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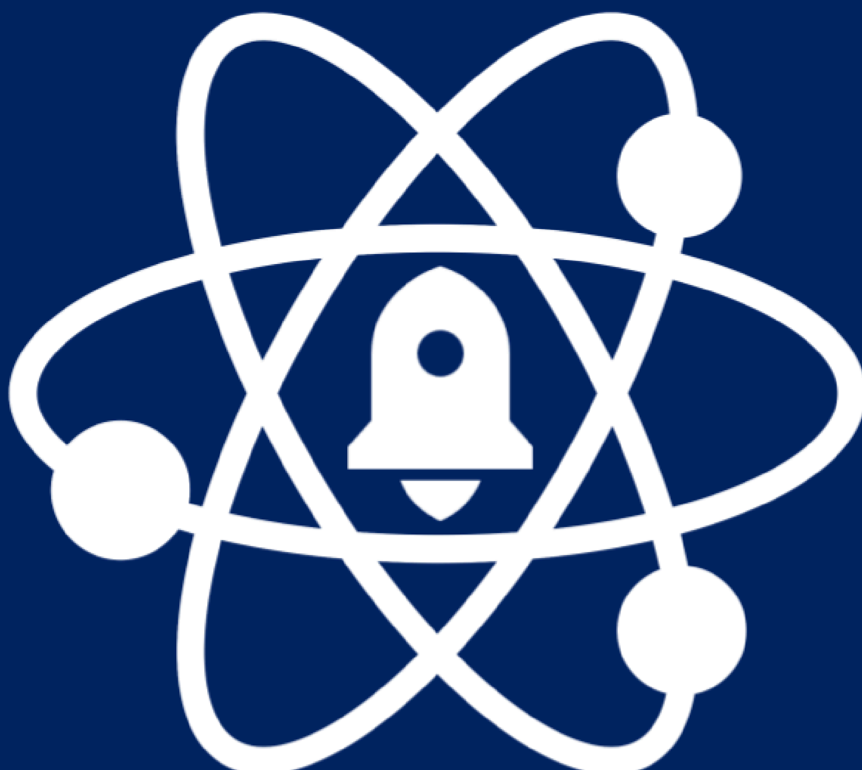
Nuclear Propulsion In Space:
Policy Approaches for the 21st Century



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Nuclear Propulsion In Space:
Policy Approaches for the 21st Century

Project Managers:
Ryan Beam
Rishita Khandwala

Research Team:
Ophelia Kimber
Steven Arroyo
Rocka Moragne
Joe Mattson
Sreya Gonugunta

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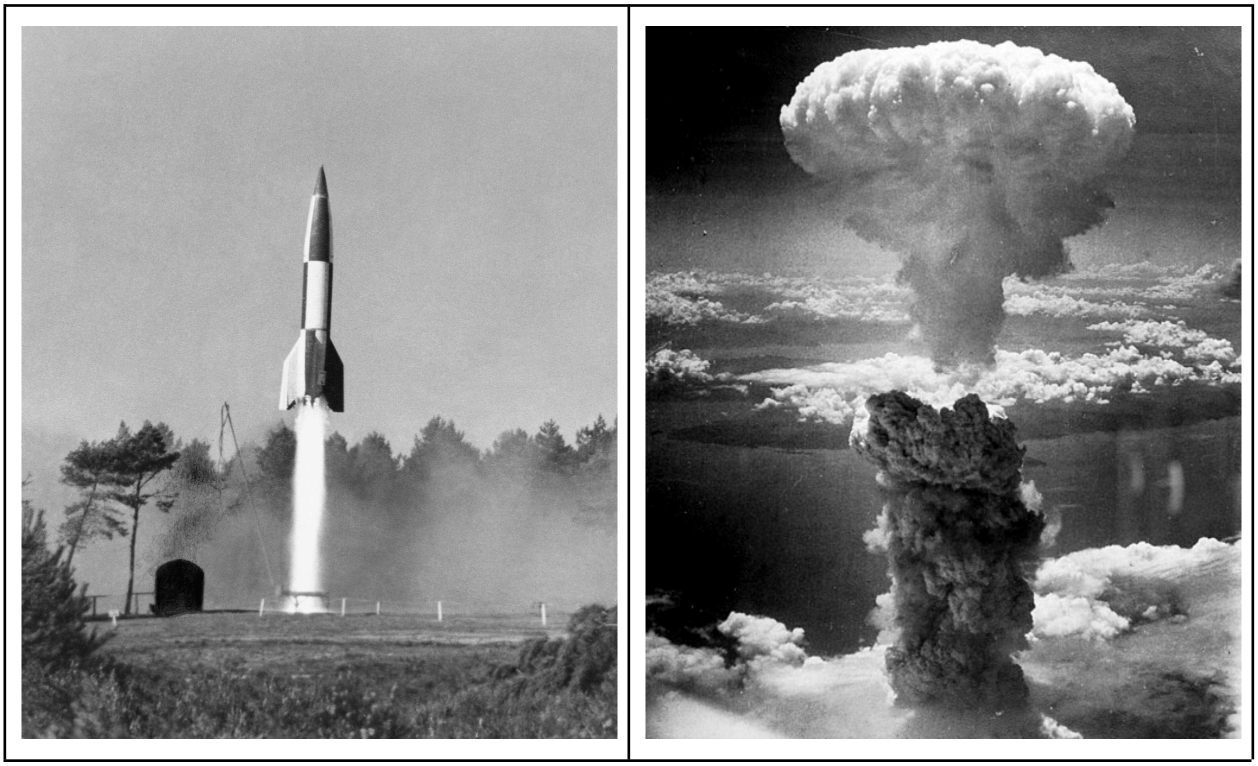
In June 1944, a German V-2 rocket became the first artificial object to reach space. Just under thirteen months later, the United States detonated the first ever nuclear bomb. Both technologies were deployed as weapons in the final years of World War II, and the prospect of using rockets to deliver nuclear weapons animated the Cold War that followed.



