Should Nuclear Energy Be Used in Advancing Space Exploration?

Rui Zhang

UCL Undergraduate Preparatory Certificate Research Project
Submitted 2 May 2024

Abstract

This report studies whether nuclear energy should be used in advancing space exploration. It compares radioisotope power systems and fission power systems with solar power and chemical batteries, focusing on operational lifetime, electrical power, reliability, safety, and ethical concerns. The argument is that nuclear systems can be technically valuable for long-duration and deep-space missions, but their use must remain tied to strict safety protocols, radiation management, and ethical evaluation.

1 Introduction

Power-generating systems are among the most important components of spacecraft. Many missions cannot be sustained for long periods without a reliable source of energy. Chemical batteries and solar power have supported a large range of missions, but both face limitations in extreme environments and in deep space. Solar power depends strongly on mission orbit and distance from the Sun, while chemical batteries are limited by storage capacity, operating temperature, and lifetime.

Nuclear power has therefore been used in space missions as a robust alternative. The use of nuclear energy in space began during the early space age. The United States launched a radioisotope-powered satellite in 1961 and a fission-based spacecraft in 1965. Since then, nuclear systems have supported missions including the Voyager spacecraft and New Horizons.

The use of nuclear energy is not only a technical upgrade. It also raises safety and social questions. This report considers the technical advantages of nuclear power, including greater electrical power, longer operating lifetime, and reliability in deep-space conditions. It then discusses safety problems and ethical considerations.

2 Nuclear Power Systems for Spacecraft

Two major categories of nuclear power system are radioisotope power systems (RPSs) and fission power systems (FPSs). RPSs convert heat released by radioactive decay, commonly from plutonium-238, into electricity. A radioisotope thermoelectric generator (RTG), sometimes called a nuclear battery, uses thermoelectric materials to convert decay heat into electric current. Because the energy source is radioactive decay, RTGs can operate continuously for years or decades.

Fission power systems also use heat from nuclear reactions, but the heat is produced by a controlled fission process, commonly involving uranium-235. The mass loss associated with fission is related to Einstein's equation,

$$E = mc^2,$$

which explains why fission can produce much higher energy density than chemical reactions. Fission systems can therefore produce power from the kilowatt scale to the megawatt scale, depending on design.

3 Technical Advantages

3.1 Operational Lifetime

The lifetime of a radioisotope power system is closely linked to the half-life of the radioactive material used. Plutonium-238 has a half-life of about 87.7 years, while americium-241 has an even longer half-life. This allows radioisotope systems to provide a stable power supply for mission durations that would be unrealistic for ordinary chemical batteries.

This long lifetime is important for deep-space missions because replacement, repair, or recharging is normally impossible. A mission travelling beyond the inner Solar System needs a power source whose output remains useful after years of travel.

3.2 Electrical Power

Nuclear systems can provide higher power output than conventional sources in mission contexts where sunlight is weak or unavailable. Fission systems are especially important for high-power requirements, including propulsion concepts and crewed mission architectures. Nuclear thermal propulsion and fission power platforms can reach power regimes far beyond ordinary spacecraft batteries.

Solar power is attractive near Earth, but its usefulness decreases as distance from the Sun increases. At around 10 astronomical units from the Sun, solar irradiance is far smaller than it is near Earth. This makes solar energy less suitable for missions to distant planets or regions with limited sunlight.

3.3 Reliability in Extreme Conditions

Spacecraft operate in severe thermal and radiation environments. Solar power depends on illumination, orbit, and dust or shadowing conditions. Batteries can suffer reduced performance at low temperatures and require careful thermal management. By contrast, RTGs do not depend on sunlight and can operate in cold, dark, and remote environments.

This explains why RTGs have been used in long-duration missions. Voyager 1 and Voyager 2 continued operating far beyond the planets, while solar-powered spacecraft are more constrained by distance from the Sun.

4 Applications in Space Exploration

Nuclear power systems have been important in long-duration and deep-space missions. Apollo lunar surface experiments, the Voyager missions, and other outer-planet missions benefited from radioisotope power. These systems are particularly useful when the mission profile requires stable power far from the Sun.

It is not always necessary to use nuclear power. For near-Earth missions, inner Solar System missions, or spacecraft with modest power needs, solar panels and batteries may be more appropriate. Nuclear systems become more compelling when the mission requires long lifetime, high energy density, operation far from the Sun, or high-power propulsion and crew support.

5 Safety Considerations

Nuclear systems introduce risks that must be taken seriously. Launch failure, accidental re-entry, and damage to containment systems could release radioactive material. RTGs are designed with protective shielding to reduce this risk, and the probability of severe release events can be very low when strict safety procedures are followed. However, low probability does not remove the need to plan for consequences.

