N01 Post Course Assignment

Design Considerations for a Lunar Convertible Nuclear Thermal Rocket

Student ID 11173631

Contents

Abstract
This report reviews the history of nuclear thermal propulsion systems with a specific focus on systems based on the Nuclear Engine for Rocket Vehicle Application (NERVA) system while introducing the concept of a convertible nuclear thermal propulsion system. It covers the successes of the 1970s program and its recent revival in the form of the Space Exploration Initiative (SEI) during the 1990s. The report presents reasons for the premature terminations of both programs. After completing the overview of past work, the report discusses methods to design a system that addresses fissile material security, cost and the reactor weight using the principles of reactor physics and design acquired in the N01 module. A new fuel element design aims to address the issues of high uranium enrichment and fuel corrosion that legacy designs face. The report concludes that the potential for design weight reduction is minimal, but spacecraft or colony integration offers avenues to reduce the overall weight. In this section, the work justifies the requirement of a reactor design to be convertible. The validation and development unto realisation of the proposed fuel design heavily involve the concepts of reactor physics, radiation transport simulations and reactor kinetics models. The report's final section correlates the future work required to realise a better thermal propulsion system design with the knowledge gained in the N01 module.

Introduction

The terrestrial nuclear reactor is a complex system comprising fissile material, coolant systems, control systems and safety mechanisms, aside from ancillary features such as turbines. The Nuclear Engine for Rocket Vehicle Application (NERVA) rocket system has largely retained these features [1]. This report analyses the design to identify hurdles to reactor operation in orbit and on the lunar surface. Once this document identifies the aspects which require improvement, it discusses the application of modern reactor physics and design principles to realise the proposed improvements.

Before describing the NERVA system design and subsequent developments in the literature based on it, the author would like to draw attention to the utility of nuclear technology for producing power and propulsion in space. Radioisotope Generators present onboard spacecraft have been the most reliable method of generating sub-100 W electrical power in deep space for decades [2]. The technology used in those generators is solid state and low maintenance, resulting in a robust and reliable power source independent of the Sun and other environmental factors, an advantage shared by nuclear power plants based on Earth. However, as humanity's use of space becomes integral to civilisation, more electrical power and efficient propulsion systems become necessary. The ongoing effort to colonise the Moon and expand outwards to Mars calls for a multi-KW power source [3] and a doubling of propulsion system efficiency to get the system to the surface [4].

The author has previously proposed a hydrogen-cooled nuclear reactor capable of providing thrust and landing on the lunar surface. Once there, the reactor design allows the addition of turbine and radiator units to adapt the system to electrical power generation without modifying any of the nuclear components. At the end of life, the colonies' robotic systems reconfigure the plant to provide thrust and send it into deep space for disposal. The previous work focused on the reactor power level and the design of the coolant system, producing a maximum reactor power of 2.25 GWt with a core radius of 63 cm. In the reconfigured mode, the reactor system could produce 1 GWe by adding turbines to the system while producing 1.82 GWt of power [5]. This report aims to analyse and update the design's engineering, which is a derivative of the original NERVA design.

The author has organised this report as follows. The next section focuses on the NERVA design, its achievements, and past work based on it published in the open literature. The following section attempts to address some of the system's design issues. The second last section discusses the application of reactor physics and design principles to future work, after which a concluding section summarises this work's findings.

The NERVA Design and its Derivatives

The Original NERVA Design

The Nuclear Engine for Rocket Vehicle Application (NERVA) project was a nuclear thermal propulsion technology development program in the USA during the late 1960s. It aimed to develop the nuclear and rocket engineering knowledge required to successfully launch a nuclear rocket and use it for NASA missions. The program is unique in its foresight and is the only one since then that physically tested and proved a nuclear propulsion system in a controlled terrestrial setting. The effort was generally successful, with fuel element corrosion being the only unsolved technical problem [4] [6]. By 1971, significant progress allowed fuel elements to withstand corrosion by the hot hydrogen coolant to a better degree. However, the US government terminated the program before testing the new fuel [6].

Figure 1 shows the NERVA reactor concept, and Figure 2 shows the coolant flow path reproduced from [1]. The author briefly covers the system's operation here for completeness. A liquid hydrogen (LH2) tank contains the working fluid for the reactor. A turbopump pushes the liquid coolant into a sheath surrounding the rocket's nozzle in a process called regenerative cooling. Regenerative cooling enables very high chamber gas temperatures while maintaining the walls of the pressure vessel below the materials' operational limit.

