American Journal of Student Research

Narrative Review Article

Nuclear Thermal Propulsion and Flight Safety: A Review

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ABSTRACT

Nuclear thermal propulsion (NTP) has long been regarded as a promising technology for advancing the efficiency and scope of space exploration. Originating in the mid-twentieth century through programs such as Project Rover and NERVA, NTP systems demonstrated the technical feasibility of nuclear-powered rocketry, offering substantial gains in specific impulse and payload capacity over chemical propulsion. Despite program cancellations and decades of limited progress, more recent initiatives—including the Space Nuclear Thermal Propulsion (SNTP) program, Project Icarus, and DARPA's DRACO project—have revitalized interest in NTP development. However, persistent public concerns regarding nuclear safety, coupled with the absence of standardized regulatory protocols, remain significant barriers to widespread adoption. This paper traces the historical development of NTP systems, evaluates recent technological advancements, and examines the regulatory landscape governing their deployment. Particular attention is given to probabilistic risk assessment (PRA), Safety Analysis Reports (SARs), and evolving U.S. policy frameworks, including NPR 8715.26 and NSPM-20, which collectively shape the future of nuclear flight safety. However, there are considerable gaps in the testing and modelling of NTP systems that must be filled to meet revised safety regulations. With the growing commercial and state interest in space exploration, particularly in the US, there is considerable potential for new NTP designs to transform long-duration space missions, with robust and transparent safety measures to ensure public acceptance and regulatory approval.

Keywords: Aerospace; Nuclear Energy; Nuclear Thermal Propulsion; Nuclear Flight Safety; Risk Assessment; Safety Regulation

INTRODUCTION

Nuclear power is frequently the subject of debate with respect to safety in energy production. The Fukushima Daiichi nuclear accident in 2011 brought public attention once more on the dangers of nuclear power (1). However, nuclear power provides efficiency benefits that are unmatched by its alternatives. When compared to renewable energy sources such as solar energy, nuclear power offers similar reductions in harmful emissions whilst affording a more reliable, consistent source of electricity, independent of external factors such as weather conditions (2).

Nuclear energy has shown considerable impact across several industries and applications and has the potential to broaden its benefits even further. Nuclear energy, produced through nuclear fission in which atomic nuclei split and release substantial energy, has

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Accepted October 10, 2025
https://doi.org/10.70251/HYJR2348.35800811

long been considered a promising method of propulsion for transportation systems (3). Within the aerospace industry, nuclear-propelled rockets can be more than two times as efficient as conventional chemical propulsion systems (4). Such propulsion systems have been of most interest in space exploration. The twenty-first century has heralded a renewed era of space exploration, characterized by intensified efforts from both private enterprises and governmental agencies. In 2017, Space Exploration Technologies Corporation (SpaceX) implemented a novel launch strategy by successfully reusing the core stage of a previously flown rocket. This approach represents a foundational element of the company's long-term objective to establish a sustained human presence on Mars. Government agencies such as the Indian Space Research Organization (ISRO) plan to utilize similar strategies to remain at the forefront of a rapidly changing industry (5). A study conducted by Analytical Mechanics Associates showed that various scenarios of lunar missions, particularly those using heavier rockets, achieved higher payload limits and reduced transit times when fueled by nuclear energy as opposed to traditional rocket fuels (6).

As interest in space exploration, and the demands for more efficient propulsion systems grows, nuclear thermal propulsion (NTP) is once more under consideration. However, given public concerns surrounding the safety of nuclear energy and its applications, the evaluation and communication methods of the safety of such systems will be of paramount importance if they are to be widely accepted as a future means of propulsion. This paper presents the evolution of NTP systems from their origins in the 1950s to the present day. Recent technological developments are examined and potential avenues for future expansion outlined. A comprehensive assessment of the most prevalent safety challenges is provided, with reference to the regulatory frameworks within both the nuclear and aerospace sectors, and targeted recommendations offered to address such challenges.

NUCLEAR THERMAL PROPULSION (NTP)

Although not widespread, nuclear energy has been utilized as a fuel source for spacecraft in the past. In 1955, the US Atomic Energy Commission (AEC) approved the development of Project Rover, widely regarded as the first NTP concept, at Los Alamos Scientific Laboratory (LASL). The Rover program was taken over by the National Aeronautics and Space Administration (NASA) soon after its creation and was the basis of NASA's Nuclear Engine for Rocket Vehicle Application (NERVA). The NERVA experiment was successful in its mission to develop an initial nuclear rocket engine, becoming one of several national programs to develop NTP designs over the years since (7).

The following section examines how early NTP-related programs, alongside more recent projects such as the Space Nuclear Thermal Propulsion (SNTP) program, Project Icarus, and the Demonstration Rocket for Agile Cislunar Operations (DRACO), expanded the use of NTP solutions within the aerospace industry and enhanced the prospect of future application.

Project Rover and NERVA

Project Rover encompassed three distinct phases, beginning with the influential Kiwi program. The Kiwi program assessed the feasibility of nuclear reactors as an energy source for propulsion and sought to test potential materials for such reactors (8).

