

NUCLEAR POWER AND PROPULSION SYSTEMS FOR UNMANNED SPACECRAFT

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Abstract— Nuclear power and propulsion systems are a smart alternative to traditional rocket systems. Topics discussed include, a brief history of nuclear power and propulsion is provided along with a background on nuclear power in space. The current nuclear technologies of Radioisotope Thermoelectric Generators (RTGs), Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) are described to provide the reader with enough knowledge to compare nuclear to chemical. The case for replacing chemical propulsion with nuclear propulsion is made by presenting the pros and cons of nuclear and chemical side by side. Furthermore, the safety and ethicality of nuclear power and propulsion systems are explained and presented against the public opposition to nuclear technology. Future potential and development of nuclear power systems are discussed and conclude the paper.

The concepts of nuclear power and propulsion systems have already been thoroughly developed but are not widely used. Nuclear power, such as RTGs generate electricity through thermal conversion generated by the decay of radioactive materials. The requirements of nuclear propulsion systems include using small amounts of fissile material to heat a liquid propellant. The process generates extreme quantities of heat through fission, just like nuclear power plants. Lastly, the super-heated gas is propelled from the spacecraft. Past unmanned rockets that have used nuclear propulsion have discovered new phenomena in our solar system. With increased space potential provided by nuclear, the possibility of increasing the knowledge of space is increased.

Keywords—Heatpipe Power Systems (HPS), Nuclear Electric Propulsion (NEP), Nuclear Thermal Propulsion (NTP), Radioisotope Thermoelectric Generators (RTGs), Specific Impulse (Isp)

NUCLEAR PROPULSION SYSTEMS: AN INTRODUCTION

The human race has been fascinated with outer space for several decades. The desire to learn more about what lay beyond the limits of Earth led humans to develop technologies for exploring the vast expanse known as outer space. Since the launching of the first man-made satellite, *Sputnik*, in 1957, humanity's understanding of space has grown exponentially. The exploration of space and development of tools for this endeavor has greatly enhanced the quality of life on planet

Earth. The development of space technologies has led to many advancements in unrelated fields such as medicine, transportation, and public safety. Examples of technologies that are a direct result of space technology development include low-cost heart pump implants, improved insulation, and faster battery chargers [1]. In order to continue these everyday technology developments, the exploration of space continue.

After a lull in nuclear space exploration, due to government cutbacks and nuclear scares, there has been a revived interest in nuclear space exploration. The increased amount of nuclear power acceptance has enabled continued development of nuclear engines. To create missions that last longer and travel further, chemical rockets need to be replaced. With today's technology, some concepts from NASA are not feasible, such as antimatter/matter collisions. Also, certain current fuel technologies, such as solar panels, have limitations. A realistic option is a nuclear fuel source. With past nuclear-propelled rockets discovering new information, such as water on Europa, one of Jupiter's moons, nuclear propulsion systems are a viable and cost effective route to further our understanding of outer space. Nuclear propulsion systems will enable both longer engine lives and greater travel speeds allowing for missions beyond the reach of conventional propulsion systems.

HISTORY OF NUCLEAR POWER AND PROPULSION SYSTEMS IN SPACE

The concept of using a nuclear reaction for generating power in spacecraft has been around since the late 1940s with the first publications detailing the applicability of nuclear power in spacecraft appearing in 1947. By 1951, the Atomic Energy Commission (AEC) began sponsoring research for the development of nuclear power for United States military satellites. The development of this technology eventually grew into the development of nuclear power systems for spacecraft other than Earth satellites. The research done during this time period led to two different technologies, small nuclear reactors and the radioisotope thermoelectric generator [2]. With the development of these technological concepts, the AEC needed to begin building and testing the systems designed. These tests, labeled as SNAP or Systems for Nuclear Auxiliary Power, began at Mound Laboratory in 1954. The tests consisted of two different technologies: Radioisotope Thermoelectric Generators (RTGs) and small nuclear reactors [2]. RTGs are powered by decaying

Plutonium-238 or similar radioactive elements, which have a high decay heat. The heat expelled is converted to power by static thermoelectric elements like thermocouples [3]. RTGs were hailed as a breakthrough that was safe and reliable.