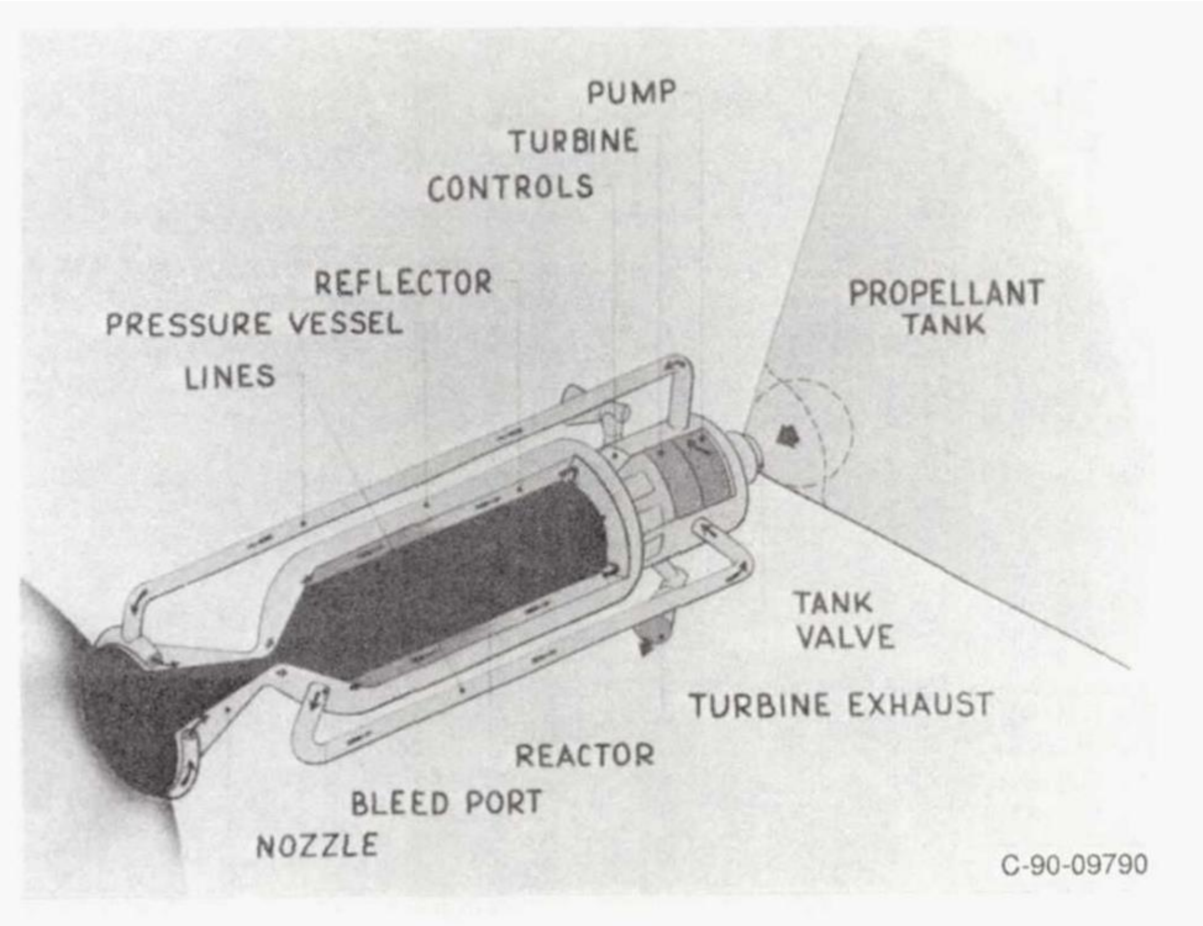

Figure 1: The NERVA System Concept. Reproduced without modification from [1]

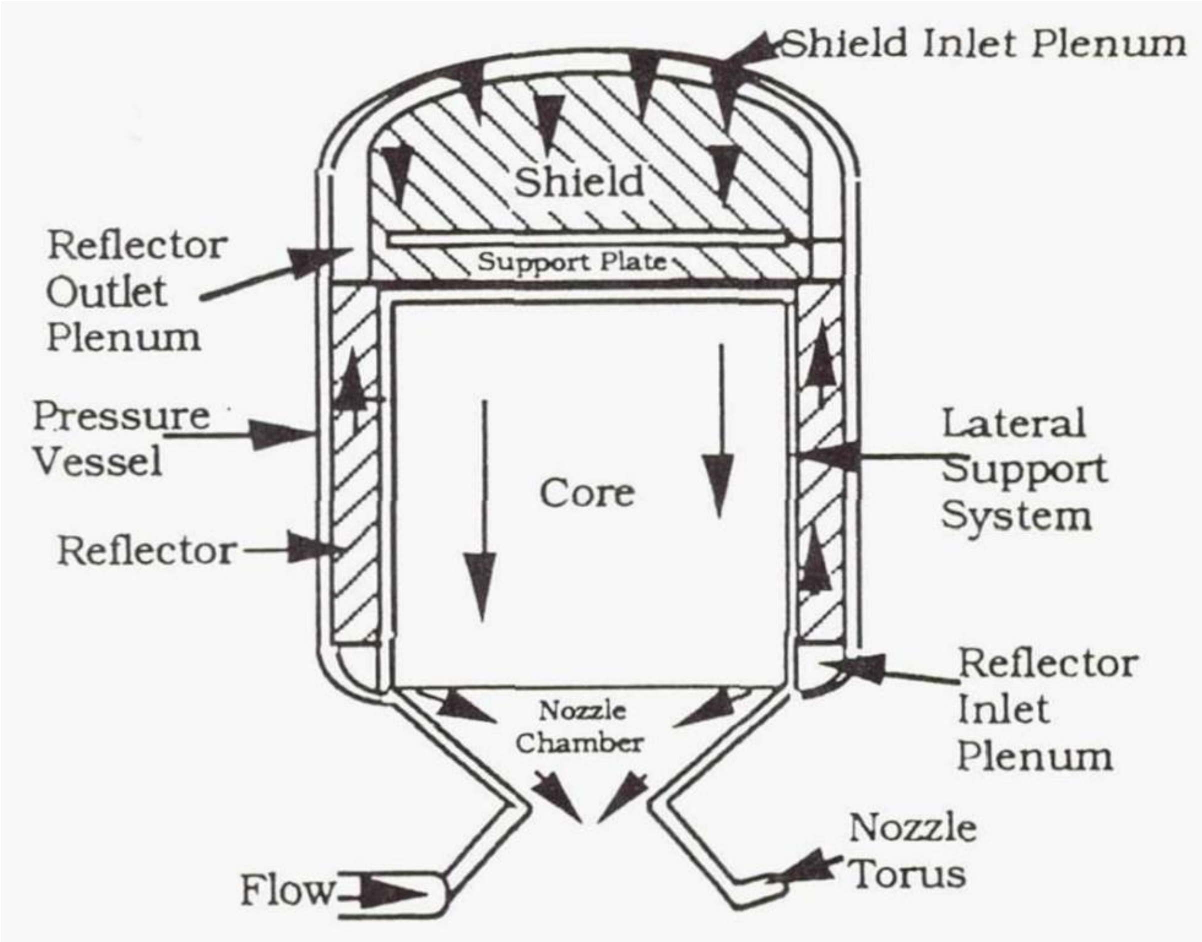

Figure 2: The NERVA System Flow Path. Reproduced without modification from [1]

The liquid coolant absorbs the heat from the wall of the rocket nozzle, converting it to gaseous or supercritical hydrogen, depending on the system pressure. The coolant continues upwards into the reflector and shield of the reactor, removing any deposited heat from those components. It finally enters the reactor plenum at the top and flows into hexagonal prismatic fuel elements with cylindrical cooling channels. At the bottom end of the fuel elements, the flow collimates in the rocket chamber, where a small amount flows into a diverter to run a turbine to power the turbopump and provide the spacecraft with power. This turbine exhausts directly into space [1]. The rest of the hot hydrogen is exhausted out of the converging-diverging nozzle to produce thrust. The system uses hydrogen gas for three primary reasons; it is inexpensive, has a very high heat capacity, and has a small molecular mass, increasing the rocket's thrust per unit propellant weight coefficient (Also known as the specific impulse).

While no open literature describes the graphite-composite fuel elements in much detail, there is a body of work addressing fuel element corrosion in hot hydrogen [6]. Initial fuel elements suffered severe corrosion because they used graphite in their composition, leading to hydrocarbons forming at high temperatures. Subsequent fuel elements contained zirconium and niobium carbides to suppress this effect but the anti-corrosion coating in the coolant channels cracked due to thermal stresses [6]. The final fuel element developed during the NERVA program had a molybdenum coating over the previous coatings to fill any gaps caused by cracking. Experiments conducted late into the program demonstrated corrosion reduction. However, the tests only lasted an hour, not resulting in a practical reusable rocket engine for use in multiple deep space missions [1]. Figure 3 shows the top view of a fuel element with circular coolant channels, reproduced from [7]. The white rings within each channel are the coatings described previously.