An NTP system comprises several critical components, each fulfilling a distinct function (Figure 1). The nuclear reactor initiates and sustains fission reactions to produce thermal energy. Surrounding the core, the neutron reflector minimizes neutron leakage by redirecting escaping neutrons back into the reactor,

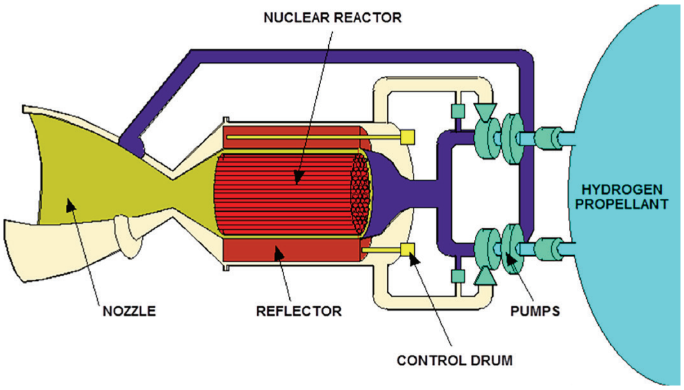

Figure 1. Design of an NTP Rocket Engine (9). A basic framework of an NTP propulsion system is shown, with various parts highlighted. Using pumps to maintain pressure, hydrogen propellant is transported to the nuclear reactor core and heated through nuclear fission. In this process, a reflector improves efficiency by redirecting neutrons into the reactor core, and control drums containing neutron absorbing materials regulate the reactor's power output. Finally, thrust is generated when the nozzle accelerates the heated hydrogen.

thereby enhancing fission efficiency. Control drums, embedded with neutron-absorbing materials, modulate reactor power output through rotational positioning that adjusts neutron absorption rates. The hydrogen propellant is circulated through the reactor where it absorbs thermal energy. Hydrogen pumps facilitate the transfer of propellant from onboard storage tanks into the reactor core. Finally, the nozzle converts the thermal energy of the heated hydrogen into kinetic energy, producing thrust via high-velocity exhaust expansion.

A key area of contention was in the selection of an appropriate reactor coolant, considering the potential for adverse chemical interactions between the coolant and fuel. Ammonia was initially proposed due to its efficient power delivery (4). However, an influential study conducted by the Rocketdyne Division of North American Aviation for the United States Air Force showed the potential weight-saving benefits of liquid hydrogen (LH_2) for high-velocity and heavy-payload operations (10). Consequently, ammonia was replaced with LH_2 as the reactor coolant, with Rocketdyne engineering a specialized pump capable of delivering hydrogen at a flow rate of 10,000 gallons per minute under a pressure of 1,500 psi. Between 1959 and 1960, three nuclear reactors, forming the Kiwi A group, were tested at the Nevada Test Site (NTS) by LASL, providing empirical validation of LH_2 as an effective reactor coolant based on its thermal performance (4).

Another challenge of the Kiwi program was to identify or synthesize a fuel that could sustain high-energy fission reactions without excessive degradation of its mechanical properties. Fuels composed of differing chemical compounds were proposed to enable higher operating temperatures. Carbon-based nuclear fuels were ultimately chosen, coated with a pyrolytic graphite solution to address their structural weaknesses, thereby improving the overall performance of the propulsion system (8). Kiwi A, the first model of the Kiwi rocket engine, began its testing on July 1st, 1959.

Kiwi A was a successful proof of concept for NTP rockets, demonstrating that hydrogen could be heated to the temperatures required for space propulsion using a nuclear reactor. Industry bids were called for to develop NASA's Nuclear Engine for Rocket Vehicle Application (NERVA), based upon the Kiwi engine design. Rover became part of NERVA, with Rover responsible for nuclear rocket reactor design, and NERVA responsible for the development and deployment of nuclear rocket engines, alongside the planning of space missions.

Building upon the success of the Kiwi A reactor series, the LASL initiated the development of the Kiwi B reactors, aiming to achieve a tenfold gain in power output whilst maintaining similar physical dimensions. These reactors were ultimately of a smaller scale than both their predecessors, the Kiwi A reactors, and the subsequent Phoebus reactor designs (Figure 2). Achieving the desired performance increase out of the Kiwi B reactors necessitated the use of higher-pressure LH_2, which Rocketdyne facilitated by upgrading its hydrogen pump, engineering a specialized feed system. Beyond elevated pressures, the LH_2 also required increased density to meet the targeted power output, which Rocketdyne fulfilled with its LH_2-cooled single-pass, high-expansion ratio tubular nozzle. In theory, the pump, nozzle, and reactor made up a prototype NTP rocket engine. Five were tested at the NTS between 1961 and 1964 and were judged to be successful, with no major drawbacks (4). The achievements of the KIWI program provided a critical precedent that informed and facilitated the development of later NTP systems.

SNTP Program

The Rover and NERVA programs were terminated in 1973 by the United States government due to a lack of funding. However, the government initiated an additional NTP project, the Space Nuclear Thermal Propulsion (SNTP) program, in 1987 under the Strategic Defense Initiative Organization (SDIO). The program, structured in three distinct stages, was designed to develop a nuclear thermal rocket engine capable of delivering twice the thrust of conventional chemical propulsion systems (12).

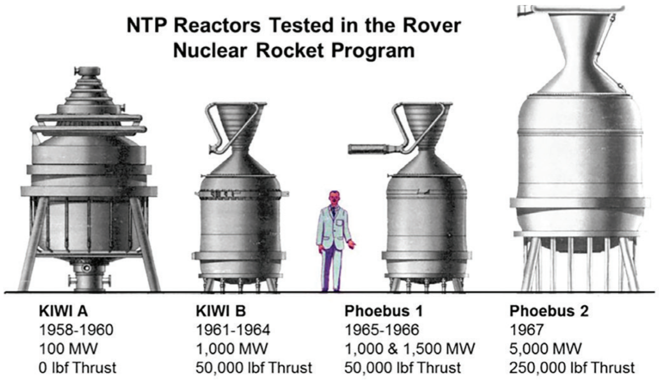

Figure 2. NTP Reactors Tested in the Rover Nuclear Rocket Program (11). As part of the Rover Nuclear Rocket Program, four NTP-powered rocket engines were tested in the 1950s and 1960s, producing varying levels of thrust.

The first stage of the SNTP program assessed the efficiency of a Particle Bed Reactor (PBR) as a fuel source for an NTP rocket engine. In a PBR, gases, such as hydrogen, are circulated through the reactor core to simultaneously extract thermal energy for cooling purposes and transfer heat to the nuclear fuel particles entrenched within the bed. Due to their greater surface area-to-volume ratio relative to the solid carbon-based fuels utilized in the Rover and NERVA programs, the particles employed in the SNTP initiative exhibited an enhanced power density, thereby contributing to an increased specific impulse (I_{SP}), defined as the amount of thrust produced per unit of propellant consumed over time (13). This relationship was exemplified in the initial phase of the SNTP program, demonstrating that increased specific impulse serves as a key indicator of greater propulsion efficiency (12).

