Essays on Nuclear Energy & Radioactive Waste Management

Ricardo Bastos Smith
(Org.)

Authors:
Ana Paula Gimenes Tessaro
Bianca Geraldo
Daiane Cristini Barbosa de Souza
Fernanda Romero
Indranil Bisuri
Júlio Takehiro Marumo
Luan Teixeira Vieira Cheberle
Mahima Sachdeva
Mychelle Munyck Linhares Rosa
Natalie Costa Rolindo
Ricardo Bastos Smith
Roberto Vicente
Tereza Cristina Salvetti

ipen

GENIO CRIADOR

Essays on Nuclear Energy & Radioactive Waste Management

Ricardo Bastos Smith (Org.)

Authors:
Ana Paula Gimenes Tessaro
Bianca Geraldo
Daiane Cristini Barbosa de Souza
Fernanda Romero
Indranil Bisuri
Júlio Takehiro Marumo
Luan Teixeira Vieira Cheberle
Mahima Sachdeva
Mychelle Munyck Linhares Rosa
Natalie Costa Rolindo
Ricardo Bastos Smith
Roberto Vicente
Tereza Cristina Salvetti

ipen

GENIO CRIADOR

Editorial lead:
Cleusa Kazue Sakamoto

Editorial project:
Gênio Criador Editora

Text revision & book cover:
Ricardo Bastos Smith

Cataloging in Publication (CIP) International Data
Angélica Ilacqua CRB-8/7057

Essays on nuclear energy & radioactive waste management [livro eletrônico] / Ana Paula Gimenes Tessaro...[et al] ; organizado por Ricardo Bastos Smith. -– São Paulo : Gênio Criador, 2021.
171 p.

Bibliografia
ISBN 978-65-86142-41-9 (e-book)

1. Tecnologia nuclear 2. Usinas nucleares 3. Resíduos radiativos, Eliminação dos I. Smith, Ricardo Bastos

21-2681 CDD 333.792 4

1st. edition, 2021

Av. Brigadeiro Faria Lima, 1616 - sala 804
Jardim Paulistano, São Paulo - SP, 01451-001
http://geniocriador.com.br

- 7 -
Plutonium-238: The Fuel Crisis[10]

Ricardo B. Smith
Roberto Vicente
Nuclear and Energy Research Institute - IPEN-CNEN/SP, Brazil
Fernanda Romero
Federal University of São Paulo (UNIFESP)

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 byproduct 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. 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, are also presented.

Resumo: O plutônio-238 ainda é atualmente o melhor combustível para alimentar satélites a serem enviados ao espaço sideral, em regiões onde os painéis solares não podem mais receber a luz do sol com eficiência. Por 50 anos, a National Aeronautics and Space Administration(NASA)vemusandoesteradioisótopocomocombustível em geradores termoelétricos de radioisótopos (RTGs) instalados em satélites como Pioneer 10 e 11, Voyager 1 e 2, Cassini-Huygens e New

10 Poster presented at the 2019 International Nuclear Atlantic Conference (INAC) on October 21-25, 2019 in the city of Santos, SP., Brazil. Available at: <https://doi.org/10.15392/bjrs.v9i1A.1312>.

Horizons, bem como nos vários “rovers” enviados à Lua e a Marte, entre outros. O plutônio-238 não é um isótopo de ocorrência natural no planeta, foi produzido em maior quantidade durante o período da Guerra Fria, como subproduto da produção do plutônio-239, usado para bombas nucleares. No entanto, após o fechamento dos reatores do rio Savannah em 1988 e o fim da União Soviética em 1991, o estoque de plutônio-238 dos Estados Unidos foi se reduzindo cada vez mais, o que ameaça os futuros projetos espaciais da NASA. Apresentam-se também comentários sobre as opções que os Estados Unidos possuem, desde o reinício da produção desse combustível, até possíveis alternativas de um novo tipo de combustível ou equipamento que possa abastecer as espaçonaves.

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, most of what is known about the outer planets of the solar system and their moons, is the result of the energy generated by Plutonium-238 [2].

As plutonium oxide, it is 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]. To this end, plutonium is encased in iridium capsule [4] and packaged in radioisotopic thermoelectric generators (RTGs), whose heat is then transformed into electrical current. Figure 1 shows a 5kg block of Plutonium-238, glowing in the high temperature reached by its own decay energy.