While the use of nuclear power sources did receive some opposition, this resistance remained predominantly among experts in the field for the first thirty years. It was this opposition that started many of the strict protocols required before a launch could take place. The year 1978 saw a major change to public opposition to nuclear spacecraft. The crash of the Soviet Cosmos 954 containing an RTG with 110lbs of Uranium-235 on January 24, 1978 led to widespread public fear of nuclear power systems. A second nuclear disaster just over a year later added to this fear. March 28, 1979 saw the partial meltdown of the Unit 2 reactor at the Three Mile Island nuclear power plant. Two major disasters only a year apart brought nuclear space technology to a crawl. President Jimmy Carter called for a moratorium on nuclear spacecraft [2]. Even though nuclear power for spacecraft suffered setbacks and public opposition, it was able to rebound, continue and provide more safe and beneficial missions.

Even though public opposition to sending nuclear materials into space had increased, NASA and other space agencies continued with launches, demonstrating the safety of these spacecraft. Several demonstrations that RTGs and nuclear power were still safe include the Galileo, Ulysses and Cassini missions. These missions provided new and surprising information about Jupiter, the Sun, and Saturn respectively. The success of these three probes helped to lessen the opposition faced by nuclear-powered spacecraft and paved the way for future innovation [2].

WHAT IS THE TECHNOLOGY?

The physics that is required in order to propel a rocket through space, while conceptually simple, can become complicated when applying it to reality. To escape Earth orbit it is required to use traditional chemical propulsion systems, built in stages, instead of nuclear thermal propulsion which is considered too dangerous to operate in Earth's atmosphere. Once in space, nuclear propulsion can be safely operated because the radiation created will be minimal when compared to the radiation produced by the Sun. To move in space, a rocket must first generate a force to propel the rocket body forward. This force, known as thrust, is generated by converting thermal energy into chemical energy by the expelling of super-heated gasses from rocket thrusters [4]. A common way to express the thrust generated is by relating it to the mass of the propellant consumed, called the specific impulse (Isp) [5]. Isp is considered to be the equivalent of an automobile's "miles per gallon" [4]. By increasing the Isp of a rocket, the traveling velocity is increased which allows for faster mission times.

FIGURE 1 [6]

$$I_{sp} = \frac{F}{\dot{W}} = \frac{V_j}{g}$$
$$F = \frac{\dot{W}}{g} V_{ex} + (p_e - p_o) A_e$$

Equations for Specific Impulse

Specific impulse (Isp) is the ratio of thrust to weight (F/\dot{W}) seen in Figure 1. Isp is also defined as the ratio of effective jet velocity (V_j) to gravity (g). The thrust (F) is the summation of the moment thrust and pressure thrust as seen in the second equation in Figure 1. The thrust equation is dependent on the following: propellant weight flow rate (\dot{W}), gravity (g), axial exhaust velocity (V_{ex}), pressure at nozzle exit (p_e), atmospheric pressure (p_o), and nozzle exhaust area (A_e) [6].

In order to generate the Isp required for missions to targets such as Mars or the outer planets of the solar system, a propulsion system other than conventional chemical propulsion must be used. Chemical propulsion systems must be built in stages to generate the required Isp to escape the gravitational field of Earth. The required amount of chemical fuel required to escape Earth's gravity is approximately 96% of the total fuel. Additionally, chemical propulsion systems must drop approximately 95% of the initial weight of the rocket to escape gravity [7]. Nuclear propulsion systems are capable of generating specific impulses up to twenty-five times greater than chemical. Because of this greater thrust to weight ratios, nuclear rockets do not need to be built in stages and drop all the weight and fuel associated with chemical propulsion [5].

A nuclear propulsion system is a system that superheats a liquid propellant and expel the propellant at extreme speeds generating thrust [3]. Nuclear propulsion systems have lifespans that vary based on several key factors. The lifespan is determined by the Isp that is generated, the core temperature of the reactor and the amount of fissile material available for the reaction. There exist two forms of nuclear propulsion systems: nuclear thermal and nuclear electric explained in the following subsections.

