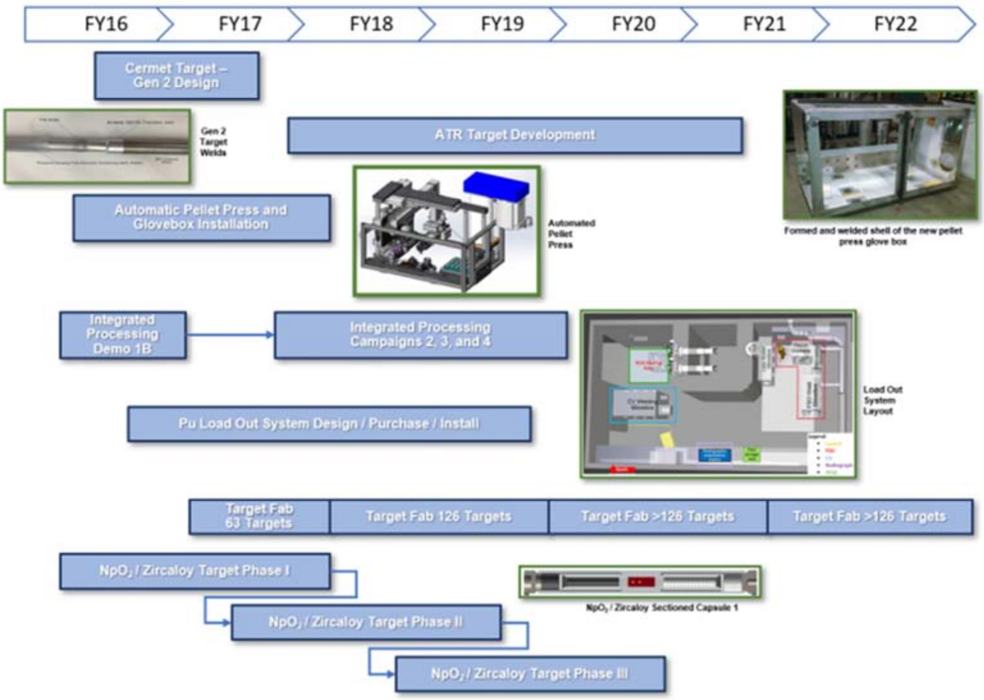

Figure 2. *Plutonuium-238 Supply Program timeline.*

At the end of fiscal year 2019, the process of scaling up beyond 400 g/y will be initiated. Production is expected to scale from 400 to 1,500 g/y, similar to the curve shown in Figure 3. In Figure 3, the blue curve shows the annual production rate in terms of grams per year. Initially only HFIR is used for production, and the Advanced Test Reactor will come online such that both reactors are used to make the entire 1,500 g/y in fiscal year 2026. The red curve shows the cumulative new production. Since new heat sourcePuO_2 will be blended with older material, the usable amount of heat source PuO_2 is larger than the cumulative amount of new production. The usable amount of heat source PuO_2 is depicted by the green curve.

