Nuclear Power Sources in Space Missions

Puya Fard

Abstract- Space missions increasingly rely on nuclear power, notably Radioisotope Thermoelectric Generators (RTGs) and nuclear fission reactors, for energy. This paper reviews their applications, focusing on Nuclear Thermal Propulsion (NTP), analysis, and data acquisition. RTGs, fueled by Plutonium-238, provide reliable energy for space probes and rovers, as seen in the Curiosity (2011) and Mars 2020: Perseverance missions. Nuclear fission reactors, particularly in NTP systems, offer potential for high-energy propulsion, enabling faster exploration. Emphasizing nuclear power's significance, this paper underscores its role in mission success, scientific discovery, and human exploration beyond Earth.

Keywords—RTGs, NTP systems, and fission reactors.

I. INTRODUCTION

In the realm of space exploration, the quest for reliable and sustainable energy sources has been a longstanding challenge. As humanity ventures further into the cosmos, the need for power systems capable of withstanding the rigors of space and sustaining missions over extended durations becomes increasingly apparent. Nuclear power emerges as a compelling solution to this challenge, offering a potent source of energy that can endure the harsh conditions of space and provide the necessary power for scientific instruments, communication systems, and propulsion [1]. This introduction delves into the advancements and applications of nuclear power sources, particularly Radioisotope Thermoelectric Generators (RTGs) and nuclear fission reactors, in space missions.

RTGs, powered by the decay of radioisotopes such as Plutonium-238, have proven instrumental in supplying continuous and reliable energy for space probes and rovers [7]. Notable examples include the Curiosity rover mission in 2011 and the recent Mars 2020: Perseverance mission, where RTGs have enabled long-term exploration and data collection on the Martian surface. These missions underscore the robustness and versatility of RTGs in powering scientific endeavors beyond Earth [7].

Additionally, the potential of nuclear fission reactors, particularly in Nuclear Thermal Propulsion (NTP) systems[6], holds promise for revolutionizing space exploration capabilities. By harnessing the energy released from nuclear reactions, NTP systems offer the prospect of faster and more efficient propulsion, facilitating expedited travel to distant celestial bodies and enabling ambitious scientific missions. This paper aims to elucidate the pivotal role of nuclear power in advancing the frontiers of space exploration [2].

II. NUCLEAR FISSION REACTORS

Nuclear fission reactors have been instrumental in powering space exploration missions since their inception. These reactors, harnessing the energy released from nuclear fission reactions, provide a reliable and efficient source of power for spacecraft traveling beyond Earth's orbit. Among the earliest examples is the SNAP-10A system [2], launched in 1965, which marked a significant milestone in space-based nuclear power. Operating for a limited duration, it demonstrated the potential of nuclear fission technology in space [2].

A. SNAP 10-A

The first nuclear reactor launched into space was the SNAP-10A system, developed for Nuclear Auxiliary Power as part of the U.S. Atomic Energy Commission's space exploration program [1]. On April 3, 1965, the United States launched this pioneering reactor with the aim of providing a reliable source of electricity for extended space missions. Weighing less than 950 pounds, the SNAP-10A reactor operated for 43 days in orbit before a voltage regulator malfunction forced its shutdown [3].

Designed to produce a minimum of 500 Watts of electricity for missions lasting one year or longer, it utilized enriched uranium fuel with zirconium hydride as a moderator and a liquid sodium-potassium alloy as a coolant [2]. Notably, the hazardous radiation associated with the nuclear fission reaction was not emitted until after the reactor safely reached orbit. The energy conversion method employed by SNAP-10A involved the direct conversion of reactor heat into electricity using thermoelectric converters located beneath the reactor's cone-shaped body [3]. Heat from the reactor was transferred by the liquid metal coolant to heat the underside of the thermoelectric elements, showcasing the innovative engineering behind this groundbreaking space reactor [2].