Fission systems create different safety issues. Before activation, some designs may emit little or no radiation, reducing launch risk. After activation, shielding and distance are necessary to protect equipment and astronauts. Enriched uranium also creates security concerns because of proliferation risk, so fission systems require strict control and protection.

There is also a trade-off for crewed missions. A high-power fission system could shorten mission duration, reducing astronaut exposure to cosmic radiation and psychological stress. At the same time, the reactor itself introduces a radiation source that must be carefully managed. The correct comparison is therefore not simply "nuclear is dangerous" versus "nuclear is safe", but a mission-specific comparison of total risk.

6 Ethical Considerations

Long-duration space exploration raises ethical questions even when the engineering is feasible. Astronauts are already exposed to cosmic radiation and isolation during spaceflight. Adding nuclear systems changes the risk profile and requires justification. The ethical goal should be to ensure that nuclear power does not impose additional unacceptable danger compared with the unavoidable risks of the mission.

For some long-term missions, robotic spacecraft may be more ethically appropriate than crewed spacecraft. A robot or probe can perform scientific exploration without exposing humans to the same level of radiation, isolation, and life-support risk. Nuclear power may still be useful in such robotic missions, but the ethical balance is different.

7 Conclusion

Nuclear power systems have significant advantages for space exploration. They can provide longer operating lifetime, higher power output, and greater reliability in deep-space environments than solar power or chemical batteries in many mission contexts. These strengths explain their use in missions such as Voyager and their relevance to future deep-space exploration.

However, nuclear systems also raise safety and ethical concerns. Launch accidents, re-entry, radiation shielding, reactor control, security, and astronaut exposure must all be addressed. Nuclear energy should therefore be used selectively, where mission requirements justify it and where safety protocols are rigorous. The decision should balance mission success with responsibility toward astronauts, the public, and the environment.

Reflective Note

This project was an important early exercise in academic writing. The original topic was too broad, and the project improved after narrowing the question to nuclear energy in aerospace and space exploration. The work also showed the need to explain technical terms carefully. Concepts such as natural decay, nuclear fission, radiation shielding, and power regimes can be difficult for readers without a nuclear-energy background.

If developed further, this project should include a more quantitative comparison of mission power needs. It could compare near-Earth, Jupiter-distance, and deep-space mission profiles, then estimate whether solar, battery, radioisotope, or fission systems are appropriate under each scenario.

References

- Araujo, E. F. and Guimaraes, L. N. F. (2018). American Space Nuclear Electric Systems. *Journal of Aerospace Technology and Management*, pp. 1–32. https://doi.org/10.5028/jatm.v10.976
- Bermudez-Garcia, J. et al. (2021). Source used for solar irradiance comparison across planetary distances.
- Bugga, R. V. and Brandon, E. J. (2020). Energy Storage for the Next Generation of Robotic Space Exploration. *The Electrochemical Society Interface*, 29(1), pp. 59–63. doi: 10.1149/2.F08201IF.
- Klein, A., Camp, A., McClure, P., Voss, S., Borenstein, E. and VanDamme, P. (2021). Operational Considerations for Space Fission Power and Propulsion Platforms. *Nuclear Technology*, 207(6), pp. 851–859.
- Krause, F. C. et al. (2018). High Specific Energy Lithium Primary Batteries as Power Sources for Deep Space Exploration. *Journal of The Electrochemical Society*, 165(10), pp. 2312–2320.
- Mason, L. S. (2019). *Comparison of Energy Conversion Technologies for Space Nuclear Power Systems*. NASA.
- NASA (2024). Juno. https://science.nasa.gov/mission/juno/
- Petrangeli, G. (2006). Nuclear facilities on satellites. *Nuclear Safety*, pp. 237–238.
- Souza, D. C. et al. (2022). How does radioisotope thermoelectric generator (RTG) work. *Brazilian Journal of Radiation Sciences*, 10(2).
- Velidi, G. and Guven, U. (2020). Nuclear-powered space reactor. In *Nuclear Reactor Technology Development and Utilization*. Woodhead Publishing, pp. 407–428.
- Verduci, R. et al. (2022). Solar Energy in Space Applications: Review and Technology Perspectives. *Advanced Energy Materials*, 12(29), pp. 2–24.
- Wang, J., Zhang, L., Qu, J. and Tong, J. (2019). Establishing safety goals on radiation protection for a space reactor through a loss-of-coolant case assessment. *Annals of Nuclear Energy*, 134, pp. 170–177.
- Xia, Y. et al. (2021). Application Prospect of Fission-Powered Spacecraft in Solar System Exploration Missions. *Space: Science & Technology*, 2021, pp. 1–12.