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Full Length Article

Application of lean manufacturing principles to improve a conceptual ^{238}Pu supply process☆

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ABSTRACT

The mission of the United States (U.S.) Department of Energy's Pu-238 Supply Project is to rebuild capability to produce ^{238}Pu at the kilogram scale in the U.S. This radioisotope is used by the National Aeronautics and Space Administration (NASA) to power deep space probes, and the supply is dwindling. It was last produced in the U.S. in 1988. A conceptual design of a ^{238}Pu supply process is described that uses existing processes and facilities at Oak Ridge National Laboratory's Radiochemical Engineering Development Center. The rate-limiting section of the conceptual process was analyzed using discrete-event system simulation to determine expected production rates, bottlenecks, and the effects of time delays on the production rate. Process alternatives were generated based on Lean Manufacturing principles, and those were examined and compared to the original process using simulation to identify better operating strategies.

1. Introduction

The Pu-238 Supply Project was initiated in 2011 at Oak Ridge National Laboratory's (ORNL) Radiochemical Engineering Development Center (REDC) in Oak Ridge, Tennessee. The purpose of the project is to reestablish capabilities to produce plutonium-238 oxide ($^{238}PuO_2$) in quantities useful for fabrication of plutonium-powered radioisotope power systems (RPS) [1] by the early 2020 s at ORNL. RPSs are used by the National Aeronautics and Space Administration (NASA) to power deep space probes and planetary rovers. ^{238}Pu is produced by irradiating neptunium-237 (^{237}Np) with neutrons in a nuclear reactor. ^{238}Pu production began in the U.S. in the early 1960s and continued until 1988 at the Savannah River Site (SRS) [2,3] near Aiken, South Carolina. After ^{238}Pu production ceased at SRS and facilities were decommissioned at that location, ^{238}Pu was purchased from Russia from 1992 until 2009. In 2009, Russia halted further sale of ^{238}Pu to the U.S. and attempted to negotiate a better contract. A new contract was never achieved, and the U.S. has not been able to purchase ^{238}Pu from Russia since that time. At present, there is no other ^{238}Pu supplier and the U.S. has only enough ^{238}Pu in storage [4] to power a handful of future space missions. ^{238}Pu production must be restarted if NASA is to continue deep space exploration using plutonium-powered RPSs.

The U.S. Department of Energy (DOE) and NASA have established expectations for a modern ^{238}Pu supply process [5]:

- The process must use existing infrastructure and facilities at ORNL rather than build new nuclear facilities to reduce setup cost, but equipment and support services may be modified, as needed.
- The process must have capability to produce 1500 g heat source PuO_2 (HS-PuO_2)/year on average. HS-PuO_2 is defined as pluto-

Abbreviations: Am, americium; ATR, advanced test reactor; Bk, berkelium; Cf, californium; Cm, curium; CONWIP, constant work in process; CT, cycle time; DOE, US Department of Energy; Es, einsteinium; Fm, fermium; HFIR, high flux isotope reactor; HNO_3, nitric acid; HS-PuO_2, heat source plutonium oxide; INL, Idaho National Laboratory; LANL, Los Alamos National Laboratory; NaOH, sodium hydroxide; NASA, National Aeronautics and Space Administration; Np, neptunium; ^{237}Np, neptunium-237; $^{237}NpO_2$, neptunium-237 oxide; ^{238}Np, neptunium-238; ORNL, Oak Ridge National Laboratory; ^{233}Pa, protactinium-233; pH, negative $\log_{10}$ of hydrogen ion concentration; Pu, plutonium; ^{238}Pu, plutonium-238; Pu-238, plutonium-238; REDC, Radiochemical Engineering Development Center; RPS, radioisotope power source; SRS, Savannah River Site; TH, throughput; VSM, value stream map; WIP, work in process.

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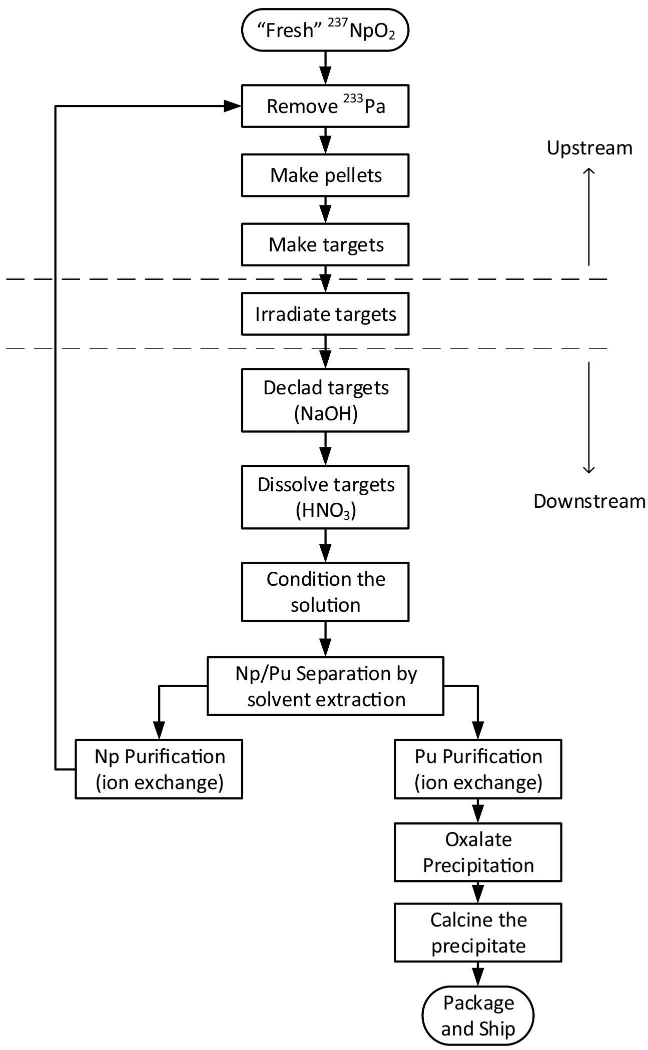

Fig. 1. Block diagram of baseline ^{238}Pu supply process.

nium oxide containing sufficient ^{238}Pu isotopic content to meet NASA RPS specifications [6].