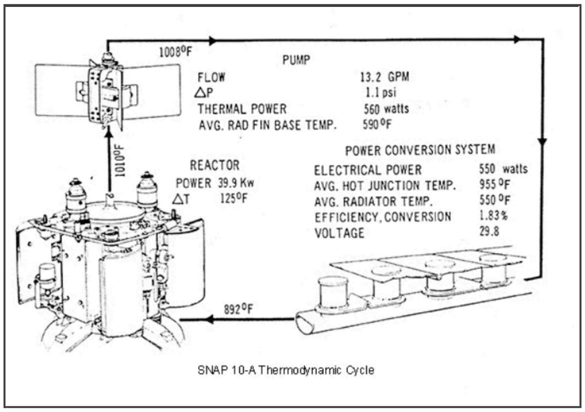


Figure 1: SNAP 10-A design flow

B. SP-100

The SP-100 was a compact nuclear reactor designed for space applications, representing a significant advancement in space-based nuclear power technology. Developed in the late 1980s and early 1990s, the SP-100 was intended to provide reliable and efficient power for long-duration space missions, including crewed missions to Mars and beyond. Unlike its predecessor, the SNAP-10A, the SP-100 was designed to operate for much longer durations and to provide higher power outputs, with some variants capable of generating up to 100 kilowatts of electricity [2]. This reactor system utilized a compact design and innovative materials to minimize its size and weight, making it suitable for integration into spacecraft while still meeting stringent safety requirements. Although the SP-100 program faced challenges and funding issues that ultimately led to its cancellation in the mid-1990s, its legacy continues to influence the development of nuclear power systems for space exploration, inspiring ongoing research and development efforts aimed at realizing the potential of nuclear energy in enabling ambitious missions beyond Earth's orbit [2].

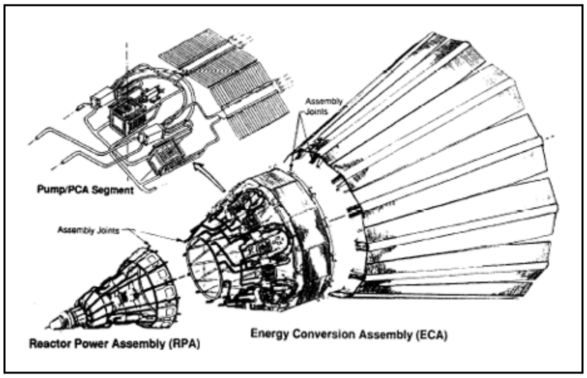


Figure 2: SP-100

III. NUCLEAR THERMAL PROPULSION

Nuclear Thermal Propulsion (NTP) represents a revolutionary advancement in in-space propulsion systems, relying on the principle of harnessing nuclear fission processes to generate heat and eventual thrust. Unlike traditional chemical propulsion systems, which burn propellant in a chemical reaction, NTP systems utilize a low molecular weight fuel, typically hydrogen, that flows through a reactor, where it undergoes nuclear fission to produce heat [6]. The higher the molecular weight of the fuel, the greater the resulting Specific Impulse (Isp), which measures the efficiency of a rocket engine. However, to maintain hydrogen in a liquid state, it must be stored at extremely low temperatures, making it a cryogenic propellant [6].

In terms of fuel type, current NTP designs are incorporating low enriched uranium (LEU) or high-assay low enriched uranium (HALEU), prioritizing non-proliferation and security considerations while still achieving efficient fission. This choice underscores the importance of balancing technological progress with international security concerns in the development of space propulsion systems [6].

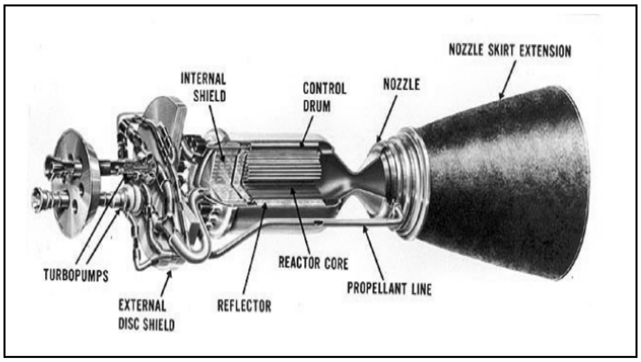


Figure 3: Rover/NERVA Engine

The applications of NTP are vast and transformative. Notably, NTP has the potential to significantly shorten travel times for interplanetary missions, such as round-trip opposition-class Mars missions, reducing transit times to approximately 4-6 months [6]. Furthermore, its versatility allows for a wide range of mission applications, including reusable lunar cargo delivery, crewed lunar landing missions, crewed asteroid missions, and high energy injection stages for shortened robotic science missions to the outer planets. This versatility enables a more standardized approach to engine development, offering a promising pathway to unlocking the full potential of space exploration.

