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Plutonium-238: The Fuel Crisis

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ABSTRACT

Plutonium-238 is currently still the best fuel to power satellites to be sent to deep space in regions where the solar panels can no longer efficiently receive the sunlight. For 50 years, the National Aeronautics and Space Administration (NASA) has used this radioisotope as a fuel in radioisotope thermoelectric generators (RTGs) installed on satellites such as Pioneer 10 and 11, Voyager 1 and 2, Cassini-Huygens and New Horizons, as well as the various rovers sent to the Moon and to Mars, among others. Plutonium-238 is not a naturally occurring isotope on the planet, it was produced in greater quantity during the Cold War period as a by-product of the production of Plutonium-239 used for nuclear bombs. However, after the shutting down of the Savannah River reactors in 1988 and the ending of the Soviet Union in 1991, the United States stock of Plutonium-238 has been increasingly reduced, which threatens NASA's future space projects. This paper presents a brief bibliographic review about the subject, as well as commentaries on the options available to the United States, from restarting the production of this fuel, to possible alternatives for a new type of fuel or equipment that may supply the spacecrafts.

Keywords: **plutonium-238, radioisotope thermoelectric generator, deep space travel, NASA, nuclear fuel.**

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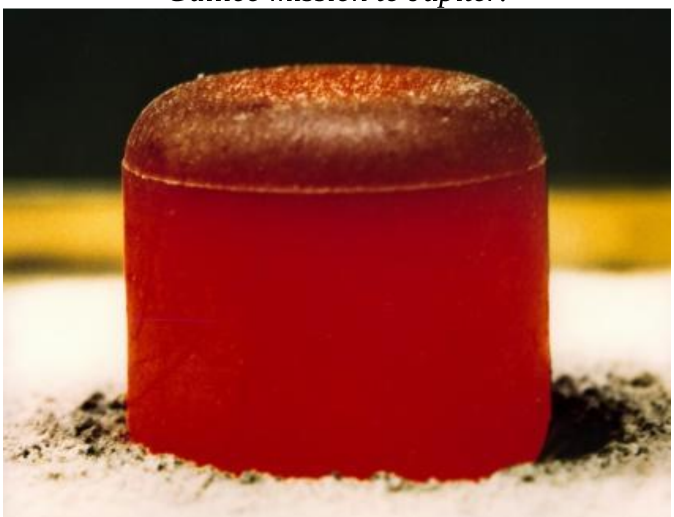
1. INTRODUCTION

Plutonium-238 is a non-natural radioactive isotope and, unlike Plutonium-239, cannot be used for nuclear weapons, nor as fuel in nuclear reactors. On the other hand, it is an important fuel for space probes, especially because it is a relatively long-lived isotope, with half-life of approximately 88 years. It is an alpha particle emitter which generates a large amount of heat per unit mass, and therefore it is considered a reliable source on missions lasting up to 50 years [1]. Because of these characteristics, the energy from plutonium-238 enabled these probes to stay longer enough in space collecting data, which provided most of what is known about the outer planets of the solar system and their moons [2].

As plutonium oxide, it has been widely used by the National Aeronautics and Space Administration (NASA) as fuel for space missions whose equipment cannot depend on the solar rays when they are too far from the sun [3]. The plutonium is encased in a capsule made of iridium [4] and packaged in radioisotopic thermoelectric generators (RTGs), whose heat is then transformed into electrical current. Figure 1 presents a 5 kg block of Plutonium-238, glowing in the high temperature generated by its own decay energy.

Figure 1: *Plutonium-238 such as the ones used for the Cassini RTG mission to Saturn, and for the Galileo mission to Jupiter.*



Source: U.S. Department Of Energy (DOE) [4].

RTGs are the equipment that supplies energy to satellites and space vehicles by converting into electricity the heat generated by the decay of Plutonium-238, using devices called thermocouples. The thermocouple consists of two plates, each one made of a different metal that conducts electricity. The union of these two plates forms a closed electrical circuit, and by keeping the two junctions at different temperatures, it produces an electric current. Each of these junctions forms an individual thermocouple. In an RTG, the radioisotope fuel heats one of the junctions while the other remains unheated, being cooled by the space environment or a planetary atmosphere [5].