Left: A captured German V2 rocket test launched by Allied forces, October 1945.
Right: The fission bomb explosion over Nagasaki, August 1945.

Question

What regulatory standards are necessary to address risks posed by the next generation of nuclear propulsion systems in space?

Executive Summary

Among the myriad technologies that defined the 20th century, few had as immediate and profound influences on the global balance of power as rocketry and nuclear fission.

In the decades after World War II, as the United States and the Soviet Union settled into the Cold War, proficiency in these technologies became a benchmark for military might. Both superpowers invested mightily in the development of nuclear warheads and intercontinental ballistic missiles (ICBMs)-- but also their more peaceful counterparts. Nuclear power plants promised to energize the world, and rockets equipped with the first telecommunications satellites ushered in a new age of global connectivity.

In a great victory for peace, the Cold War never turned hot. No ICBM ever launched a nuclear warhead at another country. Instead, nuclear powered space probes launched on missions to peacefully explore other worlds atop rockets emblazoned with the insignia of civil space agencies. A number of ICBMs were retired, refurbished and repurposed as space launch vehicles.

In the unipolar period that emerged following the collapse of the Soviet Union, the world-shaping technologies of rocketry and nuclear power have increasingly fallen under the influence of private interests. 21st century policy priorities, paired with a new preference for private-sector innovation, have together spawned a new class of company– one that sometimes blurs the long established line between contractor and customer.

In this era of increased commercialization, where private companies wield significant and growing influence over the once-government-dominated technologies of rockets and nuclear reactors, the landscape of domestic and global policy becomes more complex. Policymakers may find themselves in a delicate balancing act as they attempt to harness the benefits of private-sector innovation while ensuring strategic control and adherence to national interests. Traditional oversight mechanisms designed for government-led initiatives may not be seamlessly adaptable to commercial ventures.

This paper is intended to serve as an introduction to nuclear propulsion technology as it has been and will be used in outer space. It also assesses several real and forecasted 'worst case scenarios' dating back to the cold war; examines current regulatory regimes on the national and international levels and their limitations; and issues a set of recommendations designed to prevent these worst case scenarios from playing out as private companies join governments in this critical area.