During the second phase of the SNTP program, administrative control transitioned from the SDIO to the United States Air Force. This stage centered on ground-based evaluation of a PBR rocket engine, evaluating its performance for potential integration into NASA and Air Force space missions, including crewed expeditions to Mars. One of the primary technical challenges involved achieving sufficiently high temperatures within the fuel particles to enhance reactor efficiency, on account of improved thermal conductivity. Although various fuel compositions were evaluated, Mixed Carbide (MC) fuels were selected for their superior thermal conductivity. Multiple tests were performed in this stage. The final test being a successful nuclear element test (NET) in the Sandia National Laboratory's Annular Core Research Reactor (ACRR) (8). After fuel testing, potential reactor designs were studied. Reactors made with beryllium components were chosen for their superior moderation of neutrons in scenarios such as high-temperature operations and repetitive startups. NTP engines also saw improvements: components such as the turbopump, nozzle, and reactor pressure vessel demonstrated promising results in tests (12).

The SNTP program's third and final phase, centered on flight testing, was cancelled, with the overall program terminated in 1994 due to the escalating costs associated with the necessary comprehensive testing activities. Nonetheless, the program yielded significant advancements in nuclear thermal propulsion technologies over its seven-year duration. It was influential in addressing key challenges that hampered the viability of NTP solutions in high-stakes space missions. The SNTP system demonstrated a superior thrust-to-weight ratio in comparison to the NERVA project. Additionally, it projected an enhanced specific impulse of approximately 1000 seconds, surpassing NERVA's peak performance of 930 seconds, establishing a foundational framework for subsequent advancements in the field of nuclear thermal propulsion (8).

Project Icarus

Despite formidable technical challenges, British interstellar travel was conceptually validated in the 1960s and 1970s through initiatives like Project Daedalus, developed by the British Interplanetary Society (BIS). More recently, the BIS collaborated with the Tau Zero Foundation (TZF) to initiate Project Icarus, a revision and expansion of Project Daedalus incorporating modern scientific advancements and proposing nuclear thermal propulsion to optimize mission performance (14).

Multiple rockets and NTP configurations were evaluated, with varying stage counts tested to optimize performance. However, designs exceeding three stages necessitated reduced payloads, thereby limiting capacity for fuel and other rocket components. Suboptimal designs were additionally considered, demonstrating the tradeoffs that would have to be made to meet payload requirements. In terms of nuclear fuel, smaller particles than those used in Project Daedalus were proposed, to take advantage of their weight-saving characteristics. Mission timelines were also factored into the fuel optimization strategy, with durations between forty and seventy years the most favorable for consumption efficiency while achieving the project's goal of reaching stars such as Barnard's Star (5.9 light years) and Epsilon Eridani (10.7 light years) (14). Although it was a concept, Project Icarus further evidenced the role of nuclear power in enabling extended-duration interstellar missions.

DRACO

Recent increases in the prominence of NTP initiatives reflect a renewed emphasis on technological innovation and the strategic pursuit of space exploration. Established in 2020 by the US's Defense Advanced Research Projects Agency (DARPA), the Demonstration Rocket for Agile Cislunar Operations (DRACO) Program demonstrates this advancement through its cutting-edge testing of NTP technologies (15).

The DRACO Program was divided into three phases. The first phase established a baseline nuclear reactor design and proposed operational guidelines for a nuclear-powered rocket. This phase demonstrated that suitable reactor fuel materials were readily accessible and capable of enduring severe thermal conditions when subjected to liquid hydrogen-based cooling. Tanks were also designed to store LH_2 at cryogenic temperatures to ensure optimal thermal performance. Most importantly, the DRACO Program's rocket design was sized to fit into existing space launch vehicles, reducing development costs (12).

Following the conclusion of the initial phase in 2022, the program's objectives transitioned toward evaluating the operational performance of the NTP system without utilizing nuclear fuel in the second phase. Due to significant financial limitations and schedule constraints, the DRACO Program adopted an innovative in-space testing strategy, which optimized feasibility and resource allocation by providing more valuable performance data over a shorter time span. Tests such as engine startups and reactor performance assessments were conducted successfully. The second phase prioritized safety, with heightened attention to potential radiological consequences in the event of a system malfunction (16). Unfortunately, this is where the program, and its advancements, ended. DRACO was suspended in 2025 due to funding limitations, leaving its safety assessment unfinished, and with little published literature available on the safety assessment and challenges of NTPs, this remains a considerable hurdle towards acceptance and widespread use of nuclear thermal propulsion. Nonetheless, DRACO's advances over previous programs such as Project Rover and NERVA make it a key milestone in this pursuit.

SAFETY ASSESSMENT OF NUCLEAR THERMAL PROPULSION SYSTEMS

In both the nuclear and aerospace industries, safety cases must be developed and approved by the respective regulatory authority to conduct the relevant operations, from testing to construction and operation. A safety case constitutes a logically structured, evidence-based justification demonstrating that a system meets acceptable safety standards for a defined application within a specified operational context. The safety of a system can be evaluated using approaches that either follow established protocols or emphasize achieving specific safety outcomes (17). In the case of new technologies in the nuclear and aerospace industries, safety protocols often do not exist. Therefore, desired safety outcomes are determined. This is accomplished through methods such as probabilistic risk assessment (PRA). This section will summarize the role of PRA in analyzing failure probability and identifying key failure points to help in design optimization, from its first full-scale application within the nuclear industry to its present role in NTP within the aerospace industry. This should provide valuable insight into regulatory responsibilities and what such regulators might expect from safety analysis of future nuclear thermal propulsion systems.