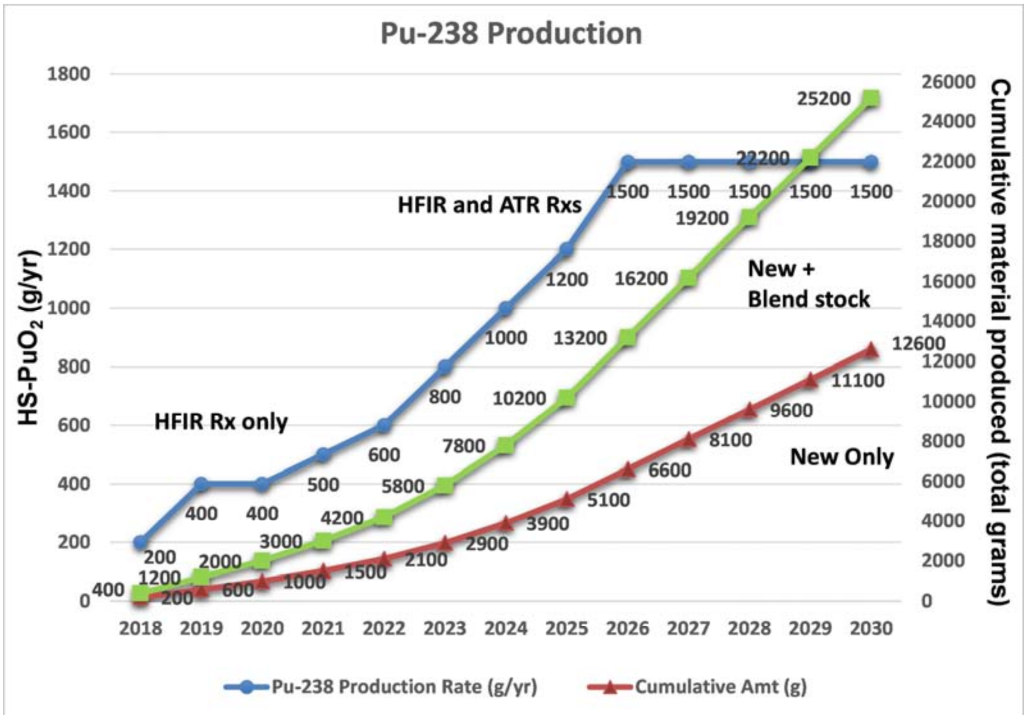

Figure 3. *Pu-238 production projections.*

3. Special Component Manufacturing and Testing

ORNL also produces special materials and components and provides technical support as needed. These production and support efforts involve materials design, development, and testing with emphasis on the design, production, testing, acceptance, and delivery of iridium alloy clad vent sets (CVS) [14,15], carbon-bonded carbon fiber (CBCF) [16], platinum alloy components for light weight radioisotope heater units plus other associated materials and components [17]. Materials science and engineering assistance are provided along with materials joining expertise and materials technology support. Additionally, specialized testing is performed to provide engineering data, support safety analyses, or both [18].

Figure 4. *Iridium alloy clad vent set.*

The CVS and CBCF insulator sets are for use in GPHS modules. The CVS, shown in Figure 4, are supplied to LANL for encapsulation of heat source PuO_2 pellets to make fueled clads, whereas the CBCF insulator sets are sent to INL for assembly into GPHS modules. ORNL is also responsible for producing platinum–rhodium (30%) components for light weight radioisotope heater units needed to maintain spacecraft temperatures for proper operation of instruments and other components [19, 20]. All production activities are performed under full configuration control. The ORNL RPS special component manufacturing and testing program consists of approximately 12 full time employees and about 60 pieces of equipment.

The CVS production process uses iridium alloy blanks and foils. The blank manufacturing process (Figure 5) begins with preparation and blending of iridium and tungsten powders followed by electron beam melting, arc melting for thorium and aluminum alloy additions, vacuum arc remelting, extrusion, rolling, electrical discharge machining, and inspection with numerous cleaning and heat treatment operations interspersed throughout the process. Processing from powder to certified blanks takes approximately 9 months.

An additional 6 months is required to produce certified CVS. The iridium alloy blanks are sandwiched between tantalum foil discs, which are then sandwiched between stainless steel waster sheet discs. A circumferential electron beam seam weld is made to complete a blank assembly. Blank assemblies are deep drawn warm (925°C) into cups using two draws. The tantalum and stainless steel are chemically removed, and the cups are acid cleaned before recrystallization. Iridium undergoes significant work hardening; consequently, subsequent fabrication operations involve grinding, lapping, and electrical discharge machining, but no turning or milling. Assembly of various foil components with the finished cups is accomplished using the electron beam weld process.