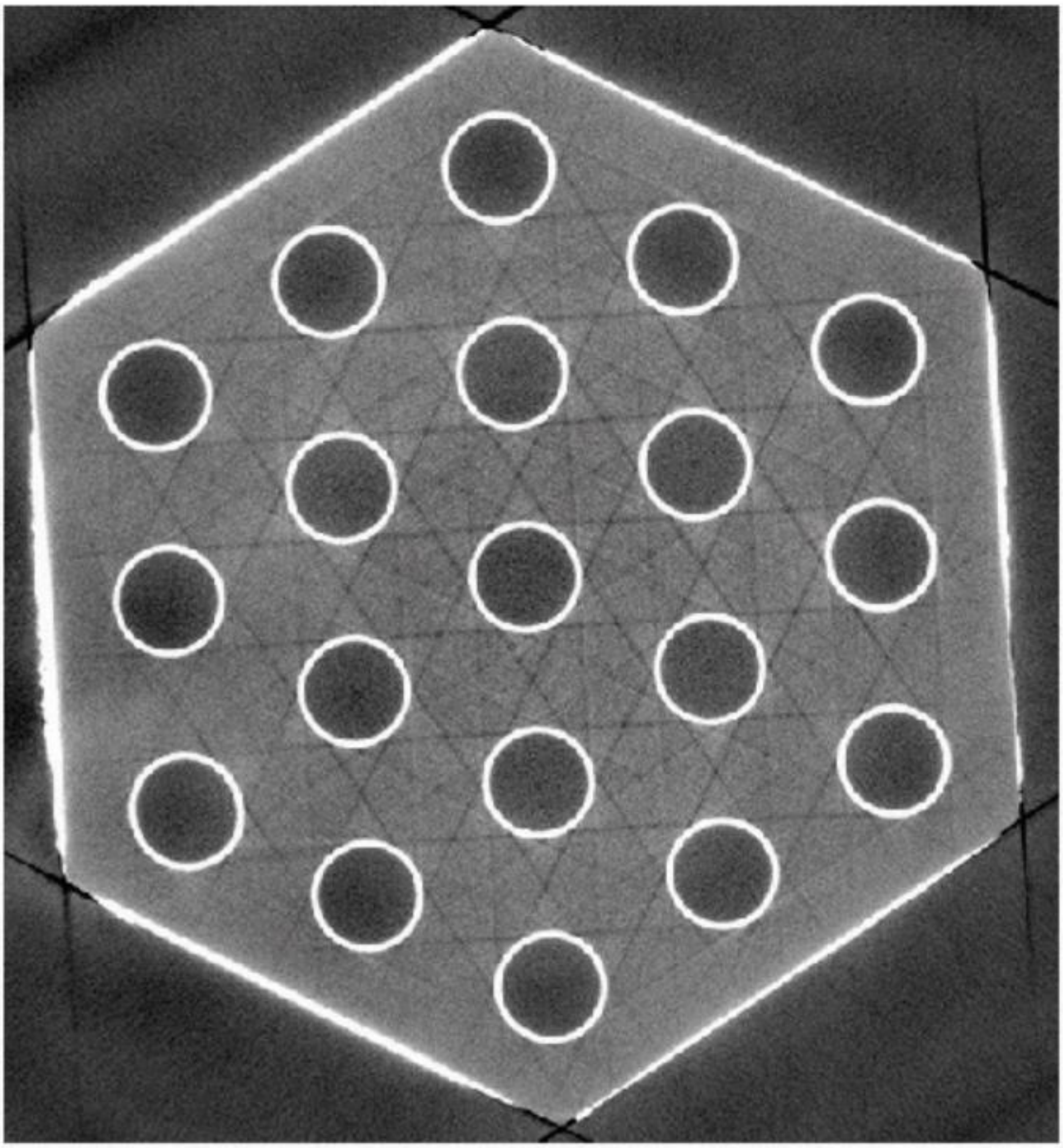

Figure 3: The NERVA System Hexagonal Prism Fuel Element. Reproduced without modification from [7]

Similarly, no specifics regarding reactor neutronics and kinetics are available in the literature. While the reactor contains zirconium hydride moderators, most research articles do not discuss the nature of its neutron spectrum. [8] provides some data on the neutron spectrum using the ratio of carbon to uranium (CU) in the reactor core. Based on the results presented therein and the fact that the fuel enrichment level is 93.2% [9], the author concludes that the original NERVA design and its derivates are fast neutron reactors. The original NERVA design included a beryllium oxide control drum that moves over the reactor core to control the system reactivity by reflecting neutrons into the core and reducing neutron leakage. The original design and more recent derivatives vary the enrichment level of individual fuel elements to flatten the radial power peaking but exhibit strong axial power peaking [9].

[8] also analysed the reactivity worth of the control drum for various CU vs thickness of the control drum. As the CU ratio approached 2500 and the neutron spectrum approached a thermal one, the worth of the control drum per cm of thickness reduced. This reduction resulted from the large size of a thermal reactor core which meant less neutron flux reaching the drum in the first place. The report also observed that the worth of control rods in such a system would show a similar trend. While the NERVA reactor does not have control rods, it uses a poison wire array [10] to put it in a safe sub-critical state regardless of the control drum position. Once the reactor is ready to operate, an unknown mechanism pulls out the poison wires, and the reactor control becomes dependent on the control drum.

[8] also thoroughly analyses the startup of a NERVA system and its associated reactor kinetics. It finds that the effect on reactivity due to the introduction of the moderating and absorbing hydrogen gas is minimal for fast neutron designs. The parametric CU study concluded that NERVA-derived designs with CU greater than 500, i.e. thermal designs, would not achieve criticality because of the significant negative reactivity insertion due to the hydrogen coolant in the reactor core in the thermal spectrum. The report also notes that the design goes prompt critical if the reactor plenum contains dense liquid hydrogen in the case of an accident. Figure 4, reproduced from [8], shows the typical power ramp-up. Note the time window for the startup transient. Chemical rockets have a negligible startup delay compared to the data presented in Figure 4.