Nuclear Thermal Propulsion Systems

Nuclear thermal propulsion systems were the first nuclear style propulsion system to be analyzed for use in spacecraft. With the concept first being realized shortly after World War II. The primary concept of a nuclear thermal propulsion system is to generate significant heat using a light nuclear reactor. The heat is generated by the kinetic energy of the Uranium-235 fuel source breaking apart and releasing gamma rays, neutrons, and smaller elemental particles. This heat is then transferred to liquid hydrogen (H_2) which serves as both a propellant for the spacecraft and as the coolant for the

reactor. The superheated H₂ is then expelled from the rocket thruster nozzle at supersonic speeds [8]. This process can be seen in Figure 2.

FIGURE 2 [9]

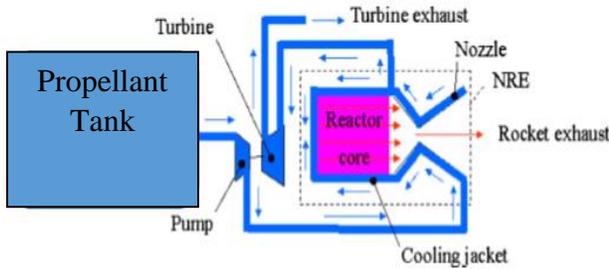


Diagram of a Nuclear Thermal Propulsion System

There are two variations of nuclear reactors used in nuclear thermal propulsion systems. The reactor can utilize either a solid core or a gas core. The reactors with solid cores provide coolant pathways through the core used to heat the propellant. These reactors reach temperatures of roughly 2500-3000 Kelvin and generate an Isp of approximately 1000s. Gas core reactors are able to attain higher temperatures and Isp's than solid core reactors. The core is either comprised of a mixture of the nuclear fuel source and the hydrogen propellant or a "lightbulb" made of silica containing the gaseous nuclear fuel source surrounded by the hydrogen propellant. Gas core reactors can reach temperatures of 5000-20000 Kelvin and generate an Isp up to 6000s [4].

FIGURE 3 [4]

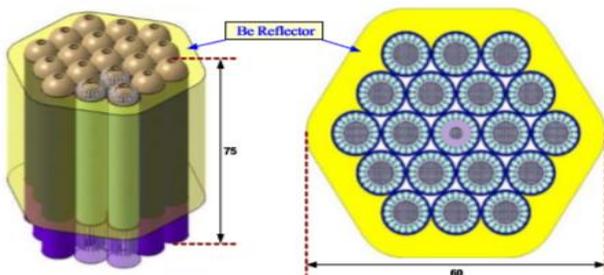


Diagram of the BORIS-H₂ reactor

One example of a nuclear thermal propulsion system is the Space Reactor Integral System (SPRIS). "SPRIS is powered by the Battery Omnibus Reactor Integral System-Hydrogen (BORIS-H₂). BORIS-H₂ is an open cycle very high-temperature gas-cooled reactor utilizing the H₂ propellant. The design specifications of SPRIS are the reactor power of 1,000 MW_{th}, the thrust of 250,000 N, the specific impulse of 1,000s, and the total mass of 600 kg including the reactor, turbo-pumps and auxiliaries" [5]. The BORIS-H₂ reactor

system is able to provide a specific impulse of slightly more than two times that of chemical propulsion [5].

The BORIS-H₂ reactor is set up as a hexagonal ring with 19 fuel elements; 18 fuel elements are designated for propulsion, and 1 is designated as general purpose electricity generation used for control systems and propellant pumping. The BORIS-H₂ reactor is able to remain lighter by utilizing a beryllium reflector rather than a heavy pressure vessel [5]. Figure 3 shows a representation of the hexagonal structure of the reactor and Figure 4 shows a model of a SPRIS using two BORIS-H₂ reactors. The Space Reactor Integral System involves two cycles; H₂ is sent through the 18 propulsion related fuel rods and helium (He) is pumped through the remaining central fuel rod. The system power output can be regulated by the emission of boron powder that absorbs the neutrons that cause the fission reaction [5].