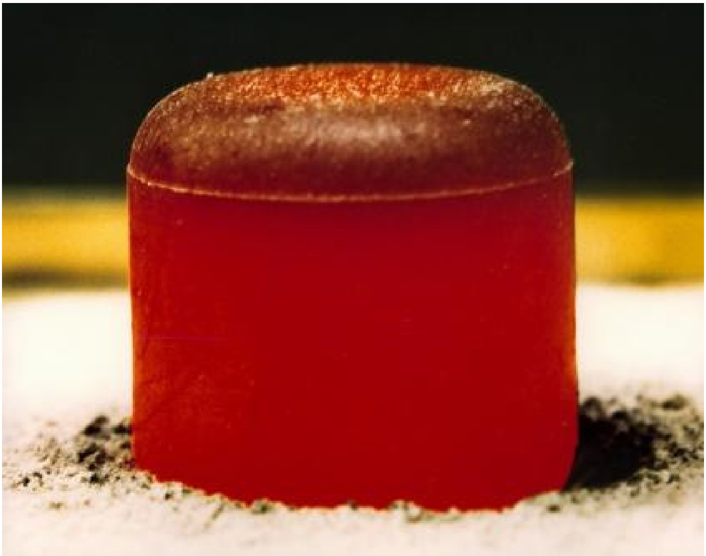

Figure 1 - Plutonium-238 made for the Cassini RTG mission to Saturn, or for the Galileo mission to Jupiter. Source: [4].

RTGs are the equipment that keeps satellites and space vehicles running because they convert the heat generated by the decay of Plutonium-238 into electricity, 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 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 Curiosity robot, 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 byproduct of the production of Plutonium-239 to be used in bombs. At Hanford Site operations in Washington State, the Plutonium-238 was left mixed in a cocktail of nuclear waste. 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.

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. Russia still continued to remove plutonium from burnt 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. 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 10 kilograms reserved for future NASA missions. And to make matters worse, in 2009 Russia refused to agree to sell other 10 kilograms to the Americans; it is not known if it was because there was no more availability, but since then the Russians no longer provide plutonium [2].

With its inventory reduced and committed to already announced future missions, NASA banned new mission projects that would use Plutonium-238 fuel RTGs 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 used for the new production of Plutonium-238.

Alternatives

From 2013 on, 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.

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: 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 insertion of the tubes, the entire assembly is taken into a pool, and the reactor is then turned on for 25 days. In this period, Neptunium-237 is bombarded

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

by neutrons to become Neptunium-238, which spontaneously decays to Plutonium-238 emitting a beta particle.

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 [7]. After 30 years, the first 50g of Plutonium-238 returned to production in December 2015 [8].

It should also be noted that the procedures for measuring, mixing and pressing the powder ingredients were done manually until the beginning of 2019, when it was automated using robotic arms. This significantly reduced the technicians' exposure to gamma radiation from the neptunium oxide, and accelerated the pellet production from about 80 per week to up to 60 per day, to meet NASA's request for 1.5 kilograms of Plutonium-238 by 2025 [9]. The material is then delivered to the Los Alamos laboratory in New Mexico where the fuel cells are made.

In a proposal to complement the production of Plutonium-238 for NASA, a public-private partnership led by Technical Solutions Management (TSM) presented in 2017 a project for radioisotope production using a DOE-like production line: the DOE Pacific Northwest National Laboratory (PNNL) supplies Neptunium-237, which is sent to the Chalk River Laboratories of the Canadian Nuclear Laboratories (CNL), where the packages are assembled for the reactor. Afterwards, these packages are sent to the Ontario Power Generation (OPG) Darlington reactor for irradiation, generating Plutonium-238, which is then transported back to the CNL for the chemical processes. The next stage of the project is dependent on funding [10].

These RTG power systems were improved by NASA and DOE, which developed the Multi-Mission Radioisotope

Thermoelectric Generator (MMRTG). The system is designed to be used in a vacuum of space or in the atmosphere of a planet, and has higher performance and lifetime capabilities than the previous version. It was firstly used in 2011 on the Curiosity Mars 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, Enhanced Multi-Mission Radioisotope Thermoelectric Generators (eMMRTGs), are being developed, as seen in Figure 3. Skutterudites have complex structures with heavy atoms such as antimony. These materials have specific characteristics that make them useful in energy production