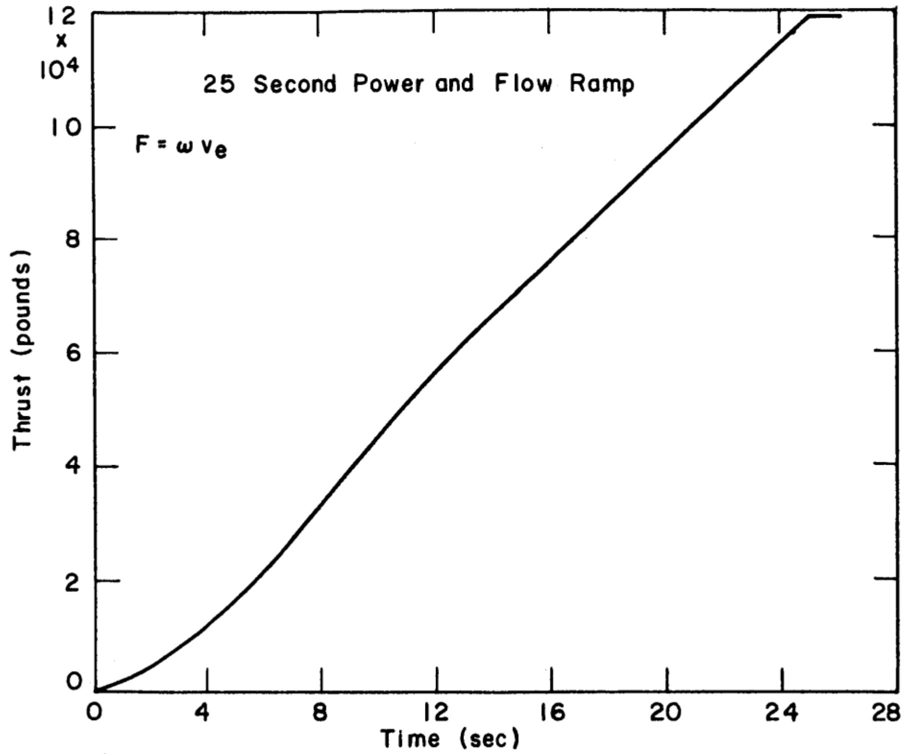

Figure 4: NERVA Theoretical Startup Thrust Curve. Reproduced without modification from [8]

Another detailed report [11] describes the control system of the NERVA system and the algorithm complexity required to implement digital control. That report concludes that digital control (with 1970s digital electronics) is much simpler than expected for such a complex plant. The report also proved that the control system is responsive enough to prevent damaging uncontrolled power transients. The work aimed to reduce the Common Analog Model (CAM), a 52nd-order mathematical model of the NERVA reactor, to a state space representation that could run a real-time control algorithm. It found that the time constants for most processes described in the CAM were minor and did not affect steady-state operation. After removing the appropriate higher-order terms, a simple digital state-space model of the 6th order proved sufficient to describe reactor behaviour. After further optimisation at the cost of some model error, a 2nd order model provided adequate control. The final nonlinear state space model could independently control the temperature and pressure within the reactor chamber during reactor startup with errors of less than 25% [11].

Recent Developments based on the Original NERVA Design

Given past results, various groups have returned to the concept and designed systems based on that work. The latest design exercise by NASA concluded in 2015 [9]. The most significant effort to recover progress in nuclear rocket design was made in the 1990s by NASA through their Space Exploration Initiative (SEI) program. The SEI program included a working group to develop operational and safety policies for nuclear systems in space, aside from the technical aspects [12]. To date, [12] represents the only published comprehensive effort to investigate the non-technical aspects of nuclear propulsion and power in space. The SEI also published a document outlining the Technology Readiness Levels (TRLs) of the proposed nuclear thermal and electric propulsion systems [13]. The author mentions nuclear electric propulsion systems because these systems utilise a nuclear reactor to generate power to feed multi-MW electric thrusters for spacecraft propulsion. Such systems generate low amounts of thrust but use minuscule amounts of propellant in the process. A lunar convertible nuclear propulsion system must generate large amounts of thrust to quickly transport large amounts of cargo. Once it has landed, it must be capable of generating large amounts of electrical power with the assistance of onsite non-nuclear components. Thus, the nuclear design of this reactor must incorporate developments for both nuclear thermal and nuclear electric systems, which are usually contradictory.

The SEI TRL report [13] recommended that fuel technology development for nuclear thermal propulsion concepts should focus on > 2500 K chamber temperature and 5 – 10 hours of lifetime. In contrast, fuel element development for nuclear electrical systems should focus on 1400K – 2000K chamber temperature operation for 2-5 years with very high burnup. Section 2.2.1.3 notes that there is little commonality between the fuel element design. The report further describes the Vapour Transport Fuel Pin concept, which the author returns to in the next section of the report. Figure 5, reproduced from [13], describes the concept.

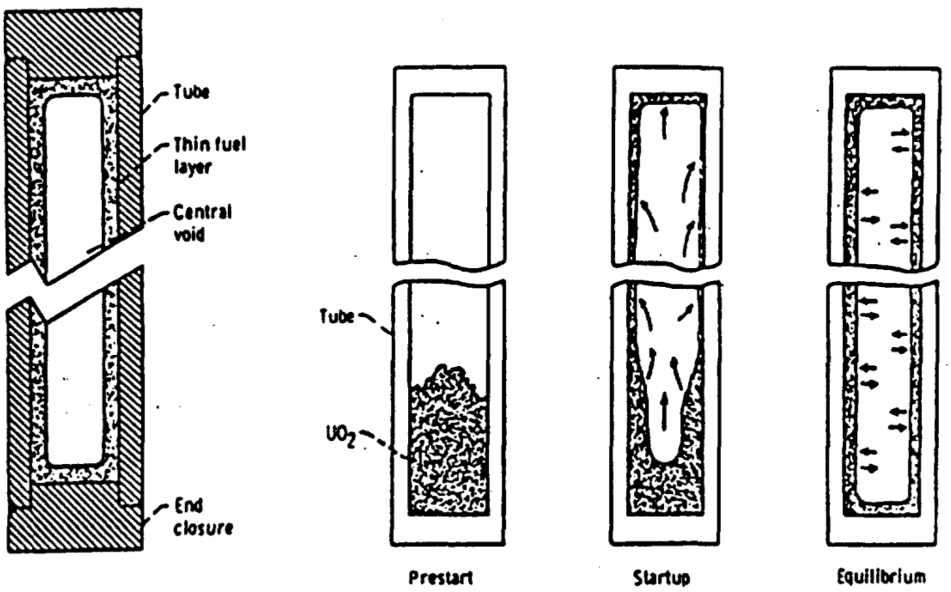

Figure 5: The Vapour Transport Fuel Pin Concept. Reproduced without modification from [13]

In parallel, the Nuclear Safety Policy Working Group [12] report aimed to complement the technical and operational design effort of NASA's SEI committee. The report established and defined As Low As Reasonably Achievable (ALARA) in the context of nuclear propulsion systems. The report considered all aspects of operational safety and provided guidelines for implementing safety procedures. The document set forth guidelines for reactor startup, inadvertent criticality, radiological release, disposal, planetary body re-entry and nuclear safeguards. These guidelines explicitly laid out the difference in operations during reactor assembly and testing on Earth and reactor flight in space. In summary, it transposed nuclear regulatory tools and frameworks to develop safety guidelines for nuclear propulsion systems. However, the guidelines about safety during reactor operation in flight left significant gaps unaddressed, which the next section discusses.