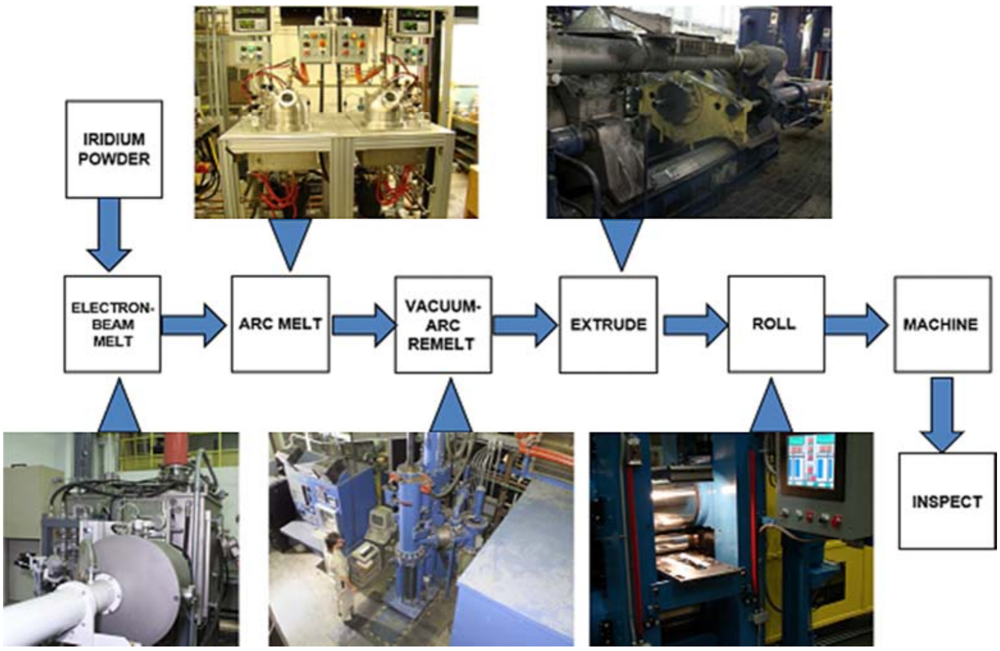

Figure 5. *Iridium alloy blank production process.*

The other long-lead special components are the CBCF insulator sets—sleeves and discs (Figure 6). Fabrication of CBCF begins with aerospace-grade rayon fiber (Figure 7) and phenolic resin (Figure 8). The fiber is precision chopped to nominally 0.5 mm length and carbonized under an inert gas atmosphere at 1400°C, shrinking the diameter and length. After the carbon fibers are deagglomerated, they are mixed with the phenolic resin and water. The prepared slurry is vacuum molded to make either plate or cylindrical preforms. After drying and resin curing, the preforms are carbonized at 1600°C under an inert atmosphere. The preforms are machined by single-point turning on a lathe to produce finished sleeves and discs. These are dimensionally inspected by non-contact methods and radiographically inspected. Specimens are removed and vacuum outgassed at 1500°C for 40 hours before characterization for density, compressive strength, thermal conductivity, ash, and impurities. The total time for CBCF fabrication and certification is more than 6 months. Currently, efforts are underway to identify and qualify new suppliers for aerospace-grade rayon fiber, fiber chopping services, and resin to ensure long-term inventories of starting materials.

Figure 6. *CBCF insulator set.*

Figure 7. *Continuous rayon fiber tow.*

Figure 8. *Phenolic resin.*

Long processing durations are common for making iridium alloy blanks, foils, CVS, and CBCF. However, once the processing "pipelines" are full, the specialized components can be produced in quantities greatly exceeding the requirements for constant rate production. Steady-state annual production capabilities are approximately 300 blanks, 100 CVS, and 70 CBCF insulator sets.

4. Fuel and Fueled Clad Production

LANL is responsible for the manufacturing the GPHS clads [21]. Before constant rate production, fueled clad production was performed only when NASA missions required nuclear heat sources. The campaign production mode required regular restart activities and resulted in significant resource fluctuations. To support constant rate production, LANL will increase manufacturing to 10–15 flight-quality fueled clads per year, creating an inventory of clads that will be available for future missions. Constant rate production also facilitates constant staffing levels of trained personnel, eliminates restart activities, and maintains an efficient manufacturing process.