Probabilistic Risk Assessment (PRA)

PRA was first considered in the aerospace sector following the 1967 Apollo flight test fire in which three astronauts were killed (18). Prior to the accident, NASA relied solely on applying good engineering practices to provide quality assurance and quality control. As a result of Apollo, in 1969, NASA'S Office of Manned Space Flight initiated the development of quantitative safety goals. Citing managers' lack of appreciation for the uncertainty in risk calculations, these goals were not adopted (19). However, with its successful adoption within the nuclear industry, The Federal Aviation Agency (FAA) and NASA began to utilize it in later decades (20).

In general terms, PRA seeks to quantify the risk of adverse events causing harm to people or property and is an integral part of determining the safety of a product or solution (21). PRA uses a combination of event trees and fault trees to systematically analyze potential hazards. Event trees are employed to model the possible outcomes resulting from a specific initiating event, while fault trees are constructed to identify and assess the underlying causes that may lead to system failures. In the context of an NTP system, a representative event tree may begin with an initiating event such as a mechanical failure within the reactor's cooling system, leading to impaired heat dissipation. The event tree would subsequently evaluate the likelihood of two distinct outcomes: a successful scenario in which the reactor core temperature is effectively stabilized, and an adverse scenario resulting in damage to the core.

The nuclear energy industry has utilized PRA extensively to enhance its safety aspects, beginning with the WASH-1400 reactor study in 1975 (20). Its findings and safety recommendations, published by the United States Nuclear Regulatory Commission (USNRC), marked the beginning of a new era in nuclear safety, and the USNRC continues to lead this effort through active regulation today. PRA quickly gained traction as a crucial part of the design process of nuclear facilities, with almost 100 use cases within the next two decades after the WASH-1400 study (20). By integrating PRA into the engineering design process, stakeholders can identify critical vulnerabilities in their designs and maintain compliance with the stringent safety standards set by regulators worldwide.

PRA methodologies are applied to quantify failure probabilities associated with both system components and human performance. For instance, data pertaining to containment breaches, cooling system malfunctions, and reactor core damage scenarios are compiled into event trees to estimate the likelihood of radioactive release events. The PRA framework is structured into the three sequential levels (Figure 3). Level 1 analyzes events that lead to core damage. Level 2 assesses containment performance and cooling mechanisms, quantifying both the frequency and magnitude of radioactive releases associated with Level 1 scenarios. Level 3 examines the environmental and public health consequences arising from the release of radioactive materials.

The WASH-1400 report was among the first to formally implement the Complementary Cumulative Distribution Function (CCDF) framework, enabling quantitative estimation of the likelihood that specific consequence thresholds are exceeded within a PRA context. Subsequent initiatives, including the Zion and Indian Point studies, represented the first regulatory applications of PRA following its foundational use in WASH-1400. Mandated by the USNRC, these studies employed PRA methodologies to conduct rigorous evaluations of plant safety under a spectrum of external hazards, such as fires, flooding, tornadoes, seismic disturbances, and aircraft impact scenarios (21). Overall, PRA has proven instrumental in advancing safety across nuclear applications by providing a structured, quantitative framework for evaluating system vulnerabilities and potential accident scenarios.

PRA in Nuclear Thermal Propulsion

The first notable use of PRA in an NTP program was in the AEC's Systems for Nuclear Auxiliary Power (SNAP) program. Over its 18-year duration, the project aimed to design an efficient and space-saving NTP solution for space travel. A diverse array of reactors was developed to support a broad spectrum of mission profiles, encompassing operations aboard space stations as well as propulsion and power systems for deep space exploration. The SNAP program was known for its consideration of mission safety, with aspects such as rocket re-entry and disposal studied to ensure protection of the environment in the event of failure. Later programs such as NASA's Space Power 100 kWe (SP-100) project of 1982 advanced the study of safety and use of PRA. As with the SNAP program, SP-100 involved manufacturing versatile NTP solutions for missions of varying sizes and performance requirements, paying special attention to safety (22).

An examination of these projects highlights the convergence and divergence in the application of PRA across the aerospace and nuclear sectors. Notably,

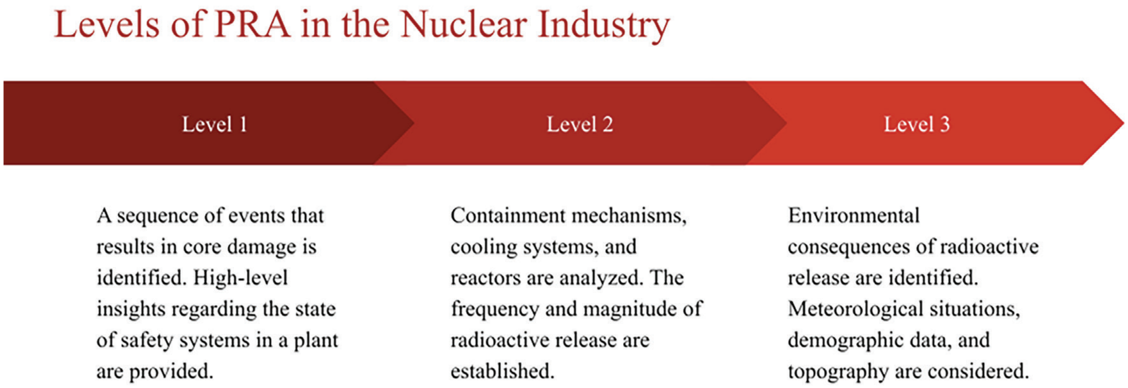

Figure 3. Levels of PRA in the Nuclear Industry. The core structure of PRA in nuclear applications is comprised of three distinct stages. First, occurrences that result in operational failure and radioactive release are determined. Next, the components of the energy system are analyzed to assess the possibility of containment. Finally, the environmental impact of such radioactive release is considered.