Finally, the 1991 SEI report [13] concluded that a first flight of a nuclear thermal propulsion system would occur in 2008 if the US government provided the "Authority to Proceed" in 1992. The SEI never went beyond the paper design phase, despite most of the concepts proposed having a TRL of 6 to 4. Figure 6, reproduced from [13], succinctly summarises the committee's hopes. Development efforts since then have similarly never gone beyond the paper design with no clear explanation for project termination. In the next section, the author aims to address gaps in the past literature to explain why the projects never resulted in a working nuclear propulsion system.

PARAMETER:		STATE – OF – THE – ART:	OBJECTIVE:
THRUST, LBf		75K – 250K NERVA – PHOEBUS	50K – 125K MAY CLUSTER
SPECIFIC IMPULSE, Sec.		825	> 925
CHAMBER PRESSURE, psia		450 – 3000 NERVA – SSME	500 – 1000
EXHAUST TEMPERATURE, K		2300 – 2500 NERVA	> 2700
	NOZZLE, TPA	3100 SSME	
LIFETIME, hrs	SINGLE BURN	1.0	1 – 3
	CUMMULATIVE	1.5	3 – 10
REUSABILITY (Missions)		1	up to 5

Figure 6: The Expectations of the Space Exploration Initiative (SEI) Committee. Here, SSME stands for the Space Shuttle Main Engine. [13] cites experimental results available by 1991 for the 'state-of-the-art' column. Reproduced without modification from [13]

A NERVA Derived Design Concept for Lunar Convertibility

Major Issues with the Original NERVA Design and Close Derivates

Despite the technical success of the NERVA program, critical aspects of reactor operation in space remained unexplored [13]. For example, the program never tested the mechanism to remove the reactor safety poison wires in orbit [10]. By the program's termination in 1972, the fuel element corrosion problem was still persistent, though not as severe. Workers in the programs proposed novel fuel elements designed to survive a practical mission in deep space but never got to test them [6].

The original NERVA program was not subject to nuclear and environmental regulations, as evidenced by open-air testing of the nuclear rockets that exhausted directly into the atmosphere [1]. One can see that the fuel element design made no attempts to contain the radioactive material within the core [7]. The 1991 SEI report [13] acknowledged that significant efforts toward developing safer testing facilities and reactor designs were necessary. The Nuclear Safety Policy Working Group report [12] set down regulatory requirements for the development effort, with most requirements directly transposed from terrestrial reactor development. However, because no such system had flown to orbit, the safety of orbital operations was not adequately regulated. Specifically, the report did not cover nuclear safety and safeguards once the system had achieved orbit.

Consider a nuclear reactor with approximately a tonne of highly enriched uranium boosted by a rocket into orbit. The conventional nuclear safeguards framework is only valid up to launch preparations. In the modern world, anti-satellite munitions have been demonstrated [14]. Given the mass and relative purity of uranium 235 in the reactor, a rogue nation-state has ample incentive and opportunity to shoot down the reactor such that it crashes at a known location accessible to them. System design regulations ensure that in the case of an uncontrolled re-entry, the reactor must not fragment and cause a radiological release, which assists such an attack [12]. [15] holds that the lack of fissile material is the only major impediment to nuclear weapons development. Thus, it is possible to imagine a scenario where a nation-state seeks to acquire the required supply of fissile material, despite the international repercussions the state may face. Even if the designers dismiss such extreme scenarios, the cost of a tonne of 93.2% enriched uranium core is exorbitant, further exacerbated by the fact that an average mission leads to less than 0.1% burnup by the end of life [9]. 59.6 Kg of uranium 235 is present in a recent 367 MWt design proposed in [9], which produces an order of magnitude lower thrust than the original NERVA design [1]. Compare that with the total civilian highly enriched (20 % or greater) uranium present in the UK at the end of 2021, which was 734 Kg [16]. Note that this value does not reflect the amount of civilian uranium 235 available, which would be significantly lower. The design is impractical, and only recently has NASA made efforts to design systems with lower uranium enrichment [17].

A related problem is the general weight of a nuclear propulsion system compared to a chemical system. A nuclear propulsion system typically weighs around 5 tonnes with a thrust-to-weight ratio of 5.3 [18], whereas the Space Shuttle Main Engine weighs around 3 tonnes with a thrust-to-weight ratio of 73.1 [19]. While it is unlikely that future designs shall reduce the system weight, no published concept in the literature has specifically addressed the issues of nuclear material safety and system weight, as far as the author is aware.

Design Changes to Reduce System Uranium 235 Content

This subsection introduces a concept based on the Vapour Transport Fuel Pin concept published in [13]. It also aims to introduce cladding of the fuel to contain fission products. Three significant changes assist in lowering the system's uranium 235 content. [8] showed that systems with a CU ratio of 500 with an epithermal neutron spectrum are still controllable. IAEA standard data shows a sharp spike to 7.5 barns from 1 barn in the averaged fission cross-section around the 1 keV range [20]. Thus the reactor can reduce uranium 235 content by designing for an epithermal spectrum that peaks around 500-1000 eV.

Secondarily, an investigation to determine the causes of fuel element corrosion found that the coolant exceeds Mach 1 in the coolant channels due to heat addition [21]. The report speculated that if the coolant reached Mach 1 inside the channel, it would cause a significant pressure drop across the resulting shockwave which would cause local corrosion. These findings highlight the need to either reduce power density, which is impractical or reduce the fuel element length. The author could not find data on preliminary designs considered during reactor development in the NERVA program. Thus, it is unclear why the reactor's nominal core length and radius settled at 0.89 m and 0.49 m, respectively. Note that the nozzle exit radius for a NERVA reactor is 1.13 m [9]. Furthermore, it is also unclear why the design considered only carbide fuel elements, especially after reports of corrosion.