The first Plutonium-238-powered RTG sent by NASA into space was the Systems for Nuclear Auxiliary Power (SNAP)-3B in 1961. Since then, RTGs have been used in Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, Galileo, Ulysses, Cassini, New Horizons and the Mars Science Laboratory, as well as the Mars Curiosity rover, sent to planet Mars in two Viking modules, in addition to the scientific experiments left on the moon by the Apollo 12 and 14 to 17 crews [6].

Historically, the United States have produced Plutonium-238 primarily in two nuclear laboratories, generated as a by-product of the production of Plutonium-239 to be used in bombs [2]. At Hanford Site operations in Washington State, the Plutonium-238 was left mixed in a cocktail of nuclear waste [2]. On those developed at the Savannah River Site in South Carolina, on the other hand, there was extraction and refinement of over 160 kilograms of such radioisotope during the Cold War to power NASA spacecrafts, as well as spy tools and spy satellites [2].

Both facilities were decommissioned in 1988, when the United States and the Soviet Union began dismantling their nuclear war facilities, and no further American production of Plutonium-238 was made [2]. Russia still continued to remove plutonium from spent nuclear reactor fuel at the Mayak nuclear industrial complex. In 1993 they sold their first batch to the United States, weighing 16 kilograms, for more than $ 1,500 a gram [2]. Therefore, Russia became the only supplier on the planet. It is estimated that in 2005 the United States Department of Energy (DOE) had just about 16 kilograms reserved for future NASA missions [2]. In 2009, Russia refused to sell other 10 kilograms to the Americans. Perhaps there was no more availability at all, it is unknown; anyway, since that time the Russians no longer provide plutonium [2].

NASA's inventory was reduced and committed to already announced future missions. Because of that situation, new mission projects that may use Plutonium-238 as fuel were banned until a solution was found.

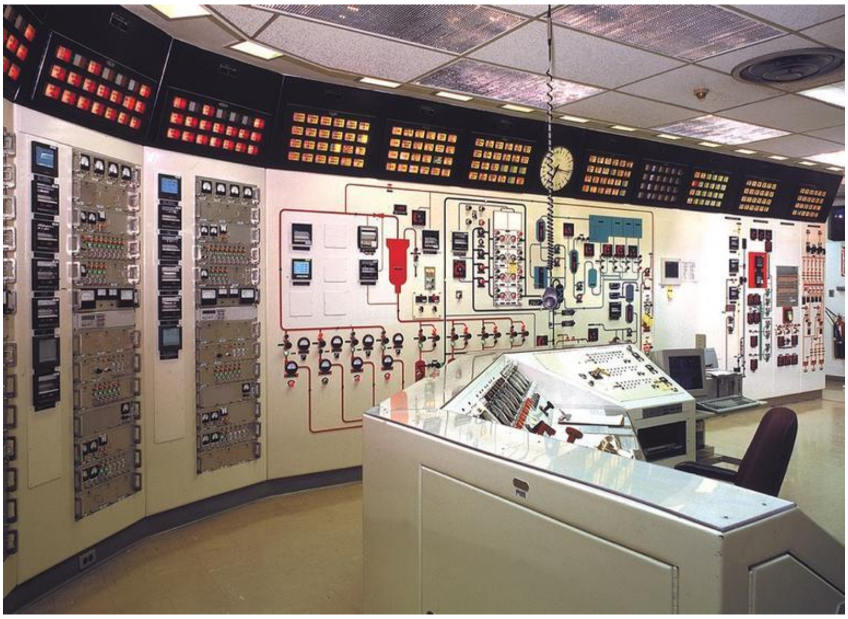
Given the situation above and based on a literature review on the subject, this paper aims to discuss the alternatives that have been found for the new production of Plutonium-238.

2. ALTERNATIVES

In 2013, NASA signed a contract with DOE to reactivate the production of Plutonium-238 at Oak Ridge. Such production, however, begins at the Idaho National Laboratory in Idaho Falls, where the Neptunium-237 isotope is chemically extracted from spent nuclear fuel [7].