FIGURE 4 [4]

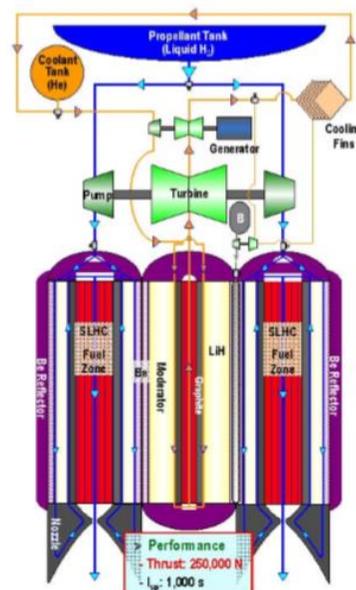


Diagram of a Bi-Modal SPRIS Using Two BORIS-H₂ Reactors

The nuclear thermal propulsion system contains certain drawbacks that have been discovered during testing of various systems. Research done in the former Soviet Union determined that when the nuclear thermal systems being tested were exposed temperatures of approximately 3000°C the half-life of the radioactive material was significantly decreased. In order to achieve the desired Isp of approximately 900s, the temperature must reach about 3000°C, but this also reduces the half-life of the Uranium fuel source to about 1 hour. While this drawback does not affect the feasibility of a Mars or equivalent mission, current nuclear thermal technology is not well suited for deeper space missions [8].

Nuclear Electric Propulsion Systems (EPS)

The former Soviet Union was the first to develop Nuclear Propulsion Systems (NPSs) in 1956 [10]. Advancements in technology since then have allowed for new and improved systems to be developed. Recent advancements in propulsion systems have created electric thrusters that generate a specific impulse several magnitudes greater than chemical systems. These electric thrusters require somewhere from 1-100 kilowatts of power per thruster, but when combined with a NPS, it is possible; this is the idea behind nuclear electric propulsion. Heat is generated by the NPS and is transferred to electric power by a conversion unit. This power is then relayed through a power line to the electric propulsion system (EPS) which fires propellant out of the thrusters [9]. This process is outlined in figure 5 below.

FIGURE 5 [9]

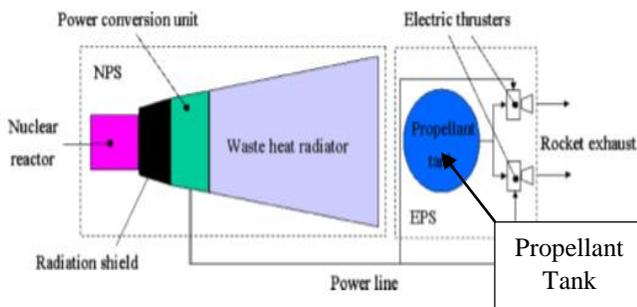


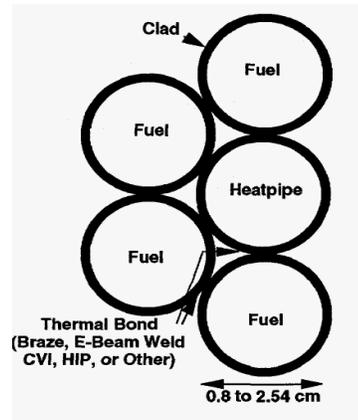
Diagram of a Nuclear Electric Propulsion System

There are a variety of thrusters that electricity created from this system can be used to operate. One such thruster is the ion thruster. An ion thruster is a thruster that uses electric fields to accelerate ions to extreme velocities. Another type of thruster is the Hall thrusters. Hall thrusters use a combination of magnetic fields to ionize the propellant and create an electric field which accelerates the ion. The last thruster type is the MPD thruster that relies on pulsed electromagnetic fields to accelerate the plasma [4]. These systems are not perfect replacements and still have some drawbacks. There is a very low power to weight ratio and a very low thrust density that means that there is a low thrust to weight ratio. This leads to EPSs not being able to be used in launches or any time where a high acceleration is needed [4].