To address all of these issues, the author proposes the following. The fuel element material shall be magnesium oxide (MgO) which has a very high working temperature of 3125 K and is inexpensive, neutronically favourable and easily sinterable [22]. It has an adequate thermal conductivity of 3 W/(mK) at a very high temperature of 3000 K [23]. MgO sintering protocols enable enough removal of porosity such that the ceramic becomes transparent [22], making for effective fission product containment at high burnup. Multiple studies show that it is stable in a hot hydrogen atmosphere and does not lose mass [24] [25].

The fuel element retains its hexagonal profile but is significantly shorter. The proposed design replaces the larger coolant channels with a finer array of holes and inserts some enriched uranium metal wire into the array. A gas adsorber, such as activated carbon, is added to the holes which contain uranium with a porous separator. Then, the element undergoes vacuum sintering to close those holes while leaving the rest open. This design has several potential advantages. It increases the net surface area over which the uranium transfers heat into the lower thermal conductivity bulk MgO. It similarly also increases the heat transfer surface area of the coolant and eliminates the possibility of the coolant reaching Mach 1. Of course, such a core has a much larger radius to maintain the overall power generated. The hydrogen coolant and the oxygen atoms in the fuel elements provide the necessary moderation to epithermal energies. Figure 7 shows a schematic of the envisioned fuel element, not to scale.

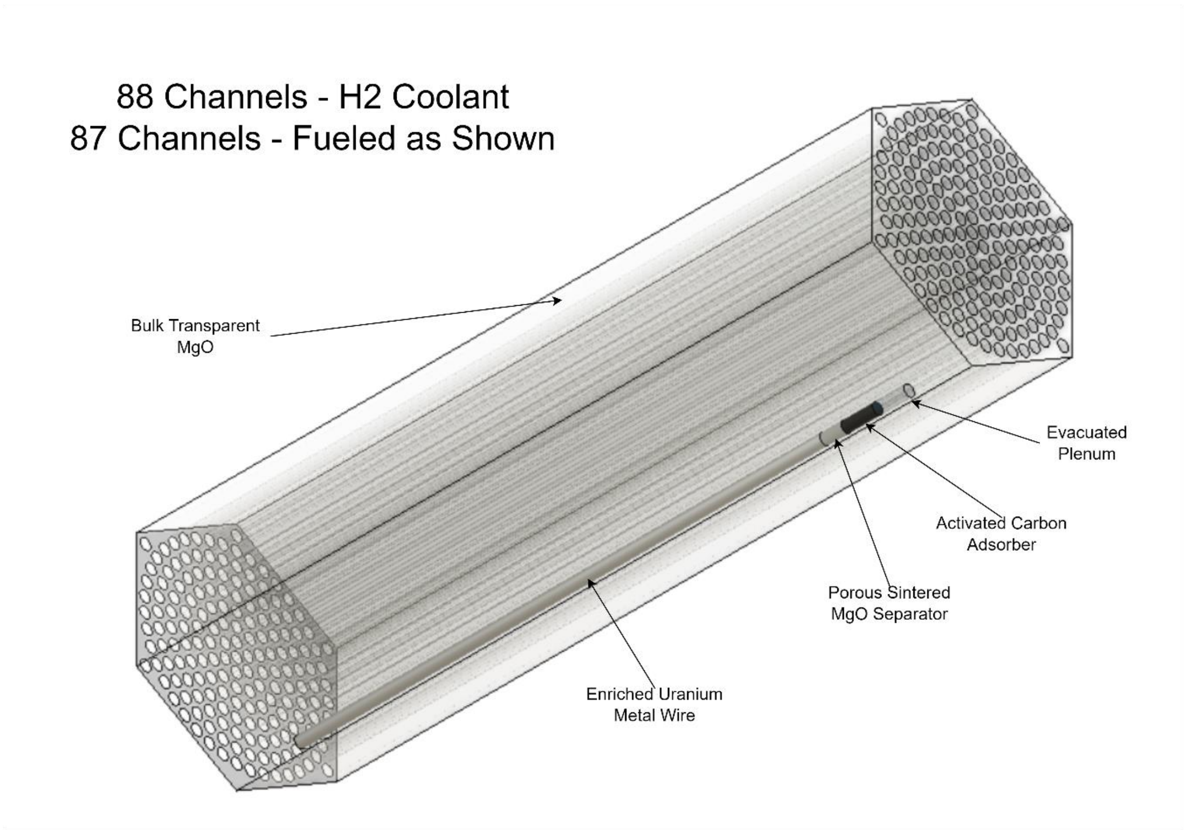

Figure 7: A Conceptual CAD of the Proposed Fuel Element

During operation, the limiting factor is the thermal limits of MgO as the uranium wire is allowed to melt. The molten uranium allows better heat transfer and does not trap fission products as burnup increases. The previous section noted the long transient times for a nuclear reactor power-up. The reactor continues to produce small amounts of thrust as it powers up or shuts down. Thus the molten uranium is constantly subjected to "thrust gravity" during operation, avoiding voidage due to microgravity. Further, molten uranium has a low vapour pressure at the temperatures of interest (3500 K), so boiling is not a concern [26]. Note the similarity of this concept to the Vapour Transport Fuel Pin concept. In summary, such a fuel element has a clear manufacturing pathway, alongside potential advantages, which result in a much larger core radially but reduce the amount of uranium enrichment required. This fuel element does not suffer from the previously known corrosion mechanisms and is compatible with high burnup and high-temperature use, which is essential for the lunar convertible concept.

Design Changes to Address System Weight

This subsection clarifies that opportunities to reduce the system weight are minimal but also justifies the necessity of a convertible reactor design. Most nuclear thermal propulsion designs weigh around 5 tonnes [18]. Most of this mass is the fuel elements, the beryllium oxide control drum and the reactor plenum shield. All these components are essential to the reactor's functioning and critical factors in neutronics designs. Hence, there is little scope for changing them without seriously affecting reactor safety and performance.

However, a typical interplanetary spacecraft has more components than the propulsion module. It has life support, communication, and an electrical power generation system to service them. This power generation system is redundant if a nuclear reactor is on board. Further, in the slim chance of reactor failure, the spacecraft shall be stranded in deep space without rescue. Thus coupling the primary power system to the reactor core is not a violation of defence in depth in terms of systems reliability, as long as other short-term sources of backup power, such as batteries, are present. In emergencies, the reactor can also supply the life support systems with heating and provide process heat for carbon dioxide removal from the air. Thus, weight reductions in the total spacecraft design are possible due to the flexibility of a nuclear reactor. A chemical rocket can provide all of the above benefits but does not have the weight penalty associated with it that would force designers to consider the abovementioned changes.