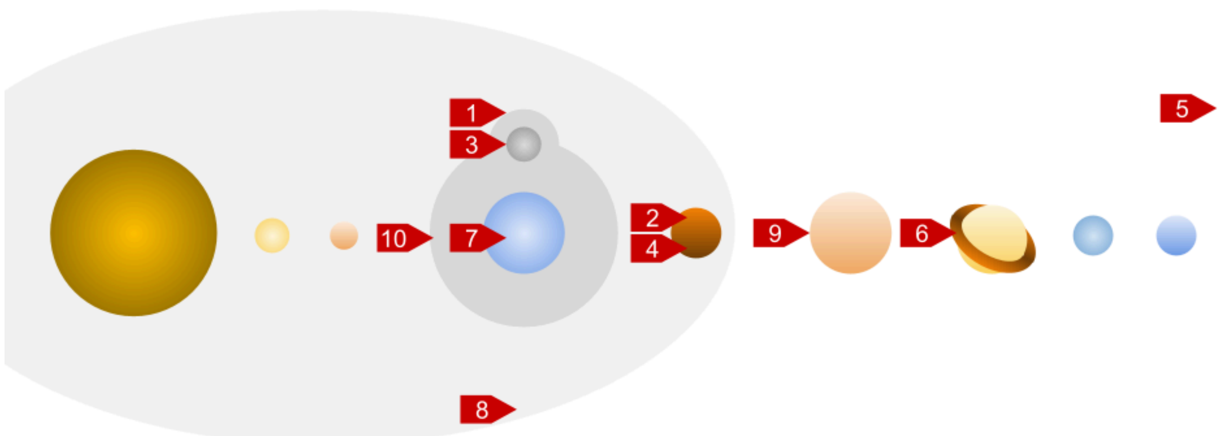
Background

About Nuclear Power in Space

Nuclear power is an attractive option for a variety of space mission profiles, both civil and military. Today, spacecraft with nuclear power supplies exist on the moon, Mars, outside of the solar system, and in a variety of orbits around the Sun and Earth. Recent nuclear-powered missions include India’s Chandrayaan-3 lunar orbiter (2023), the United States’s Perseverance Mars rover (2020), and China’s Chang'e 3 lunar lander and rover (2013).

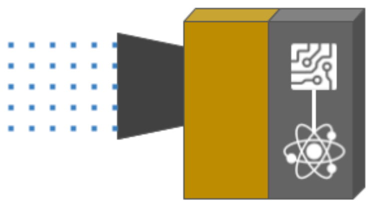
10 most recently launched nuclear power systems (2023)

1.	Chandrayaan-3	Lunar orbit	2023	6.	Cassini probe	Saturn orbit	1997
2.	Perseverance rover	Mars surface	2020	7.	Mars 96 rover	crashed on earth	1996
3.	Chang'e 3 rover	Lunar surface	2013	8.	Ulysses probe	heliocentric orbit	1990
4.	Curiosity rover	Mars surface	2011	9.	Galileo probe	Jupiter orbit	1989
5.	New Horizons probe	deep space	2006	10.	Kosmos 1932	Earth orbit	1982



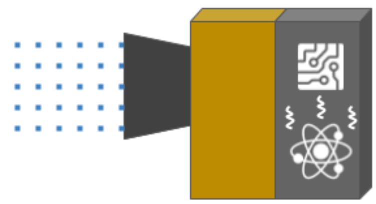
It is important to note that not all applications of nuclear energy in space are propulsive. In fact, most are not– nearly all 'nuclear-powered' spacecraft in operation as of 2023 use either radioisotope thermal generators (RTGs), a type of nuclear battery that merely powers onboard electronics; or radioisotope heater units (RHUs), which provide heat to allow onboard electronics to operate. Both RTGs and RHUs take advantage of heat produced by radioactive decay, an entirely different process than nuclear fission.

Radioisotope Thermoelectric Generator (RTG)



RTGs convert radioactive decay to electricity, which powers onboard electronics

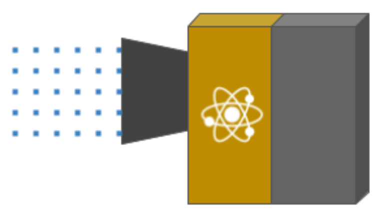
Radioisotope Heater Unit (RHU)



RHUs use heat from radioactive decay to maintain operational temperature for electronics

Though we will discuss RTGs and RHUs in some detail, we will also pay considerable attention to *propulsive* technologies, where nuclear power is used not just to power or warm electrical components, but to propel spacecraft– a role historically fulfilled by chemical engines. Compared to decay-powered RTGs and RHUs, propulsive technologies are more likely to rely on nuclear fission, which offers more and finer control of power, while also introducing new risks, such as nuclear meltdown.

Propulsive Fission Reactor



A nuclear fission reactor is used to propel a spacecraft, either electrically or thermally.

We consider propulsion the highest-risk, highest-reward use of nuclear technology in space, and foresee movement towards this somewhat novel approach unfolding across the public and private sectors.