Another form of nuclear electric propulsion is the Heatpipe Power System (HPS). An HPS reactor system is able to provide power for spacecraft for up to ten years providing 100 kWe. The HPS system is able to convert the thermal energy generated by the reactor using a Stirling or Brayton cycle converter to generate the needed electric energy. The transfer of the energy from the reactor to the cycle converter uses heatpipes filled with sodium vapour. "A heatpipe is a heat transfer device combining thermal conductivity with phase change. At the hot end a liquid vapourises under low pressure

and at the other end it condenses, releasing its latent heat of vapourisation. The liquid then returns to the hot end, either by gravity or capillary action, to repeat the cycle" [3]. The reactor set up contains a hexagonal core containing 97% enriched uranium nitride fuel elements. The control system is six stainless steel clad beryllium drums used to move the controlling boron carbide into or out of the reactor [3].

FIGURE 6 [11]



Schematic of the HPS Power Module

The SAFE-400 reactor system is an example of an HPS used for space vehicles. The SAFE-400 is capable of generating 400 kWt of energy that translates to 100 kWe. This reactor setup contains 127 heatpipe elements each containing 3 fuel pins. The SAFE-400 has been used to provide power to electron-ion drive propulsion systems [3].

The capabilities of NEPs are much more than chemical rockets that are inefficient due to limited specific energies released by chemical reactions and the subsequent need for rocket stages [9]. NPSs have the ability to exceed the limitations that chemical rocket engines suffer, such as lower velocities and Isp.

COMPARISON OF NUCLEAR PROPULSION TO CHEMICAL PROPULSION

Current rocket technologies utilize chemical propulsion systems to propel rockets from Earth to their destinations. In chemical propulsion systems, thermal energy is generated by a chemical reaction between a hydrogen and oxygen mixture that generates heats of 3000-4000 Kelvin. The thermal energy must then be converted to kinetic energy used to propel the rocket forward. Chemical propulsion suffers from the limitation of bond energy. Chemical propulsions generate energy by breaking chemical bonds and forming new ones in a chemical reaction, but there is only so much energy that can be gained by breaking and reforming these bonds. The energy

that is generated in a chemical propulsion system translates to specific impulses of about 400-500s. This low Isp, along with a low thrust to weight ratio, is the very reason that rockets are built in stages in order to escape Earth's gravitational pull [4]. While the Isp shown in Table 1 shows that NTRs and NEPs are more efficient than chemical, these systems are beaten out in the thrust-to-weight ratio. Nuclear electric systems can generate considerable thrust in the emptiness of space, but they cannot do the same when within a gravitational pull such as Earth's.

FIGURE 7 [12]

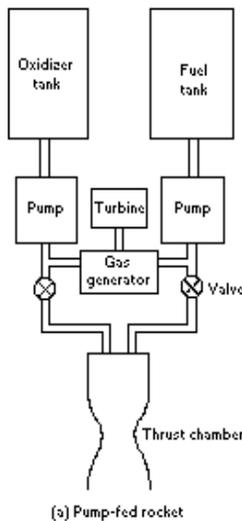


Diagram of a Chemical Rocket Engine

Nuclear propulsion systems offer the ability to overcome the limitations of the chemical propulsion systems. The limitations of a chemical reaction are almost non-existent in NPSs because of the high energy density of nuclear fuel. The output is so great that only 1 gram of fissile uranium can produce one megawatt of power for a whole day. Both nuclear thermal and nuclear electric propulsions systems are able to generate specific impulses 2-12 times greater than the Isp of chemical propulsion. For example, a nuclear thermal system, while operating at lower temperatures than a chemical propulsion system, can generate an Isp of up to 1000s where the chemical propulsion is only reaching up to 500s. Even more impressive is the comparison of nuclear electric to chemical Isp generation. Nuclear electric systems have been recorded as generating Isp's of 6000s and the only believed limit to this is the operational voltage [4].