Figure 9 shows the manufacturing process for GPHS clads. The oxide will be purified through aqueous processing, which includes dissolution, oxalate precipitation, and calcination. Aqueous purification removes impurities from the fuel that could impact pellet fabrication and eventually interact with the iridium cladding. Oxide fabricated at ORNL will eventually be used during the manufacturing process once the current inventory within specification is unavailable. Based on manufacturing projections, the remaining Russian-procured oxide will be consumed by 2022, and future manufacturing operations will consist of blended ORNL and out-of-specification fuel.

Figure 9. *GPHS fueled clad manufacturing process.*

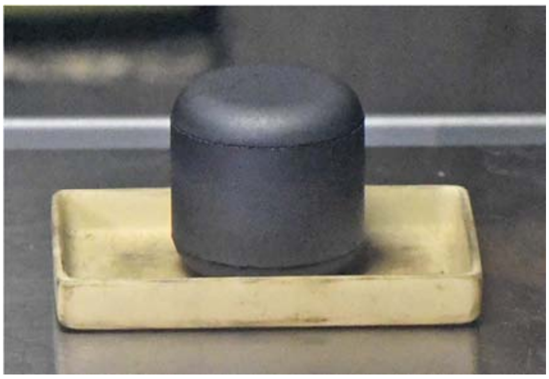

Figure 10. *Plutonium-238 ceramic pellet.*

Fuel processing operations prepare the oxide product to fabricate the ceramic ^{238}Pu pellet (Figure 10), which is encapsulated in the iridium clad. Nondestructive testing is performed to validate the clad meets safety class and flight-quality requirements. All operations are performed and verified per RPS quality requirements and validated during the process. Once the clads have been determined to meet specifications, they are then packaged into 9516 shipping containers and transported to INL. All manufacturing from aqueous processing to clad decontamination are performed within glove boxes, and all operations must meet safety management program requirements as defined by the plutonium facility's design safety analysis to ensure safety of the environment, public, and workers.

To meet constant rate production by fiscal year 2019, LANL will be manufacturing product at its highest rate since the Cassini mission in the late 1990s. Figure 11 outlines the production history and future strategy. Integration with other programs in the nuclear facility started in fiscal year 2017, and equipment projects are ongoing to modernize and replace aging equipment to increase reliability and productivity of the manufacturing process. LANL is implementing the following upgrades:

(1) Install and perform operational readiness on a new hot Press (designated Hot Press #4).
(2) Install and perform operation readiness on additional furnaces.
(3) Complete a 9516 cask welder upgrade for shipping activities.
(4) Modernize ultrasonic testing system.
(5) Modernize control systems for safety testing.
(6) Process improvements to address radiological and ergonomic concerns for workers.