- The product must be a drop-in replacement for HS-PuO_2 feed material used currently in Los Alamos National Laboratory's (LANL) RPS pellet-making process.

The Pu-238 Supply Project identified a conceptual process based on the original SRS process [7] and more recent modifications [8] suggested by Idaho National Laboratory (INL) in Idaho Falls, Idaho, and is working to demonstrate, scale up, and optimize that process. In the process, ^{237}Np feedstock at INL is transported to ORNL where it is fashioned into ^{237}Np pellets and targets, and then the targets are irradiated in a nuclear reactor to form ^{238}Pu. The ^{238}Pu in the targets is separated, purified, converted into powder, packaged, and shipped to LANL to be made into ^{238}Pu oxide pellets for RPSs. Residual ^{237}Np is recycled to be made again into targets.

ORNL proposed the process block flow diagram shown in Fig. 1. The process shown is the preferred alternative among many process options considered [9,10]. At INL, ^{237}Np oxide ($^{237}NpO_2$) is removed from storage, re-packaged, and shipped to ORNL (in Fig. 1, "Fresh" $^{237}NpO_2$). After arrival, the $^{237}NpO_2$ is processed to remove the protactinium decay daughter (^{233}Pa) by dissolving the material in nitric acid (HNO_3), purifying it by ion exchange, and heating it in a high-temperature furnace to remake the $^{237}NpO_2$ as a powder free of ^{233}Pa, a method called Modified Direct Denitration [11] (in Fig. 1, Remove ^{233}Pa). ^{237}Np recycled from the processing of irradiated targets is also treated by this method. The $^{237}NpO_2$ powder is mixed with aluminum powder and compressed into pellets (in Fig. 1, Make pellets). The pellets are loaded into aluminum tubes and fabricated into targets using target designs [12] approved for use in the High Flux Isotope Reactor (HFIR) at ORNL or the Advanced Test Reactor (ATR) at INL (in Fig. 1, Make targets). In the nuclear reactor, ^{237}Np reacts with neutrons to form ^{238}Np, which decays to ^{238}Pu by the emission of a beta particle [7] (see Eq. (1); in Fig. 1, Irradiate targets).

$$ {}^{237}_{93}\mathrm{Np}(n,\gamma) \rightarrow {}^{238}_{93}\mathrm{Np} \xrightarrow[2.1\mathrm{d}]{\beta} {}^{238}_{94}\mathrm{Pu} \qquad (1) $$

After irradiation, the targets are stored for several months at the reactor sites to allow short-lived fission products to decay. When sufficiently decayed, the irradiated targets are transported from the reactor facilities to the chemical processing facilities [13,14] (i.e., radiation shielded hot cells) at REDC where they are chemically processed to make a Pu product stream, a recovered Np stream, and waste streams containing unwanted fission products and residual actinides. In the hot cells, the aluminum target bodies and the aluminum powder in the irradiated pellets are dissolved (in Fig. 1, Declad targets (NaOH)) using a combination of sodium hydroxide (NaOH) and sodium nitrate. The remaining oxide material is dissolved in a subsequent step using HNO_3 [15] (in Fig. 1, Dissolve targets (HNO_3)). Next, the acidic solution is concentrated by evaporation, and chemical additives are applied to adjust the oxidation states of Np and Pu, and to adjust the solution pH (in Fig. 1, Condition the solution). Solvent extraction is used to perform the Np/Pu separation [8] (in Fig. 1, Np/Pu Separation by solvent extraction). The Np and Pu streams are further purified using ion exchange [16] (in Fig. 1, Np purification (ion exchange), Pu purification (ion exchange)). The purified Np stream is recycled, and the Pu stream is converted into an oxide using oxalate precipitation (in Fig. 1, Oxalate precipitation) and calcining methods [17] (in Fig. 1, Calcine the precipitate). The final product, HS-PuO_2, is then packaged and shipped to LANL (in Fig. 1, Package and ship).

Ideally, the Pu-238 Supply Project would have defined the production requirements, and then designed the equipment and facilities to meet the requirements. Upstream of the nuclear reactor, this is the case. The automated equipment needed to make pellets and targets were not available, and new equipment is being designed and fabricated to meet the process requirements. However, the nuclear reactors (ATR and HFIR) and the downstream processing equipment are already in place, and the existing equipment and facilities must be adapted to meet the process requirements. This is especially true for the downstream equipment, which was designed and built for production and separation of isotopes other than ^{238}Pu (i.e., Am, Cm, Bk, Cf, Es, and Fm [14,15]); it is not specifically sized or optimized for ^{238}Pu production. Simple schedule analysis indicates the desired production rate can be achieved under nominal conditions with this equipment, but the outcome is uncertain when nuclear safety constraints and potential process variabilities are recognized.

From informal study of equipment capacities and throughput rates, it is suspected the rate-limiting processing step(s) lies somewhere within the downstream processing section (see Fig. 1, downstream from "Irradiate targets"). Collectively, the Pu-238 Supply Project calls those downstream processing steps the chemical processing section. The automated pellet and target fabrication equipment are new, and are being designed and fabricated to generate an excess number of targets per year. The nuclear reactors (i.e., ATR and HFIR) are large user facilities with excess capacity for multiple simultaneous irradiation activities. The downstream