As seen in Table 2 there is more than just one or two advantages to nuclear engines. While nuclear rockets maintain the same payload weight as a chemical rocket, the nuclear-powered spacecraft's total weight is about one third the total weight of the chemical rocket. This allows the nuclear rocket to increase its efficiency. The mass ratio is the

comparison to rocket without fuel to one with fuel. There is much less fuel needed for a nuclear spacecraft to operate which saves on cost while not lowering the efficiency of the rocket. "If we assume that it costs about \$5000 per kg to put hardware and propellant into orbit, the chemical system will cost at least 3 billion dollars, while the NTR system would cost about 1.3 billion dollars" [4]. With the money saved by using an NTR system, it would be possible to launch two nuclear rockets compared to only one chemical rocket.

TABLE 1 [4]

Type	Isp	T/W
Chemical (H ₂ /O ₂)	400 - 500 s	50-75
NTR - Solid Core	500 - 1000 s	1-20
NTR - Gas Core	1000 - 6000 s	1-10
NEP - Ion Thruster	2000 - 10000 s	<< 1
NEP - Hall Thruster	1000 - 5000 s	<< 1
NEP - MPD Thruster	1000 - 8000 s	<< 1

Table Comparing Isp and T/W of Chemical Propulsion to Multiple Nuclear Systems

TABLE 2 [4]

Parameter	Chemical (H ₂ /O ₂)	NTR - Solid Core
Payload Mass	100 tonnes	100 tonnes
Travel Time	1 year	1 year
Mission Delta-V	7.7 km/s	7.7 km/s
Isp	500 s	1000 s
Mass Ratio	4.806	2.192
Structural Mass	25 tonnes ($\epsilon=0.05$)	15 tonnes ($\epsilon=0.10$)
Propellant Mass	475 tonnes	137 tonnes
Total Initial Mass in LEO	600 tonnes	252 tonnes
Payload Fraction	0.167	0.397

Table Comparing Many Factors of Chemical and Nuclear Thermal Propulsion

THE SAFETY OF NUCLEAR PROPULSION

Safety has always been a major concern in regards to nuclear power. Safety became an even more emphasized value when nuclear power was chosen to be a fuel and power source for rockets and space vehicles. From the beginning of the nuclear initiative, no absolute code of safety measures was

laid down. Guidelines were created and followed in research, development, and launches as they occurred. In 1990, it was decided that nuclear power would be crucial for the Space Exploration Initiative (SEI). Because nuclear power was a must have for SEI, the Nuclear Safety Policy Working Group (NSPWG) was formed in order to recommend the necessary policies and safety concerns associated with using nuclear power for SEI. The guidelines developed by NSPWG have become a standard when nuclear power and fuel sources are required for space missions [13].

The NSPWG created recommendations for six major areas: reactor start-up, inadvertent criticality, radiological release and exposure, disposal, entry, and safeguards. Additional required safety test recommendations were also included in the NSPWG report including ground test safety and ground facility and equipment safety. Reactor start-up section states that the reactor should remain inactive prior to deployment and achievement of orbital unless low powered testing is being done on the ground [13]. This safety procedure allows for the lowest possible risk of a reactor malfunction having any impact on the quality of life on Earth. The inadvertent criticality section states: "Inadvertent criticality shall be precluded for both normal conditions and credible accident conditions" [13]. In others words, the reactor will be designed in such a way that neither normal conditions nor foreseeable accident conditions would cause the reactor to become critical. This requirement results in dozens of rigorous tests to determine the safety of a reactor set up. The third major requirement, radiological release and exposure, deals only with reactors while they are active in space. This requirement states that any form of radiological release from a reactor must not render the spacecraft useless, increase the radioactivity of the local space environment over long periods of time, must not have any significant impact on the radioactive levels on Earth, and that the probability of any form of accident must be low [13]. These three requirements dealt with all operations from prelaunch up to normal operations.