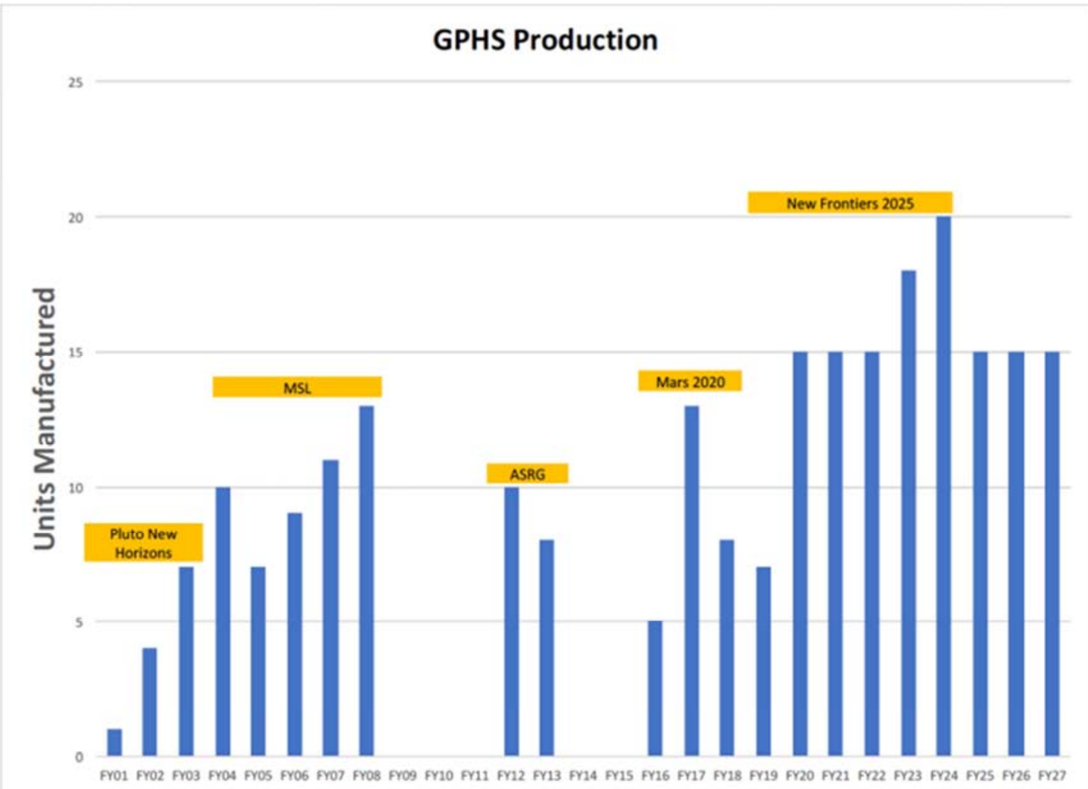

Figure 11. *LANL GPHS production.*

5. RPS Assembly and Testing

INL performs the final assembly of the various components (generator, fueled clads, fine-weave pierced fabric pieces, and CBCF insulator sets), resulting in a fully functionable radioisotope power system [22, 23]. The system is subjected to various acceptance tests as requested by the NASA customer [24]. The suite of testing capabilities at the INL consists of 1) vibrational testing to simulate a launch environment, 2) mass properties testing to confirm the center of mass, 3) magnetic property testing to confirm that the magnetic field generated from the power system is below a specified value, 4) power system measurements in simulated space-like environments, and 5) radiation field measurements to ensure proper radiation safety preparations.

The implementation of the constant rate production mode of operations will lead to annual shipments of fueled clads being received from LANL that may not be used for several years. These heat sources will be part of an annual campaign where they are taken through most of the process to construct GPHS modules stopping just short, with placement of the heat sources into graphite impact shells. These fueled shells are then placed onto the module reduction manifold where they will be subjected to environmental conditions that prepare the PuO_2 for use in a power system. This condition is stable and allows these items to be used in the future for a new mission.

When the mission is selected and it is necessary to construct the GPHS modules, the various graphite impact shells will be inventoried, and a build plan will be written. The shells will be matched based on two criteria: 1) the thermal output of the heat sources in watts and 2) the neutron emission rates. In general, the goal is to balance the total thermal output of the GPHS module so that the various modules are all roughly equal and to balance the neutron emission rate to be roughly equal as well.

The annual activities will serve the goals of maintaining qualifications of the workforce and ensuring that there is "product on the shelf" to lessen the ramp-up time required for a mission.

6. Conclusion

DOE and NASA are committed to reestablishing the capability to make new supplies of ^{238}Pu and to provide for an RPS production infrastructure to support NASA deep space missions for the next decade and beyond. This paper has described the implementation for DOE's constant rate production approach. This approach is advantageous because it stabilizes the workforce, minimizes fluctuations in staffing, and reduces the cost of RPSs for missions.

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