comparative analysis reveals parallels in initiating events, including mechanical failures such as cooling system malfunctions, and external hazards like fires, which are common to both industries. However, the aerospace domain also features distinctive initiating events, such as anomalies during rocket ascent and challenges associated with atmospheric re-entry, which have no direct analogues in nuclear power reactor operations (22). The wide variability in initiating events within both the aerospace and nuclear industries introduces significant complexity to risk modeling. As a result, the utility of PRA may be limited under constrained timeframes, given its reduced capacity to anticipate failures arising from a broad spectrum of potential scenarios. PRA also exhibits significant limitations in addressing events characterized by low probability yet high consequence (23). These constraints are particularly detrimental because such rare failures can lead to catastrophic mission losses and human fatalities. Finally, PRA has demonstrated inconsistency across various mission stages. When an initiating event spans multiple phases, it becomes challenging to accurately attribute its origin, thereby undermining the clarity and reliability of the risk model (23). Despite these inherent limitations, the spacecraft previously examined, such as NERVA, Project Icarus, and DRACO, exhibit both distinct and common safety concerns, some of which PRA can help address. Insufficient data on component reliability and risks may hamper evaluation of new designs; however, future configurations may set regulatory precedents and reduce associated certification costs as a result.

NPR 8715.26 – Nuclear Flight Safety

In the US, the 2019 National Security Presidential Memorandum (NSPM)-20 introduced an overhaul of the federal process for nuclear launch authorization of space nuclear systems. This, alongside the 2020 release of Space Policy Directive-6 (SPD-6), established a national strategy to ensure the safe development and use of space nuclear power and propulsion systems (24).

When issuing NSPM-20, the US Administration pointed to the fact that previous nuclear flight safety processes (i) lacked safety guidelines to inform mission planners, designers, and relevant authorities, (ii) lacked sufficient guidance for commercial use of space nuclear systems, (iii) treated almost all space nuclear systems identically, regardless of the relative risk they might pose, (iv) referenced material quantity thresholds from outdated sources, and (v) inhibited early engagement by safety evaluators with mission planners and system designers due to the ad hoc and mission-specific nature of the Interagency Nuclear Safety Review Process (INSRP) process (25). These limitations have led to delayed safety integration, mischaracterized risk profiles, and regulatory ambiguity in nuclear thermal propulsion missions. As a result, PRA has struggled to inform early design decisions, adapt to commercial contexts, and accurately model the unique hazards of NTP systems such as the previously described SNTP program, undermining its effectiveness as a decision-support tool.

To address these issues, NASA's Office of Safety and Mission Assurance (OSMA) issued its revised safety requirements for nuclear space flight – the NASA Procedural Requirement (NPR) 8715.26 - Nuclear Flight Safety (26). OSMA has responsibility for ensuring potential risks to the public, workers, assets and the environment associated with a planned space launch of radioactive materials have been appropriately evaluated, and that the required notifications and approvals have been made prior to launch. NPR 8715.26 establishes the procedural requirements of risk-informed safety analysis for the launch of nuclear systems into space, specifying the analysis and review process necessary for launch approval. It describes the operational protocols for characterizing and reporting potential risks associated with the planned launch of radioactive materials into space, launch vehicles and spacecraft, and normal or abnormal flight conditions.

NPR 8715.26 specifies a three-tiered system of safety assessment procedures, with the tier under which a mission sits dependent upon (i) the quantity of radioactive material on the flight, (ii) the probability of a credible accident scenario that might result in radiation exposure of a defined Total Effective Dose (TED) to any member of the public, and (iii) whether the space nuclear system is a nuclear reactor. Each tier requires a different approach to safety assessment, with tier II and III necessitating a review of the Safety Analysis Report by the INSRB, and tiers having different launch authorizing bodies; the head of the sponsoring department agency for tiers I and II, and the president for tier III. As such, the NSPM-20, SPD-6, and NPR 8715.26 are considerable revisions in the approach US commercial and government agencies must take to ensure comprehensive safety analysis of nuclear space flight, with a considerable reliance on PRA, evaluated against specific, quantifiable risk limits, that will no doubt have a considerable impact on future NTP design. The tiered framework improves interagency transparency and coordination, enabling earlier incorporation of safety into mission planning compared to previous ad hoc approaches. Nonetheless, challenges persist, particularly around commercial implementation and alignment with international regulatory systems. Arguably of most importance when overcoming these barriers will be how a designer factors in the regulations and requirements during the design phase, considering the requirements and review of the necessary SAR.

Safety Analysis Reports and Safety Evaluation Reports

A central element of both past and current regulatory frameworks for flight safety is the Safety Analysis Report (SAR). Originally developed by the Department of Energy (DOE), the agency historically responsible for creating and manufacturing mission-related technologies, the SAR was submitted to the NASA Administrator (z). The report evaluates the credible potential for radioactive material to be released into the biosphere, typically using probabilistic risk assessment methods. Such assessments:

a. use launch vehicle accident probabilities and accident environment data as inputs to models that estimate the likelihood and magnitude of radiological releases;
b. predict environmental transport and deposition;
c. estimate accident consequences; and
d. evaluate variability and uncertainty in the results, including knowledge gaps or incomplete information that may affect the accuracy of the estimates.

SARs may be developed for individual systems or in the broader context of a mission. A system-specific SAR establishes a *safety basis*—a set of conditions under which safety analyses and hazard controls are judged sufficient to ensure safe operation. For mission-level reviews, the SAR must either demonstrate that operations fall within this safety basis or provide supplemental safety analyses for deviations outside the established envelope.

Historically, SAR development was accompanied by the formation of an ad hoc Interagency Nuclear Safety Review Panel (INSRP). This panel included representatives from NASA, DOE, the Department of Defense (DoD), and the Environmental Protection Agency (EPA), with technical advice from the Nuclear Regulatory Commission (NRC). The INSRP reviewed accident scenarios, probabilities, environmental specifications, atmospheric transport modelling, and consequence estimates. Its evaluation of the SAR's completeness and defensibility was documented in a Safety Evaluation Report (SER). The SER, along with the SAR and related documents, was then submitted to the NASA Administrator for consideration prior to requesting nuclear launch approval from the President or their designee.