Most missions that necessitate a nuclear propulsion system tend to service the colonisation of the Moon or Mars [13]. [3] exhaustively reviews colony designs for the Moon and concludes that a nuclear reactor on the lunar surface is necessary to service baseload power demand. The author observes that instead of using a chemical rocket to transport multiple 10-kW nuclear reactors, which [3] implies, a convertible nuclear thermal rocket provides large amounts of power on the lunar surface after landing and offers high cost and net weight savings. Landing a rocket on the surface of the Moon is not a technical challenge, and the Apollo missions have demonstrated it.

Additionally, no party has demonstrated electrical power generation at a large scale in space. No turbogenerator has flown to space [2]. If colonies are to become self-sufficient via mining local resources and manufacturing local products, they shall require a significant, long-term power source. By changing the design of the nuclear thermal propulsion system, the proposed fuel elements can handle high burnup. If the melting point of the uranium wire defines the chamber temperature limit in the lunar configuration, it runs at a temperature of 1400 K [26]. This temperature is coincidentally the maximum operating limit for simply cooled blade turbines [27]. Simply cooled blade turbine technology is highly reliable, lightweight, mechanically simple, requires low maintenance, and has a long heritage of use [27]. All these features strongly suggest its use in robust space turbogenerators as non-nuclear components attached to the landed nuclear thermal propulsion system to generate GW-level power for creating a self-sustaining colony. In summary, while minimal mass optimisation is possible, a nuclear thermal propulsion system designed for convertibility offers many benefits to the colony and spacecraft design, which may offset the weight penalty.

Application of Reactor Physics and Design Principles to Future Work

Reactor Neutronics Simulation and Verification

In this section, the author aims to correlate the teaching provided in the N01 module with the work required to realise a convertible lunar thermal propulsion system. The previous section put forward a fuel element concept based on the Vapour Transport Fuel Pin concept published in [13]. Table 1 presents the differences between this conceptual fuel element over the standard fuel element described in [7] [9].

Table 1: Summary of Proposed Fuel Element Changes Contrasted with Original Fuel Element [7] [9]

Parameter	***Original Fuel Element***	***Proposed Fuel Element***
Hexagonal Width	1.905 cm	1.905 cm
Element Height	0.89 – 1.32 m	7 cm (Targeted)
Fissile Material	Uranium Carbide	Molten Uranium Metal
Uranium 235 Enrichment	93.2 %	<20 % (Targeted)
Clad Material	None	MgO
No. Coolant Channels	19	88 (Targeted)
Coolant Channel Diameter	1.33 mm	1 mm
Fission Product Containment	None	Plenum + Gas Adsorber
Maximum Operating Temperature	< 2800 K	< 3100 K

As seen with [8], a detailed neutronics calculation shall be essential to understand the neutron flux inside this disk-like reactor. When [8] was published, the investigator could not access the computing power required to perform modern deterministic or Monte Carlo calculations. Using the knowledge of radiation transport gained in this module, the author aims to apply modern simulation codes to study the fuel element performance and compare that with results published in [6]. Modern computers allow in-silico simulation of assemblies to virtually prototype systems. The author is unaware of any study on NERVA derivates that utilises such simulations and aims to apply them to augment fuel element design and validate it.

Of course, these simulations shall provide numerical outputs of buckling factors, neutron lifetimes, burnup ratios and other system parameters. The learnings of reactor physics help the author interpret and manipulate these system parameters to achieve the goal of a high burnup and high power density fuel element. The output parameters shall also drive the reactor shielding and reflector design, conclusively determining the possibility of weight reduction for those components.

Reactor Startup and Fission Product Buildup

As pointed out earlier in the report, the startup transient of a chemical rocket compared to a nuclear thermal rocket is negligible. Further, the thrust-to-weight ratio of nuclear thermal propulsion systems is an order of magnitude lower. These characteristics necessitate a reactor kinetics and control model similar to the one developed in [11] to understand avenues to improve them. The knowledge imparted to the author during the reactor kinetics lectures assists in developing a six-group delayed precursor model for a reactor that implements the changes proposed in the previous section. As burnup is critical for a convertible reactor system, the reactor kinetics model is essential to quantify the lifespan of the proposed fuel elements, accounting for the variance in power level for the different operating modes.

The reactor kinetics model shall also provide the variation of various fission product concentrations in the molten uranium over time. The data informs the author during diffusion studies to evaluate fission product containment by the MgO bulk of the fuel element. A reactor kinetics and control model is also essential to developing an operational and environmental safety case compliant with the guidelines outlined in [12].

Design Safety, Manufacturing Cost and Reliability

The proposed design must incorporate lessons learned from past projects to be of use. The reactor accidents and designs lectures provide valuable insight to the author on what concepts have proven themselves in the past. The knowledge also informs which aspects of reactor design are prone to failure and in what mode the failure occurs. They inform the author of the concepts of operational safety and constraining risk to As Low As Reasonably Practicable (ALARP). After the experiences of the nuclear industry with graphite corrosion in Advanced Gas Reactors (AGR), it is clear to the author that the original NERVA design must investigate other materials as it suffers from a much more severe form of the same issue. The lessons from Chornobyl and Windscale motivated the author to include cladding in the proposed fuel element even though it is not strictly required by [12]. A significant motivation for changing the fuel element was reducing the required enrichment and manufacturing cost.

While this report only briefly touches on system reliability, the lectures on gas-cooled reactors in the UK helped inform the author on the reliability issues faced by such a reactor type. The NERVA design and its derivates are gas-cooled reactors that share many similarities with the AGR but significantly differ in neutron spectrum and power density. However, the design can still draw from the AGR designs' operational experience, which the author was made aware of during those lectures. The author observes that during the literature review of this report, they did not find any contributions to the literature by UK researchers or companies. The author's interactions with industry personnel during the modules taken also solidified the conclusion that professionals in the nuclear industry are unaware of the rich heritage of nuclear technology applications in space. Considering that NASA committed in the last week of January 2023 to a nuclear flight test in 2027 [28], the author emphasises the need for training personnel in rocket and nuclear engineering to realise such a system in the UK, drawing upon the decades of design and operational experience with gas cooled reactors available in this country.

Conclusion

The cumulative results at the termination of the NERVA program in 1972 were ground-breaking. The program demonstrated for the first time (and the only time) that a working nuclear thermal propulsion system was viable, controllable and suitable for deep space missions. The original design used hydrogen coolant forced through the rocket nozzle sheath to cool the nozzle wall, enabling it to withstand the > 2500 K temperature on the other side in the reactor chamber. The design demonstrated double the thrusting efficiency of the best modern rockets with comparable thrust levels. Over the years, its success attracted workers to revive the concept on paper many times, but the efforts never proceeded further.