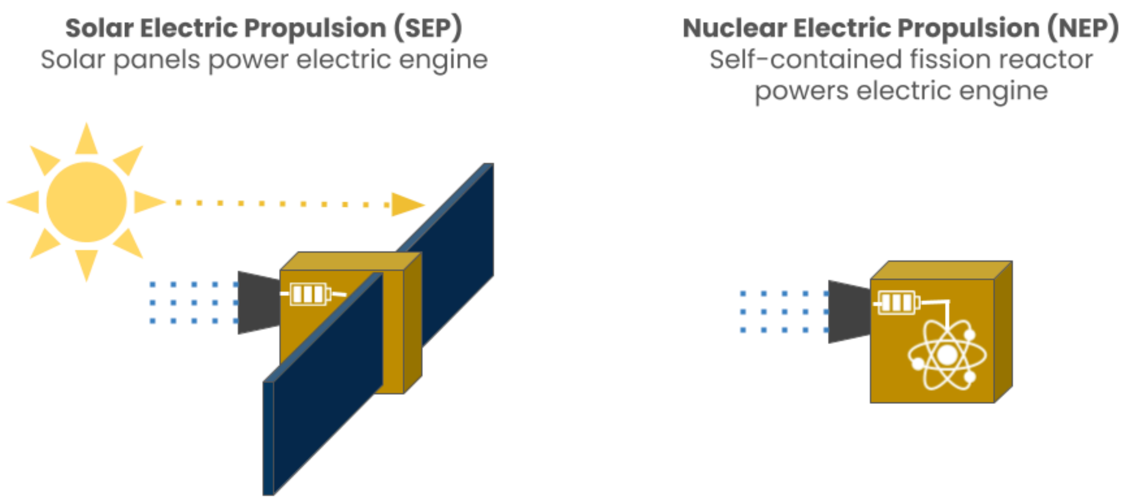
To date, no private actor has launched a spacecraft with *any* type of nuclear power supply aboard– whether RTG, RHU, or propulsive. However, as private sector ambitions grow along with public sector appetite for advanced space technologies, the likelihood of a privately built and operated nuclear spacecraft entering service also increases. Understanding how to deal with these developments as a regulator requires familiarity with the main types of nuclear power and propulsion, as well as their use cases in space.

I. Types of Nuclear Propulsion

i. Nuclear Electric Propulsion

What is it?
Today, spacecraft with electric thrusters tend to be powered by massive solar arrays. This approach is referred to as Solar Electric Propulsion (SEP).

Electric propulsion is suited for missions into deep space, but solar panels are not: as a spacecraft moves further from the sun, its solar arrays necessarily gather less energy. Their energy output is dependent on distance to the sun. Nuclear reactors do not have this problem making it perhaps the most suitable approach to powering deep space missions. This has given rise to the concept of Nuclear Electric Propulsion (NEP).



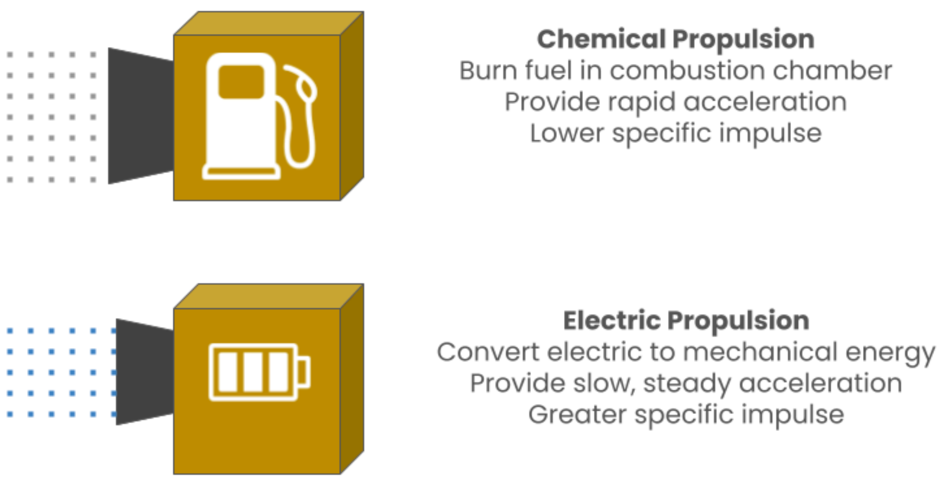
In NEP, a small fission reactor is used to generate heat, which is converted into electricity, which powers an electric thruster. As of 2023, NEP is the only type of nuclear propulsion technology that has actually been used in space.

The reactor:
Nuclear reactor fuel– commonly uranium– is highly energy-dense, and allows nuclear power plants to generate vast amounts of heat energy and electricity with minimal fuel. This is an ideal combination for spacecraft, which must be designed to minimize mass and size (to accommodate

rocket payload space); can not be refueled after launch; and may need to operate for decades at a time.