This process benefited from strong NASA–DOE collaboration and a "best science" approach to SAR development. However, the ad hoc nature of the INSRP and the absence of standardized safety and risk analysis methodologies meant that risk thresholds were often influenced by the composition of each panel. This variability increased both cost and schedule uncertainty (27).

To address these challenges, NSPM-20 replaced the INSRP with a standing Nuclear Safety Review Board (INSRB), administered by NASA. The INSRB is formalizing its procedures through a trial-use guidance document, improving consistency and transparency in its reviews (28). In parallel, the Department of Transportation (DoT) has been designated as the licensing authority for commercial nuclear spaceflight, with clearer guidelines for evaluating public safety. Together, these developments enable NASA to leverage commercial innovation and capabilities in its future exploration programs, though details of consistent and effective policy implementation remain under development.

With these new policies, NASA and other agencies must align their internal regulations with those of external authorities. Beyond NSPM-20 and Space Policy Directive–6 (SPD-6), relevant regulations include the Atomic Energy Act of 1954 (mandatory in certain cases) (29), Title 14 of the Code of Federal Regulations for FAA-licensed launches (mandatory in certain cases) (30), the Nuclear/Radiological Incident Annex (mandatory) (31), Department of the Air Force Manual 91-110 (mandatory) (32), UN Conventions and Resolution 47/68 (mandatory) (33), and the voluntary safety framework established by the UN and International Atomic Energy Agency (IAEA).

Finally, the Office of Safety and Mission Assurance (OSMA) will need to transition gradually toward objectives-driven approaches. Such a phased adoption will minimize disruption to established programs, maintain coordination across disciplines, and allow time for adaptation to new regulatory practices.

DISCUSSION

Safety concerns remain one of the main barriers to the adoption of nuclear energy in aerospace applications. To lessen the risk of radioactive contamination, the probability of a catastrophic failure in an NTP system must remain extremely low. Furthermore, safety considerations should be integrated across all phases of a space mission utilizing NTP technology, with particular attention paid to ground-based procedures and operations within Earth's atmosphere.

Groundwork

First, ground operations must guarantee the safety of the surrounding environment. The transportation of nuclear fuels or reactors to be used in an NTP system before the start of the mission may result in a nuclear disaster in the case of a hazardous event. For example, fuel leaks can result in fires and radioactive contamination in the environment. To reduce the risk of such incidents, the United States Department of Transportation (USDOT) and the USNRC mandate transportation approval processes that encompass detailed safety analyses and procedural documentation (22).

In addition to transportation, ground testing of NTP systems must prevent radioactive release in the case of failure. One effective approach to achieving this objective involves the implementation of radioactive material removal scrubbers, which are designed to capture fission gases and mitigate environmental contamination. A scrubber system was evaluated during the Kiwi program in the 1960s, yielding promising results: a controlled reactor explosion test did not result in detectable levels of nuclear contamination (34).

Radioactive release events are not always preventable. Therefore, comprehensive action plans must be established to protect people and property in the event of such an incident. An ideal solution would be to implement emergency planning zones (EPZ) around the launch sites of NTP rockets. Commonly utilized in the nuclear industry, EPZs represent designated areas in the vicinity of nuclear reactor sites that are at risk of being affected by radioactive contamination. The zones are often allocated in stages, wherein regions closer to a reactor are classified as higher-risk and consequently prioritized for enhanced resource allocation and safety measures (35). Similar classifications can easily be applied in the case of NTPs to protect the surrounding environment when preventative safety measures fail.

Uncontrollable occurrences such as fires and explosions pose a risk to environmental damage from radioactive release. Yet safety analyses in studies such as Project Pyro in 1968 have determined that most reactors are designed in such a way to withstand extreme thermal environments and prevent radioactive release, allaying system integrity uncertainties (34). Broad international adoption of these safety protocols would significantly enhance environmental protection in the event of an NTP system initiating a nuclear accident prior to the start of the mission.

In-flight Operations

Along with ground operations, the safe operation of an NTP rocket must be ensured throughout its atmospheric ascent and spaceflight phases. In the event of an inflight system malfunction, the release of radioactive materials from the spacecraft could pose a risk of environmental contamination in both the surrounding space and terrestrial regions. Moreover, a radioactive release event in space may negatively affect the performance of nearby spacecraft, multiplying the damage caused (34). Accordingly, shutdown mechanisms must be engineered to promptly interrupt fuel flow and terminate thrust, thereby mitigating the potential release of radioactive materials.

Furthermore, self-destruct systems should be designed to be utilized in catastrophic failures as a final step in preventing radioactive release. However, if such a system is activated, it is imperative to prevent the dispersal of radioactive materials to avoid environmental contamination in the vicinity of the event. This can be achieved through solutions like the implementation of neutron poison systems, which suppress reactivity and minimize the risk of radioactive release when brought into contact with radioactive material (36). Executing these approaches will uphold safety standards and enhance operational resilience across all operational domains.

Rules and Regulations

NASA is entering a new era of nuclear spaceflight, accompanied by a redefined approach to safety assessment. The revised U.S. framework emphasizes expanded interagency, commercial, and international participation in nuclear flight activities. Within the Office of Safety and Mission Assurance (OSMA), the primary objectives remain consistent: to support NASA programs and projects, to provide independent insight to agency leadership, and to engage effectively with interagency and international partners.