The neptunium is then sent to the Oak Ridge National Laboratory (ORNL), where it is compressed into pellets in the shape and size of a pencil eraser. The pellets are then fitted one by one into long aluminum tubes, and taken to one of the lab's most historic buildings: the High-Flow Isotope Reactor, the site of the largest neutron flux in the Western Hemisphere for more than 50 years (Figure 2). There is a 2.4 meter diameter beryllium cylinder with dozens of holes where the aluminum tubes with the pellets are inserted. In this way, they are fully exposed to the reactor core. After the tubes being introduced, the entire assembly is inserted into a pool, and the reactor is then turned on for 25 days. During this period, Neptunium-237 is bombarded by neutrons to become Neptunium-238, which spontaneously decays to Plutonium-238 emitting a beta particle [7].

Figure 2: *High Flow Isotope Reactor control room, used to make Plutonium-238 in Oak Ridge.*



Source: U.S. Department Of Energy (DOE) [4].

After the completion of this procedure, the aluminum tubes are removed and taken to hot cells to remove the pellets from the tubes, and then dissolved in nitric acid. Plutonium-238 is extracted and concentrated as an oxide powder, and this powder is then compressed into fuel pellets. The material is then delivered to the Los Alamos laboratory in New Mexico where the fuel cells are made [7]. In December 2015, 30 years after ceasing production, 50g of Plutonium-238 were produced again in the U.S. [8].

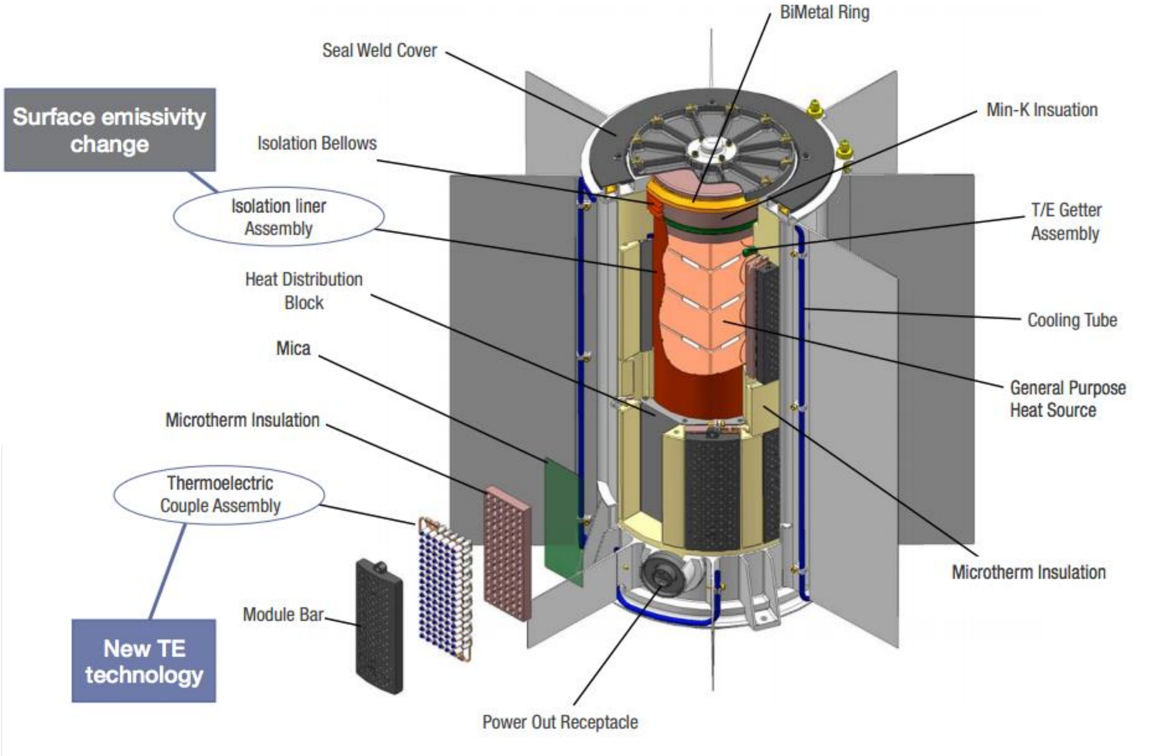
The procedures for measuring, mixing and pressing the powder ingredients were done manually until the beginning of 2019, when they were automated by using robotic arms [9]. This equipment significantly reduced the technicians' exposure to gamma radiation from the neptunium oxide. Due to such improvement, the pellet production increased from about 80 pellets per week to up to 60 pellets per day, to meet NASA's request for 1.5 kilograms of Plutonium-238 by 2025 [9].