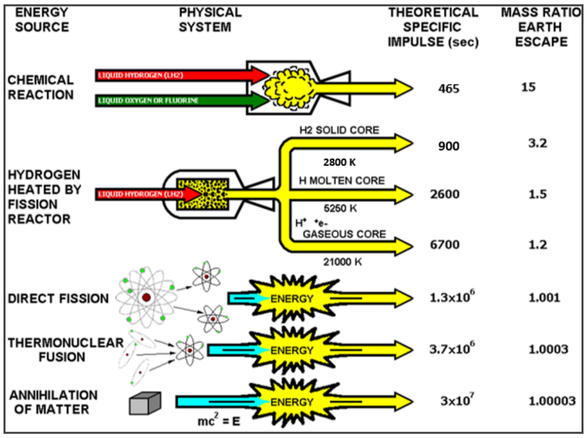


Figure 4: Comparison of States

Figure 2 illustrates a comprehensive comparison of state-of-the-art propulsion concepts, providing insights into their respective strengths and limitations in the context of space exploration. Each propulsion concept is evaluated based on key parameters such as specific impulse (Isp), thrust-to-weight ratio, and mission applicability. The comparison highlights the unique advantages offered by Nuclear Thermal Propulsion (NTP) in terms of its high specific impulse and potential for shortening travel times for interplanetary missions. NTP stands out as a promising candidate for future space missions, offering the capability to achieve faster transit times while accommodating a variety of mission objectives.

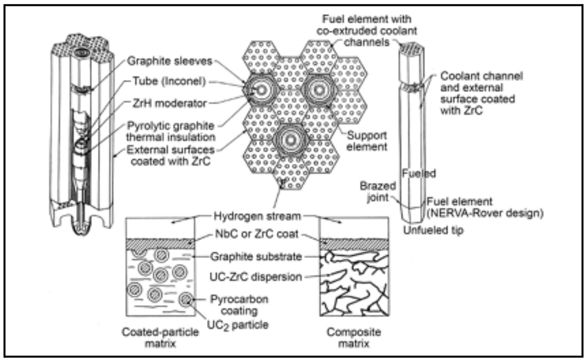


Figure 5: Tube arrangement

This basic FE shape was introduced in the KIWI-B4E reactor and became the standard used in the 75 klbf Phoebus-1B, 250 klbf Phoebus-2A, 25 klbf Pewee and the 55 klbf NERVA NRX series of engines. Also included in the engine's reactor core were cooled coaxial tie tube (TT) elements that provide structural support for the FEs, as well as a source of energy for turbine drive power. The TTs also included a sleeve of zirconium hydride (ZrH) moderator material to help raise neutron reactivity (shown in Fig. 5). In the larger size engines tested in Rover/NERVA, a "sparse" FE—TT arrangement was used with each FE having two adjacent TTs and four adjacent FEs comprising its six surrounding elements. In this sparse pattern, the FE to TT ratio is ~3 to 1.

IV. NUCLEAR THERMAL PROPULSION

Radioisotope Thermoelectric Generators (RTGs) represent a hallmark in spacecraft power systems, renowned for their lightweight, compact design and unparalleled reliability. The underlying principle behind RTGs lies in their ability to harness the heat generated from the natural radioactive decay of plutonium-238 [5] , typically in the form of plutonium oxide. This heat differential, created between the hot fuel and the frigid vacuum of space, is exploited through specialized solid-state metallic junctions known as thermocouples. These thermocouples, composed of materials like Bismuth Telluride, facilitate the conversion of thermal energy into electrical power without the need for any moving parts, ensuring a robust and maintenance-free energy source for space missions [6].