The transition toward objectives-driven approaches aligns with NASA's broader policy of "risk leadership," which seeks to accelerate decision-making while maintaining an appropriate risk posture. This is achieved through the definition of technical standards (or equivalents) and transparent communication of risks and benefits. In this context, objectives-driven safety assessments, when integrated with emerging nuclear space policies that operationalize the question of "how safe is safe enough?", provide a mechanism for more effective evaluation and management of nuclear spaceflight risk. At the same time, NASA is advancing a "whole-of-government" approach, working with the Department of Transportation (DoT), Department of Defense (DoD), Department of Energy (DOE), and Nuclear Regulatory Commission (NRC) to harmonize safety practices and promote conditions favorable for future nuclear thermal propulsion (NTP) operations.

The incorporation of bounding estimates for accident probabilities and hazards, alongside reliance on Safety Analysis Reports (SARs), underscores the need for a revised approach to NTP safety. While legacy accident analyses offer a foundation for SAR development, significantly more structured testing and modeling will be required to generate sufficient data for probabilistic risk assessments of novel systems. SAR findings will inform the appropriate authorization pathway under the established three-tiered decision framework, which considers system characteristics, hazard magnitude, and national security implications.

The issuance of National Space Policy Memorandum–20 (NSPM-20) reflects a U.S. commitment to transparency in nuclear safety policy. The memorandum establishes a coherent architecture for meeting fundamental safety requirements, for defining the processes by which they are satisfied, and for aligning with the principles of the International Atomic Energy Agency (IAEA) and United Nations safety frameworks. In future applications, commercial entities will be better positioned to engage collaboratively with government agencies, thereby promoting alignment between private initiatives and established regulatory frameworks. The tiered structure of NPR 8715.26 facilitates this integration by proportionally calibrating safety and oversight requirements to the radiological risk and operational scale of each mission. Together, these developments mark a critical step in ensuring both regulatory clarity and the safe application of nuclear power in space exploration.

CONCLUSION

The evolution of nuclear thermal propulsion reflects a recurring pattern of technological promise constrained by financial, political, and safety-related challenges. From the early milestones of Project Rover and NERVA to the more recent DRACO program, each generation of NTP research has demonstrated incremental technical advances while also highlighting unresolved safety concerns. Probabilistic risk assessment, supported by comprehensive Safety Analysis Reports, has proven central to bridging aerospace and nuclear regulatory frameworks, yet its limitations in addressing low-probability, high-consequence events underscore the need for continued methodological refinement. Recent policy initiatives, including NSPM-20, SPD-6, and NPR 8715.26, mark a decisive step toward a coherent and risk-informed safety architecture for space nuclear systems, but their practical implementation will require careful coordination across governmental, commercial, and international stakeholders. Ultimately, the future viability of NTP will depend not only on technical performance but also on the ability of designers, regulators, and policymakers to establish safety frameworks that inspire public confidence. If these challenges are met, NTP could play a transformative role in enabling sustained human exploration of the Moon, Mars, and beyond.

CONFLICT OF INTERESTS

The authors declare that there are no conflicts of interest regarding the publication of this article.

REFERENCES

1. Bhele VD, Bhosale SS, Ghanekar TM & Jadhav AG. Nuclear Accidents: An In-Depth Analysis of Historical Events and Lessons for Future Safety. 2024, September 21. Available from: https://ssrn.com/abstract=5016274 (accessed on 2025-08-21). https://doi.org/10.2139/ssrn.5016274
2. Jones CM. Deciding on the Future: Comparing the Environmental and Economic Advantages of Renewable Energy and Nuclear Power. *Mānoa Horizons.* 2018; 3: 29-33.
3. Galindo A. What is Nuclear Energy? The Science of Nuclear Power. 2022, November 15. Available from: https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power (accessed on 2025-08-15).