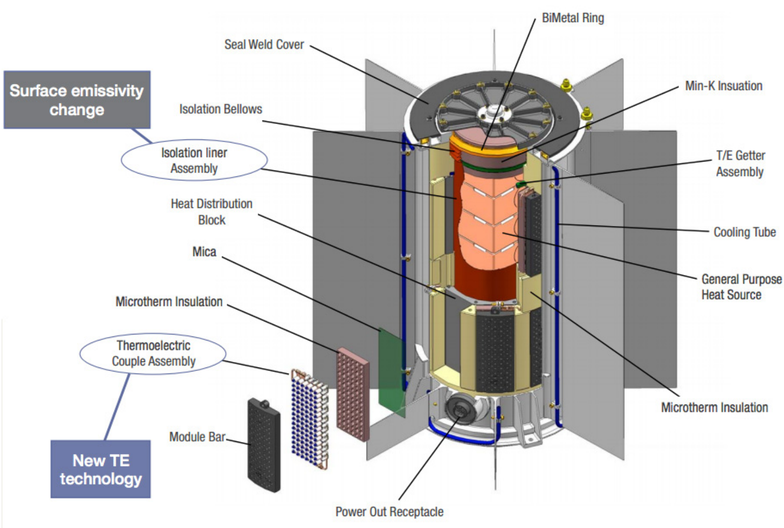

Figure 3 - Enhanced Multi-Mission Radioisotope Thermoelectric Generator (Source: [13]).

systems: they conduct electricity like metal and heat like glass, and can generate considerable electrical voltages [12].

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.

Conclusions

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].

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 it will send in 2026 a Plutonium-238-powered drone to Saturn's largest moon, Titan, for checking for signs of life [16, 17].

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, 19].

The oil industry is also interested in RTG batteries for use at remote stations [20] and in the deep sea, especially on oil platforms. 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.

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 outer space missions for decades to come.

References

[1] NASA, *About plutonium 238*. Retrieved from <https://rps.nasa.gov/about-rps/about-plutonium-238/> (N/A).

[2] D. Mosher, NASA's plutonium problem could end deep-space exploration, *Wired*. Retrieved from <https://www.wired.com/2013/09/plutonium-238-problem/> (2013).

[3] L. Grush, Ideas for new NASA mission can now include spacecraft powered by plutonium, *The Verge*. Retrieved from <https://www.theverge.com/2018/3/19/17138924/nasa-discovery-program-radioisotope-thermoelectric-generators-plutonium-238> (2018).

[4] S. Zhang, Estamos ficando sem o combustível nuclear que viabiliza as viagens espaciais, *Gizmodo*. Retrieved from <https://gizmodo.uol.com.br/plutonio-238> (2014).

[5] NASA, *Power systems - a legacy of exploration*. Retrieved from <https://rps.nasa.gov/power-and-thermal-systems/power-systems/current/> (N/A).

[6] Radioisotope thermoelectric generator. Retrieved from <https://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator> (2019).

[7] A. Witze, Nuclear power: Desperately seeking plutonium, *Nature*. Retrieved from <https://www.nature.com/news/nuclear-power-desperately-seeking-plutonium-1.16411> (2014).

[8] NASA, *U.S. Demonstrates Production of Fuel for Missions to the Solar System and Beyond*. Retrieved from <https://mars.nasa.gov/news/us-demonstrates-production-of-fuel-for-missions-to-the-solar-system-and-beyond/> (2015).

[9] E. Stoye, Robot speeds up production of plutonium spacecraft fuel, *Chemistry World*. Retrieved from <https://www.chemistryworld.com/news/robot-speeds-up-production-of-plutonium-spacecraft-fuel/3010014.article> (2019).

[10] M. Wall, Production of plutonium spacecraft fuel could boom in early 2020s, *Space.com.* Retrieved from <https://www.space.com/36217-plutonium-238-nuclear-spacecraft-fuel-production.html> (2017).

[11] Curiosity (rover). Retrieved from <https://en.m.wikipedia.org/wiki/Curiosity_(rover)> (2019).

[12] NASA, *Spacecraft 'Nuclear Batteries' Could Get a Boost from New Materials*. Retrieved from <https://www.jpl.nasa.gov/news/news.php?feature=6646> (2016).

[13] NASA, *Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) Concept*. Retrieved from <https://rps.nasa.gov/resources/56/enhanced-multi-mission-radioisotope-thermoelectric-generator-emmrtg-concept/> (N/A).

[14] American Chemical Society (ACS), *'Plutonium-238 production for space exploration' named National Historic Chemical Landmark*. Retrieved from <https://www.acs.org/content/acs/en/pressroom/newsreleases/2018/november/plutonium-238-production-for-space-

exploration-named-national-historic-chemical-landmark.html> (2018).

[15] NASA Lifts Ban On Radioactive Batteries Powered By Plutonium For Mission Proposals, *Tech Times*. Retrieved from <https://www.techtimes.com/articles/223297/20180320/nasa-lifts-ban-on-radioactive-batteries-powered-by-plutonium-for-mission-proposals.htm> (2018).