Utilization of RTGs in NASA missions has been pivotal, especially in scenarios where alternative power sources such as solar panels are impractical or insufficient to meet the mission's power demands. Often likened to "nuclear batteries," RTGs [7] provide a continuous and dependable source of electricity for spacecraft, enabling the accomplishment of scientific and operational objectives in harsh space environments. It's essential to note that RTGs differ from traditional fission reactors, and the plutonium used in RTGs is not of the type used in nuclear weapons. Since the inaugural RTG mission in 1961, more than two dozen U.S. space missions have relied on this technology, highlighting its proven track record and enduring relevance in space exploration endeavors [7].

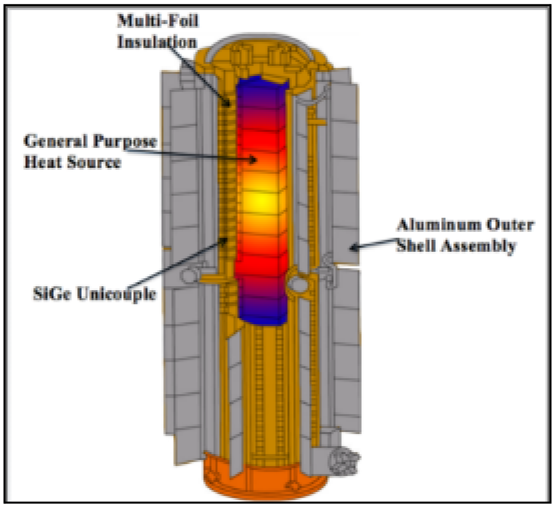
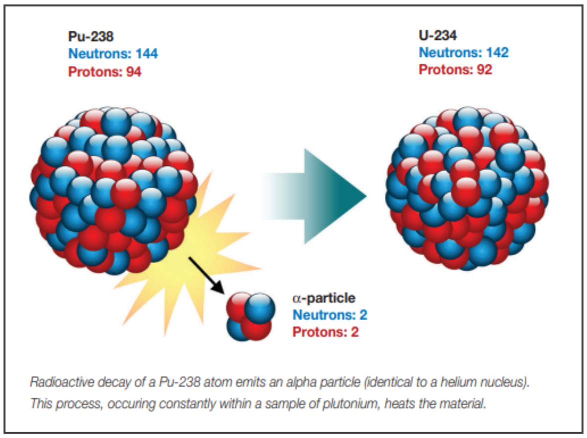


Figure 6: Components of RTG

As could be observed on figure 6, the components of a Radioisotope Thermoelectric Generator (RTG) encompass a sophisticated ensemble designed to harness the energy derived from the natural decay of plutonium-238. Integral to this system is the Multi Foil Insulation, a specialized material meticulously engineered to minimize heat loss and maintain thermal stability within the generator [7]. At the heart of the RTG lies the General Purpose Heat Source, encapsulating the plutonium-238 fuel in a robust containment structure to ensure safe and efficient heat generation. Surrounding this core element is the SiGe (Silicon Germanium) Thermocouple, a crucial component responsible for converting the thermal energy into electrical power through the Seebeck effect. Lastly, the Aluminum Outer Shell Assembly provides structural integrity and protection to the RTG, safeguarding its intricate components against the harsh conditions of space [7].

A. Plutonium-238

Plutonium-238 (Pu-238), chosen as the heat source to power space missions, underscores its critical role in advancing space exploration. Selected by the Department of Energy (DOE) for Radioisotope Power Systems (RPS) provided to NASA, Pu-238 has been instrumental in fueling some of the most iconic missions in space history [5]. Notable examples include the Curiosity Mars rover, which relies on Pu-238 for its energy needs, and the legendary Voyager 1 and 2 spacecraft. With a half-life of approximately 88 years, Pu-238's enduring heat output ensures the longevity of RPS-equipped missions [5]. This longevity is crucial for deep space exploration, allowing spacecraft to operate for extended periods in environments where traditional power sources like solar panels are impractical or ineffective. This process is simply shown on the figure below figure 7.