The following requirements deal with the safety of the reactor once it is done with normal operations. Disposal is the topic of the fourth requirement. While the disposal plans can vary for different missions to different places, there are generalized requirements. "Furthermore, the method of disposal must be safe; that is, the radioactive materials of the disposed reactor system must not endanger the public or the environment. Strategies for disposal must preclude entry by orbital decay in order to comply with requirement for no planned Earth entry (next topic)" [13]. The previous quote states that the radioactive materials cannot increase the levels of radiation on Earth. Additionally, the disposal must make sure that any orbiting satellites with radioactive materials do not reenter the atmosphere and fall to Earth, which also falls under requirement five. Requirement five states that while any form of planned reentry is off-limits, accidental reentry probability must be as small as possible, and the consequences of a possible reentry must be confined to as

small an area as possible. This requirement has resulted in extensive testing in order to make the reactor as strong as possible to resist predictable crash scenarios. Finally, the sixth major requirement dictates the implementation of safeguards. These safeguards are to be put in place in order to prevent theft, diversion, loss, or sabotage and to provide the ability to quickly receive reactor status and location if needed for a recovery mission [13].

In addition to these six safety requirements, the NSPWG provided recommendations for safety regulations for testing at ground facilities. The NSPWG recommends: "The Ground test element of the safety program should focus on data required to assure that safety objectives for flight systems will be achieved. These data are necessary to obtain flight approval" [13]. Ground facilities are necessary therefore for all of the required testing of the nuclear systems, such as nuclear thermal propulsion and nuclear electric propulsion reactors before the systems are sent into space. The extensive safety protocols that have been put in place by government agencies, the Department of Energy (DOE) for example, are thanks to groups like the Nuclear Safety Policy Working Group and the requirements recommended by them.

ETHICAL CONSIDERATIONS ASSOCIATED WITH NUCLEAR PROPULSION

Nuclear engines face some of the same oppositions that nuclear energy power plants face. There is a large amount of individuals who do not know how safe nuclear technology truly is and are opposed to anything nuclear. Those who oppose nuclear power worry for the safety of the environment and the effect it can have on future generations [14]. Events such as the Cosmos 954 and Chernobyl have many dead set on their opinion against nuclear, but it truly is a safe system for generating power.

The main concern of the public is the waste produced during nuclear reactions and where it is being put. In the case of NEP, nuclear engines would not be able to provide lift for a rocket so a different source would have to be used for takeoff. Theoretically the rocket would then enter lunar orbit and remain stationary until the next takeoff would happen. This concept would prevent any debris from falling to Earth, and no waste would be made in the vicinity of Earth. Some would argue that the waste being produced while in space could also be a cause for concern but the waste being produced can also be used as fuel for these engines. There can be safety concerns for when the spacecraft reenters the Earth's atmosphere, but these are unnecessary. The engine will never need to reenter Earth's atmosphere because the rocket would be disposed of by being launched into the Sun [10].

Environmental concerns are another topic when it comes to nuclear power. With the waste being disposed of in the Sun, there is little to no chance of debris contaminating the environment. If the engines used for takeoff were nuclear

powered, there could be a possibility of radiating the atmosphere but that is not the case. A current nuclear engine could not produce enough thrust to successfully launch a spacecraft out of Earth's atmosphere. On the other hand, currently used forms of power, such as coal, produce and release 1.7 billion tons of CO₂ into our atmosphere. With this being recognized, there has been a shift in opinion for some.

NUCLEAR PROPULSION IN THE PUBLIC'S EYE

Nuclear power and propulsion systems for space vehicles has overcome many obstacles in the public and political realms. The first RTG proposed for use in United States Naval navigational satellites, Transit, received major disapproval from officials in the Kennedy administration. The skittishness of these officials lead to public protests over the impending launch. Had it not been for President John F. Kennedy's stamp of approval, Transit-4A would have flown without the RTG [2]. With initial successes, most opposition withered into the background. The Transit 5BN-3 malfunction caused minor ripples, but the real damage was done with the Cosmos 954 crash and Three Mile Island disaster. Rocket launches containing nuclear material after these disasters were widely protested and somewhere taken to court. While the protests and court proceedings never prevented any launches, they did aid in creating concrete safety regulations and procedures for nuclear rockets [2]. While there may not appear to be as significant an opposition today, nuclear space power still faces many public challenges. "As it stands at present the continued use of nuclear power for spacecraft seemingly, from the perspective of the American public, to adopt a phrase concerning the legality of abortion offered by President Bill Clinton, must remain 'safe, legal, and rare'" [2].