In this report, the author covered the original NERVA system design and the significant efforts to revive it. The work identified a lack of in-flight operational safeguards, which led to potentially dangerous security situations with the tonnes of enriched uranium within the reactor in orbit. The high level of enrichment that previous designs had led to exorbitant costs, and the designs' weight was not competitive with chemical rockets. The report points to the above reasons to explain why most design efforts never made it past the paper design stage, despite the legacy of the NERVA program.

The report's midsection aimed to modify the system design to address the issues uncovered in the past. A novel fuel element design modifying the Vapour Transport Fuel Pin concept attempted to address the issues of cost, moderation, fuel enrichment, lifetime, burnup and corrosion in the hot hydrogen coolant. Then, the work explored the importance of system convertibility and integration to offset the additional weight and cost of deploying a nuclear thermal propulsion system compared to a chemical rocket.

The final section addressed how the learning received in the N01 module contributed to the proposed changes to the system design. The section covered the application of modern computer codes to nuclear thermal propulsion systems and how modern reactor physics and kinetics assist in developing, augmenting and validating the proposed fuel element. The work also noted the increased safety requirements. It explained how a computer model of the reactor's neutronics and kinetics assists in developing a safety case in compliance with regulatory guidelines. Finally, the section closed with a brief discussion of operational and design reliability and the lack of UK participation in nuclear thermal propulsion development, despite having extensive national expertise with gas-cooled reactors.

Bibliography

[1] W. Robbins, "An historical perspective of the NERVA nuclear rocket engine technology program," in *Conference on Advanced SEI Technologies*, 1991.

[2] A. Mazzetti, M. G. Pret, G. Pinarello, L. Celotti, M. Piskacev and A. Cowley, "Heat to electricity conversion systems for moon exploration scenarios: A review of space and ground technologies," *Acta Astronautica,* vol. 156, p. 162–186, 2019.

[3] M. Kaczmarzyk and M. Musiał, "Parametric study of a lunar base power systems," *Energies,* vol. 14, p. 1141, 2021.

[4] G. Farbman, "Upgraded NERVA systems: Enabler nuclear system," in *NASA. Lewis Research Center, Nuclear Thermal Propulsion: A Joint NASA (DOE) DOD Workshop*, 1991.

[5] Y. Jain, "Initial Reactor Thermal Hydraulic Design," in *N12 - Reactor Thermal Hydraulics Post Course Assignment*, 2022.

[6] D. G. Pelaccio and M. S. El-Genk, "A review of nuclear thermal propulsion carbide fuel corrosion and key issues," 1994.

[7] S. V. Raj and J. A. Nesbitt, "Development of Advanced Coatings for NERVA-type Fuel Elements," *NETS2015-5072, Nuclear and Emerging Technologies for Space (NETS),* 2015.

[8] W. W. Little Jr, "Reactivity changes during startup in large nuclear rockets," 1964.

[9] S. K. Borowski, R. J. Sefcik, J. E. Fittje, D. R. McCurdy, A. L. Qualls, B. G. Schnitzler, J. Werner, A. Weitzberg and C. R. Joyner, "Affordable development and demonstration of a small NTR engine and stage: how small is big enough?," in *AIAA SPACE 2015 Conference and Exposition*, 2015.

[10] *NERVA Program Summary Report No. 6 (1967),* NASA, 1967.

[11] L. E. Kendrick, On-line digital computer control of the NERVA nuclear rocket engine, The University of Arizona, 1972.

[12] A. C. Marshall, J. H. Lee, W. H. Mcculloch, J. C. Sawyer Jr, R. A. Bari, H. S. Cullingford, A. C. Hardy, G. F. Niederauer, K. Remp and J. W. Rice, "Nuclear safety policy working group recommendations on nuclear propulsion safety for the space exploration initiative," 1993.

[13] J. S. Clark, P. Mcdaniel, S. Howe, I. Helms and M. Stanley, "Nuclear thermal propulsion technology: Results of an interagency panel in FY 1991," 1993.

[14] G. V. Milowicki and J. Johnson-Freese, "Strategic choices: examining the United States military response to the Chinese anti-satellite test," *Astropolitics,* vol. 6, p. 1–21, 2008.

[15] *Introduction to the Nuclear Weapons Archive,* 2019.

[16] *2021 Annual Figures for Holdings of Civil Unirradiated Plutonium,* 2021.

[17] C. Skelly, *Nuclear propulsion could help get humans to Mars faster,* NASA, 2021.

[18] *Near-term nuclear propulsion FY92 Final Review - NASA,* NASA, 1992.

[19] *RS-25,* Wikimedia Foundation, 2023.

[20] *IAEA 2017 Neutron Data Standards in Table Format,* IAEA, 2018.

[21] T.-S. Wang, F. Canabal, Y.-S. Chen, G. Cheng and Y. Ito, "Thermal Hydraulics Design and Analysis Methodology for a Solid-Core Nuclear Thermal Rocket Engine Thrust Chamber," *Nuclear Reactor Thermal Hydraulics and Other Applications,* p. 107, 2013.

[22] X. Chen and Y. Wu, "Fabrication and optical properties of highly transparent MgO ceramics by spark plasma sintering," *Scripta Materialia,* vol. 162, p. 14–17, 2019.

[23] A. M. Hofmeister, "Thermal diffusivity and thermal conductivity of single-crystal MgO and Al2O3 and related compounds as a function of temperature," *Physics and Chemistry of Minerals,* vol. 41, p. 361–371, 2014.

[24] G. Himpel, M. Herrmann and S. Höhn, "Comparison of the high-temperature corrosion of aluminium nitride, alumina, magnesia and zirconia ceramics by coal ashes," *Ceramics International,* vol. 41, p. 8288–8298, 2015.

[25] H. Kobayashi, M. Yamaguchi and T. Ito, "Ab initio MO study on adsorption of a hydrogen molecule onto magnesium oxide (100) surface," *Journal of physical chemistry,* vol. 94, p. 7206–7213, 1990.

[26] *Uranium,* Wikimedia Foundation, 2023.

[27] U. Unnikrishnan and V. Yang, "A review of cooling technologies for high temperature rotating components in gas turbine," *Propulsion and Power Research,* 2022.

[28] R. Bardan, *NASA, DARPA will test nuclear engine for future Mars Missions,* NASA, 2023.