Radioactive decay of a Pu-238 atom emits an alpha particle (identical to a helium nucleus). This process, occuring constantly within a sample of plutonium, heats the material.

Figure 7: Decay of Pu-238

Pu-238's suitability as a radioisotope fuel in RPS stems from its unique properties, particularly its reliable and efficient heat generation over long durations. This characteristic ensures that spacecraft equipped with Pu-238-based RPS can function effectively for missions lasting upwards of 14 years or more [5]. Moreover, Pu-238 is considered safe for use in RPS, offering a dependable power source with minimal risk to both the spacecraft and the surrounding environment. Its proven track record in powering spacecraft such as Pioneer 10 and 11, Voyager 1 and 2, Cassini–Huygens, and New Horizons, along with its utilization in devices like the Mars Science Laboratory and Mars 2020 Perseverance Rover, underscores its reliability and importance in enabling long-term nuclear power generation for space exploration endeavors [5].

B. Curiosity: 2011

One of the most recent nuclear-powered space missions, Curiosity, launched in 2011, stands as a remarkable feat of scientific exploration, even engaging in social media interactions through "tweets from space" [4]. Curiosity's power source is a single multi-mission radioisotope thermoelectric generator, meticulously constructed, assembled, and tested by a collaboration between the Energy Department and several National Laboratories including Idaho, Oak Ridge, Los Alamos, and Sandia. Its primary objectives include studying rock layers and climate on Mars, as well as determining the potential existence of past life on the Red Planet. With a projected lifespan of two years, Curiosity relies on approximately 10.6 pounds (4.8 kilograms) of plutonium dioxide to provide a steady supply of heat, generating slightly over 100 watts of power for its scientific missioN [4].

C. Mars 2020: Perseverance

The Mars 2020 rover, known as Perseverance, carries on the legacy of its predecessor, Curiosity, sharing a similar design and launched on July 30, 2020 [8]. Tasked with seeking signs of ancient life and collecting samples of rock and regolith for potential return to Earth, Perseverance relies on a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to power its mission. This generator harnesses the heat generated by the natural radioactive decay of plutonium-238, utilizing thermoelectric materials to convert this heat into electricity. Plutonium-238, a radioactive isotope, undergoes continuous decay, producing heat as a byproduct, which Perseverance effectively utilizes to generate approximately 110 watts of power, meeting the energy demands essential for its scientific objectives on the Martian surface [8].

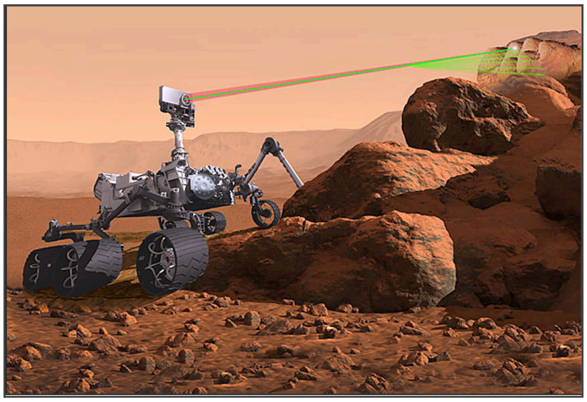


Figure 8: Mars Perseverance

V. CONCLUSION

In summary, nuclear power has been instrumental in advancing space exploration, from the deployment of the first nuclear reactor in space with the SNAP-10A system to recent missions powered by Radioisotope Thermoelectric Generators (RTGs) like Curiosity and Mars 2020 Perseverance. These technologies have enabled long-duration missions and facilitated groundbreaking scientific discoveries. Nuclear fission reactors, such as the SP-100, and Nuclear Thermal Propulsion (NTP) systems offer promise for faster interplanetary travel and ambitious exploration beyond Earth's orbit. As humanity continues to push the boundaries of space exploration, nuclear power remains a cornerstone technology, providing reliable and efficient energy solutions.

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