THE FUTURE OF SPACE TRAVEL

The development of spacecraft has been an important human endeavor for the past sixty years. The exploration of space has aided in developing society and increasing the general human knowledge. It is vital, therefore, that continued efforts are made to further explore outer space. While traditional propulsion systems have provided the knowledge we currently have, these systems have their limitations. Nuclear power and propulsion systems are one viable route that can decrease the limitations of spacecraft.

Nuclear technology has evolved to a point where it is both safe and cost effective for the application of space travel. Nuclear propulsion systems are able to provide an increase of specific impulse and a decrease of fuel mass when compared to traditional chemical propulsion systems. Additionally, nuclear propulsion can lead to faster and safer space journeys for manned missions, thus allowing manned missions to go

farther. While such a dramatic shift in rocket technology may not be entirely feasible in the current economic state, it is an important idea to consider as the development of space technology continues.

REFERENCES

- [1](2011). "Spinoff: NASA Technologies Benefit Society." *National Aeronautics and Space Administration*. (online publication).
- [2] R. Launius. (2014). "Reacting to nuclear power systems in space: American public protests over outer planetary probes since the 1980s". *Acta Astronautica*. 96(1), 188-200. 10/2013. (journal article).
- [3] (2015). "Nuclear Reactors and Radioisotopes for Space." *World Nuclear Association*. (online article). <http://www.world-nuclear.org/info/non-power-nuclear-applications/transport/nuclear-reactors-for-space/>
- [4] B. Bromley. (2001). "Nuclear Propulsion Getting More Miles Per Gallon." *Space Exploration*. (online article). <http://www.astrodigital.org/space/nuclear.html>
- [5]B. Halimi, Seung H. Nam, Kune Y. Suh. (2011). "Engineering of Nuclear Thermal Propulsion System for Space Application" *Transactions of the American Nuclear Society* 105, 1-2. 11/2011. (journal article).
- [6] R. Mohler. (1947). "Stability and Control of Nuclear Rocket Propulsion." *The Los Alamos Scientific Laboratory*. (government publication).
- [7] Douglas Aircraft Company, Inc. (1947). "Satellite Rocket Power Plant." *Project RAND*. (government publication).
- [8]C. Bruno, DMA, University of Rome, Italy. C. Dujarric, ESA Headquarters. (2013). "In-space nuclear propulsion." *Acta Astronautica*. 82(2), 159-165. 10.1016/j.actaastro.2012.08.022. (journal article).
- [9]V. Zakirov, V. Pavshook. (2011). "Feasibility of the recent Russian nuclear electric propulsion concept: 2010." *Nuclear Engineering and Design*. 1529-1537. 02/2011. (journal article).
- [10]W. Strobl, R. Hora, J. Mildice. (2011). "Nuclear electric propulsion and human space exploration." *AIAA Space Conference and Exposition 2011*. (Conference Article).
- [11] M. Houts, D. Poston, W. Emrich Jr. (1997). "Heatpipe Power System and Heatpipe Bimodal System Design and Development Options." (conference article).
- [12] "5. Propulsion Systems." *NASA History*. (gov. website). <http://www.history.nasa.gov/conghand/propulsn.htm>
- [13] A. Marshall, J. Sawyer. (1992). "Nuclear safety policy working group recommendations for SEI nuclear propulsion safety." *AIP Proceedings*. (conference article).
- [14] K. Flanagan. (2013). "Ethical Considerations for the Use of Nuclear Energy." *Global Ethics Network*. (online blog). <http://www.globalethicsnetwork.org/profiles/blogs/ethical-considerations-for-the-use-of-nuclear-energy>

ADDITIONAL SOURCES

(2000). "Nuclear Propulsion." *Military Analysis Network*. (online article). <http://fas.org/man/dod-101/sys/ship/eng/reactor.html>

S. Summerford. (2013). "Nuclear Thermal Rocket: A Misunderstood Beast (2)." *Discover News*. (online article). <http://news.discovery.com/space/private-spaceflight/icarus-interstellar-nerva-nuclear-fission-propulsion-space-exploration-1301301.htm>

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