4. Gunn S. Nuclear Propulsion-a Historical Perspective. *Space Policy.* 2021; 17 (4): 291-298. https://doi.org/10.1016/S0265-9646(01)00044-3
5. Reddy VS. The SpaceX Effect. *New Space.* 2018; 6 (2): 99-183. https://doi.org/10.1089/space.2017.0032
6. Harnack C, *et al*. Capabilities of Single Launch NTP and Chemical Spacecrafts for Cis-Lunar Tug Missions. Nuclear and Emerging Technologies for Space (NETS 2023). *Idaho Falls: American Nuclear Society.* 2023. https://doi.org/10.13182/NETS23-41745
7. DeHart MD, Schunert S & Labouré VM. Nuclear Thermal Propulsion. In M. D. DeHart, S. Schunert, & V. M. Labouré, Nuclear Reactors - Spacecraft Propulsion, Research Reactors, and Reactor Analysis Topics. *IntechOpen*. 2021. https://doi.org/10.5772/intechopen.103895
8. Bhattacharyya SK. An Assessment of Fuels for Nuclear Thermal Propulsion. Technology Development Division Technical Memorandum. 2001. Available from: https://www.osti.gov/biblio/822135 (accessed on 2025-08-21).
9. Deo K & Srinidhi C. Uses of Advanced Spacecraft Propulsion Systems for in-Space and Deep-Space Applications. *International Journal of Science and Research.* 2021; 10 (5): 645-649. https://doi.org/10.21275/SR21513120259
10. Thomas D, *et al*. Establishing the Feasibility of the Centrifugal Nuclear Thermal Rocket. AIAA Propulsion and Energy 2021 Forum. *Virtual Event: American Institute of Aeronautics and Astronautics*. 2021. https://doi.org/10.2514/6.2021-3604
11. Gerrish Jr. HP. 2014, February 25. Nuclear Thermal Propulsion Ground Test History: The Rover/NERVA Program. Huntsville, Alabama, United States of America.
12. Thomas D. Nuclear Thermal Propulsion - Progress and Potential. *Journal of Space Safety Engineering.* 2024; 11 (2): 362-373. https://doi.org/10.1016/j.jsse.2024.04.001
13. Emrich B. Promises and Challenges of Nuclear Propulsion for Space Travel. Atoms for Space: Nuclear Systems for Space Exploration. 2022. Available from: https://nucleus.iaea.org/sites/fusionportal/Atoms%20for%20Space/04_Emrich%20Promises%20and%20Challenges%20of%20Nuclear%20Propulsion%20for%20Space%20Travel.pdf (accessed on 2025-08-21).
14. Long KF, Obousy RK & Hein A. Project Icarus: Optimisation of Nuclear Fusion Propulsion for Interstellar Missions. *Acta Astronautica.* 2011; 68 (11-12): 1820-1829. https://doi.org/10.1016/j.actaastro.2011.01.010
15. Scoles S. Companies and Government Agencies Propose Nuclear Reactors for Space. 2021, May 28. Available from: https://pubs.aip.org/physicstoday/Online/5053/Companies-and-government-agencies-propose-nuclear (accessed on 2025-08-21). https://doi.org/10.1063/pt.6.2.20210528a
16. Machi V. Nuclear Reactor Test Requirements Put DRACO Launch Plans On Hold. 2025, January 17. Available from: https://aviationweek.com/space/launch-vehicles-propulsion/nuclear-reactor-test-requirements-put-draco-launch-plans-hold (accessed on 2025-07-28).
17. Leveson N. The Use of Safety Cases in Certification and Regulation. *Massachusetts Institute of Technology Engineering Systems Division Working Paper Series.* 2011; 13.
18. Needell A. Learning from Tragedy: Apollo 1 Fire. 2017, January 27. Available from: https://airandspace.si.edu/stories/editorial/learning-tragedy-apollo-1-fire (accessed on 2025-08-21).
19. Jones HW. The Challenger Tragedy was Caused by an Apollo Mistake, Terminating Risk Analysis. 11th IAASS Conference "Managing Risk in Space". International Association for the Advancement of Space Safety. 2021.
20. Kompella JD, Ravichandran K & Anandan V. Application of Probabilistic Risk Assessment Approach in Nuclear Power and Space Sectors. In C. S. Kumar, *et al*., Advances in Reliability and Safety Assessment for Critical Systems. 2022; pp. 325-345. Springer. https://doi.org/10.1007/978-981-99-5049-2_25
21. Hayns MR. The Evolution of Probabilistic Risk Assessment in the Nuclear Industry. *Transactions of the Institution of Chemical Engineers.* 1999; 77 (3): 117-142. https://doi.org/10.1205/095758299529947
22. Camp A, *et al*. Potential Improvements to the Nuclear Safety and Launch Approval Process for Nuclear Reactors Utilized for Space Power and Propulsion Applications. *Hampton: NASA*. 2019.
23. Lane K, *et al*. Probabilistic Risk Assessment (PRA) for Artemis and Future Space Exploration Programs. Acta Astronautica 2025; Journal Pre-proof. https://doi.org/10.1016/j.actaastro.2025.06.045
24. Trump D. Memorandum on the National Strategy for Space Nuclear Power and Propulsion (Space Policy Directive-6). 2019, August 20. Available from: https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-national-strategy-space-nuclear-power-propulsion-space-policy-directive-6/ (accessed on 2025-08-21).
25. Shockley S. Literature Review: Safety Review Process for Space Nuclear System Launches. 2023. Available from: https://ww2.nrc.gov/docs/ML2322/ML23226A004.pdf (accessed on 2025-08-21).

26. NASA Procedural Requirements: Nuclear Flight Safety. Office of Safety and Mission Assurance, National Aeronautics and Space Administration. 2022, February 3. Available from: https://sma.nasa.gov/sma-disciplines/nuclear-flight-safety (accessed on 2025-07-28).
27. Forsbacka MJ & Helton DM. Evolution of NASA's Nuclear Flight Safety Program to Meet Changing Needs. 11th IAASS Conference. 2021. Washington, DC: International Association for the Advancement of Space Safety.
28. Helton D, *et al*. Overview of the Interagency Nuclear Safety Review Board Playbook. Nuclear and Emerging Topics in Space Meeting (NETS 2023). 2023. Idaho Falls: American Nuclear Society. https://doi.org/10.13182/NETS23-41868
29. Atomic Energy Act of 1954. 1954. Available from: https://www.govinfo.gov/content/pkg/COMPS-1630/pdf/COMPS-1630.pdf (accessed on 2025-08-21).
30. Aeronautics and Space, 14 C.F.R. pt. 417. (2006). Available from: https://www.ecfr.gov/current/title-14/chapter-III/subchapter-C/part-417 (accessed on 2025-08-21).
31. U. S. Department of Homeland Security. Nuclear/Radiological Incident Annex to the Response and Recovery Federal Interagency Operational Plan. U.S. Department of Homeland Security. 2023. Available from: https://www.fema.gov/sites/default/files/documents/fema_incident-annex_nuclear-radiological.pdf (accessed on 2025-08-21).
32. Nuclear Safety Review and Launch Approval for Space or Missile Use of Radioactive Material. 2022, February 24. Available from: https://www.e-publishing.af.mil/Product-Index/ (accessed on 2025-08-21).
33. Principles Relevant to the Use of Nuclear Power Sources in Outer Space. 1992, December 14. Available from: https://www.unoosa.org/oosa/oosadoc/data/resolutions/1992/general_assembly_47th_session/res_4768.html (accessed on 2025-08-21).
34. Buden D. Safety Questions Relevant to Nuclear Thermal Propulsion. Ninth Symposium on Space Nuclear Power Systems. 1991. Albuquerque: American Institute of Physics. https://doi.org/10.1063/1.41909
35. Blul JC. Determination of Emergency Planning Zones Distances and Scaling-Based Comparison Criteria for Downsized Nuclear Power Plants. *Nuclear Engineering and Design*. 2021; 382. https://doi.org/10.1016/j.nucengdes.2021.111367
36. Buden D. Tutorial on Nuclear Thermal Propulsion Safety for Mars. AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference and Exhibit. 1992. *Nashville: American Institute of Aeronautics and Astronautics*. https://doi.org/10.2514/6.1992-3696