[16] Nasa vai enviar em 2026 drone a Titã, maior lua de Saturno, em busca de sinais de vida, *Folha de S.Paulo*, São Paulo, 99(32960), p.B6 (jun.30, 2019).

[17] NASA, *NASA's Dragonfly Will Fly Around Titan Looking for Origins, Signs of Life*. Retrieved from <https://rps.nasa.gov/news/31/nasas-dragonfly-will-fly-around-titan-looking-for-origins-signs-of-life/> (2019).

[18] Generador Termoeléctrico de Radioisótopos. Retrieved from <https://es.wikipedia.org/wiki/Generador_termoel%C3%A9ctrico_de_radiois%C3%B3topos> (2019).

[19] G.F.R. Duarte & B.V. Carlson, *Geradores Termoelétricos Radioisotópicos*. Retrieved from <http://www.bibl.ita.br/xiencita/Artigos/Fund15.pdf> (2009).

[20] S.R.A. Farias, *Protótipo de um Microgerador Termoelétrico de Estado Sólido: cogeração a gás*, Master's Dissertation in Petroleum Science and Engineering, Universidade Federal do Rio Grande do Norte. Retrieved from <http://www.dominiopublico.gov.br/pesquisa/DetalheObraForm.do?select_action=&co_obra=161533> (2009).

PLUTONIUM-238: THE FUEL CRISIS

Ricardo B. Smith[1], Fernanda Romero[2] and Roberto Vicente[1]

1. INTRODUCTION

Plutonium-238 (Figure 1) is a non-natural radioactive isotope that cannot be used for nuclear weapons, nor as fuel in nuclear reactors. On the other hand, it is an important fuel for space probes, being considered a reliable source on missions lasting up to 50 years [1]. Most of what is known about the outer planets of the solar system and their moons is the result of the energy generated by Plutonium-238 [2].

It is 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]. To this end, plutonium is packaged in radioisotopic thermoelectric generators (RTGs), whose heat is then transformed into electrical current [4].

RTGs are the equipment that keeps satellites and space vehicles running because they convert the heat generated by the decay of Plutonium-238 into electricity, using devices called thermocouples. The thermocouple consists of two plates, each one made of a different metal that conducts electricity. 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]. They have been used since 1961 in probes such as Pioneer 10 and 11, Voyager 1 and 2, Galileo, Ulysses, Cassini, New Horizons and the Mars Science Laboratory, the Curiosity robot sent to planet Mars, among others [6].

The United States produced Plutonium-238 as a byproduct of Plutonium-239 used in bombs. The facilities which produced it were decommissioned in 1988 when the United States and the Soviet Union began dismantling their nuclear war facilities. Russia still continued to remove plutonium from burnt nuclear reactor fuel at Mayak. In 1993 they sold 16 kilograms to the United States for more than $ 1,500 a gram. In 2005 the United States Department of Energy (DOE) had just about 10 kilograms reserved for future NASA missions. And to make matters worse, in 2009 Russia refused to agree to sell other 10 kilograms to the Americans [2]. NASA banned new mission projects that would use Plutonium-238 fuel RTGs 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 used for the new production of Plutonium-238.

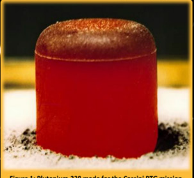

Figure 1: Plutonium-238 made for the Cassini RTG mission to Saturn, or for the Galileo mission to Jupiter. Source: [4].

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

2. ALTERNATIVES

From 2013 on, 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.

The neptunium is then sent to the Oak Ridge National Laboratory (ORNL), where it is taken to a beryllium cylinder at the High-Flow Isotope Reactor, the largest neutron flux in the Western Hemisphere for more than 50 years (Figure 2). The cylinder is then taken into a pool, and the reactor is turned on for 25 days. In this period, Neptunium-237 is bombarded by neutrons to become Neptunium-238, which spontaneously decays to Plutonium-238. After that, the aluminum tubes are dissolved in nitric acid. Plutonium-238 is extracted and concentrated as an oxide powder, which is then compressed into fuel pellets [7]. After 30 years, the first 50g of Plutonium-238 returned to production in December 2015 [8]. The procedures for measuring, mixing and pressing the powder ingredients were done manually until the beginning of 2019, when it was automated using robotic arms [9].