Another project for production of Plutonium-238 was presented in 2017 by Technical Solutions Management (TSM): the DOE Pacific Northwest National Laboratory (PNNL) supplies Neptunium-237, the Chalk River Laboratories of the Canadian Nuclear Laboratories (CNL) assemble the packages, which are irradiated at the Ontario Power Generation (OPG) Darlington reactor. The Plutonium-238 produced is then transported back to CNL for the chemical processes. Nevertheless, the next stage of such project is dependent on funding [10].

These RTG power systems were subsequently improved by NASA and DOE, which developed the next generation of RTGs: the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The system is designed to be used in the vacuum of space or in the atmosphere of a planet, and has higher performance and lifetime capabilities than the previous version [5]. It was firstly used in 2011 on the Mars Curiosity rover, which landed with success on the red planet nine months later, in 2012, and so far remains operational [11]. The excess of thermal energy from an MMRTG can be used as a convenient and stable source of heat to maintain proper operating temperatures for a spaceship and its instruments in cold environments [5].

At NASA's Jet Propulsion Laboratory in Pasadena, California, the "skutterudites", materials for the next generation of RTGs, the Enhanced Multi-Mission Radioisotope Thermoelectric Generators (eMMRTGs), are being developed, as seen in Figure 3 [13]. Skutterudites have complex structures with heavy atoms such as antimony. These materials have specific characteristics that make them useful in energy production systems: they conduct electricity like metal and heat like glass, and can generate considerable electrical voltages [12].

Figure 3: *Enhanced Multi-Mission Radioisotope Thermoelectric Generator*.



Source: NASA [13].

Thermocouples made from skutterudites for the eMMRTG replace the tellurium thermocouples used in the MMRTG, with an increase in heat output from 25% to over 50%, thus requiring less Plutonium-238 [13]. The eMMRTG's debut mission has not yet been announced.

In recognition of the importance of Plutonium-238 production, the American Chemical Society (ACS) in November 2018 named the National Chemical Historic Landmark at the Savannah River Site Legacy Museum, in celebration also of the institution's former employees, who at the time of the Cold War worked there in secret, unable to tell family and friends what they were doing [14].

2.1. On Earth

Batteries like these have also been used on Earth in lighthouses and weather stations closer to the Arctic, where there is no other type of power source, mainly by the United States and the extinct Soviet Union. Due to the high production cost of Plutonium-238, most of the RTGs in these facilities used Strontium-90, despite presenting a shorter half-life of 28.1 years, very low energy density and emission of beta particles [18].

The oil industry is also interested in RTG batteries for use at remote stations [19] and in the deep sea, in wellhead control equipment [20]. In Brazil there are evidences of Petrobras projects in this regard, but due to the state of confidentiality of such research, so far there has been no open information available to describe the operation and type of these energy sources in such circumstances.

3. CONCLUSION

With confirmation of the return of fuel element production, in March 2018 NASA suspended the design ban on new space missions using Plutonium-238 RTGs [15]. In June 2019 NASA has announced that will send in 2026 a Plutonium-238-powered drone to Saturn's largest moon, Titan, for checking for signs of life [16, 17].

But before that, a new mission that has been under development for 5 years is set for launch at the end of July 2020: the Mars 2020 Perseverance rover [21]. With a configuration similar to the previous rover, Curiosity [22], the Perseverance rover carries a Multi-Mission Radioisotope Thermoelectric Generator with 4.8 kilograms of plutonium dioxide as the source of steady supply of heat, charging the rover’s two primary batteries. The 14-year operational lifetime of an MMRTG provides significant reserve for Mars 2020 prime mission duration of 1.5 Mars years (three Earth years) [23].

Nuclear bombs have been of great concern to almost any individual on this planet, but nowadays they have become a dark distant memory, partly clouded after the Chernobyl and Fukushima nuclear accidents. This way, the production of Plutonium-238 no longer needs to have the obstacles and suspicions that the more easily fissile Plutonium-239 will be done again for military purposes. NASA has already secured the fuel for future deep space missions for decades to come.

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