As a way to improve the engines at space, NASA and DOE developed then the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The system has higher performance and lifetime capabilities than the previous version. It was firstly used in 2011 on the Curiosity Mars rover, which landed with success on the red planet nine months later and so far remains operational [11].

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. Skutterudites have complex structures with heavy atoms such as antimony: they conduct electricity like metal and heat like glass, and can generate considerable electrical voltages [12], and 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.

3. CONCLUSIONS

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].

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 it will send in 2026 a Plutonium-238-powered drone to Saturn's largest moon, Titan, for checking for signs of life [16].

Nuclear bombs have been of great concern to almost any individual on this planet, but nowadays they have become a dark distant memory. 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 outer space missions for decades to come.

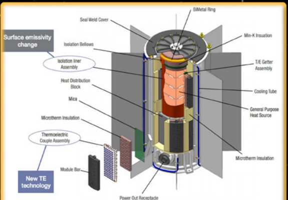

Figure 3: Enhanced Multi-Mission Radioisotope Thermoelectric Generator (Source: [13]).

REFERENCES

1. NASA, "About plutonium 238", https://rps.nasa.gov/about-rps/about-plutonium-238/ (N/A).
2. D. Mosher, "NASA's plutonium problem could end deep-space exploration", *Wired*, https://www.wired.com/2013/09/plutonium-238-problem/ (2013).
3. L. Grush, "Ideas for new NASA mission can now include spacecraft powered by plutonium", *The Verge*, https://www.theverge.com/2018/3/19/17138924/nasa-discovery-program-radioisotope-thermoelectric-generators-plutonium-238 (2018).
4. S. Zhang, "Estamos ficando sem o combustível nuclear que viabiliza as viagens espaciais", *Gizmodo*, https://gizmodo.uol.com.br/plutonio-238 (2014).
5. NASA, "Power systems - a legacy of exploration", https://rps.nasa.gov/power-and-thermal-systems/power-systems/current/ (N/A).
6. "Radioisotope thermoelectric generator", https://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator (2019).
7. A. Witze, "Nuclear power: Desperately seeking plutonium", *Nature*, https://www.nature.com/news/nuclear-power-desperately-seeking-plutonium-1.16411 (2014).
8. NASA, "U.S. Demonstrates Production of Fuel for Missions to the Solar System and Beyond", https://mars.nasa.gov/news/us-demonstrates-production-of-fuel-for-missions-to-the-solar-system-and-beyond/ (2015).
9. E. Stoye, "Robot speeds up production of plutonium spacecraft fuel", *Chemistry World*, https://www.chemistryworld.com/news/robot-speeds-up-production-of-plutonium-spacecraft-fuel/3010014.article (2019).
10. (XXX) M. Wall, "Production of plutonium spacecraft fuel could boom in early 2020s", *Space.com*, https://www.space.com/36217-plutonium-238-nuclear-spacecraft-fuel-production.html (2017).
11. "Curiosity (rover)", https://en.m.wikipedia.org/wiki/Curiosity_(rover) (2019).
12. NASA, "Spacecraft 'Nuclear Batteries' Could Get a Boost from New Materials", https://www.jpl.nasa.gov/news/news.php?feature=6646 (2016).
13. NASA, "Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) Concept", https://rps.nasa.gov/resources/56/enhanced-multi-mission-radioisotope-thermoelectric-generator-emmrtg-concept/ (N/A).
14. American Chemical Society (ACS), " 'Plutonium-238 production for space exploration' named National Historic Chemical Landmark", https://www.acs.org/content/acs/en/pressroom/newsreleases/2018/november/plutonium-238-production-for-space-exploration-named-national-historic-chemical-landmark.html (2018).
15. "NASA Lifts Ban On Radioactive Batteries Powered By Plutonium For Mission Proposals", Tech Times, https://www.techtimes.com/articles/223297/20180320/nasa-lifts-ban-on-radioactive-batteries-powered-by-plutonium-for-mission-proposals.htm (2018).
16. "Nasa vai enviar em 2026 drone a Titã, maior lua de Saturno, em busca de sinais de vida", *Folha de S.Paulo*, São Paulo, 99(32960), p.B6 (jun.30, 2019).

[1] Nuclear and Energy Research Institute (IPEN/CNEN–SP)
Av. Professor Lineu Prestes, 2242 - 05508-000 São Paulo, SP., Brazil
rbsmith@ipen.br / rvicente@ipen.br

[2] Federal University of São Paulo (UNIFESP)
Rua Sena Madureira, 1500 - 04021-001 São Paulo, SP, Brazil
romero_fcr@yahoo.com.br

XIV ENAN