Generating electricity with a fission reactor is a familiar concept– nuclear power plants use the same technology here on Earth. While earthbound fission reactors take advantage of the fission process' extensive heat generation to boil water– which rotates a turbine and in turn generates electricity– a water-boiling system is not feasible for a spacecraft. Space-based fission reactors instead use small thermoelectric converters to convert heat to electricity[1].

The thrusters:
The electricity produced by a nuclear reactor may be used to power an electric thruster. Electric thrusters are an increasingly common feature on spacecraft. Compared to conventional liquid chemical thrusters, electric thrusters are lighter, more efficient, longer-lived, and capable of reaching speeds up to ten times as great[2].



The main disadvantage of electric thrusters is that they can not provide acceleration as rapidly as conventional chemical engines. Electric propulsion therefore mostly suits missions that must travel great distances, such as the United States's *Dawn* probe, which surveyed parts of our solar system's asteroid belt. Dawn's electric ion engines achieved 5.9 years of runtime, over which time they eventually achieved a maximum velocity change of 25,700 mph[3].

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1 https://www.etec.energy.gov/Operations/Major_Operations/SNAP_Overview.php
2
3

Launch History
The United States launched the first NEP system in 1965, as an experimental payload on the SNAP 10A satellite[4]. As of 2023, this remains the only time the United States has launched a fission reactor into orbit, and the only time the United States launched an NEP mission. The Soviet Union launched more than thirty fission reactors into orbit, mostly to power radar units on surveillance satellites, but twice for NEP missions. Its two nuclear propelled surveillance satellites, Kosmos 1867 and Kosmos 1818, have both since fragmented into orbital debris[5].

ii. Nuclear Thermal Propulsion

Spacecraft may skip the step of converting the heat from nuclear fission into electricity, and instead deploy fission's heat to directly generate thrust. Though this approach, known as nuclear thermal propulsion (NTP) has never been tested in space, it has been investigated seriously since at least the 1960s.

Ever since NASA's experimental Nuclear Engine for Rocket Vehicle Application (NERVA)[6] program in the 1950s and 60s, a rocket engine design using the power of a nuclear reactor's thermal energy to produce high-velocity superheated gas has been explored extensively. NTP has become a technology of interest due to its high potential as a long-distance propulsion method[1]; proposed NTP engines have around twice[7] the specific impulse of today's most advanced liquid chemical propulsion rocket engines.

This potential has led researchers and engineers to explore this technology as a method suitable for long-distance space flight missions,[2] as high specific impulse means high fuel efficiency - essential to long duration missions. Additionally, NTP's high fuel efficiency is essential for carrying the heavier rockets required for extended missions, and may reduce mission time by as much as 25%[1] due to NTP engines' ability to continuously use fuel and generate thrust throughout the mission. This opens the door to Mars space flight missions, further solar system exploration, and deep space exploration.

iii. Other Use Cases

While NTP and NEP are best suited for long missions[3], there are also interests in using both for satellites and shorter-distance missions. This is due to NTP's high specific impulse, allowing it to carry heavy payloads much more efficiently while still at reasonable velocities, and NEP's ability to be exceptionally fuel efficient through its even higher specific impulse. This allows both to power spacecraft for years, especially with nuclear power generators' ability to completely shut

[4]

[5]

[6] (6 Things You Should Know About Nuclear Thermal Propulsion)

[7] (Rom, 1968)

down fission and save fuel indefinitely - making it a viable option for satellites, rovers, and other space infrastructure purposes.

II. Use Cases

i. Civil Use Cases

The US government has long been interested in being at the forefront of all technological frontiers - space exploration is no exception. Through NASA, the US government has accomplished many technological groundbreaking feats: Explorer 1, the Hubble Space Telescope, and, of course, Apollo 11 - the moon landing. These feats are just a few of the many advancements the United States, through NASA, has spearheaded.

In 1969, the Space Task Group (NASA's group of engineers that managed human missions) proposed that, with NASA's overwhelming success of the Apollo program and NASA's evident aptitude in organization and technological breakthroughs, a program with the aim of sending astronauts to Mars was the next logical groundbreaking feat - achievable within 15 years. This proposal indicated that this mission would be done through nuclear propulsion - again, NASA's NERVA program during the 1960s, was having great success with its land-only NTP tests. This indicated a 15-year timeline was very promising. Under Nixon, however, the US government had other plans and, with a suggested budget of 70 billion in today's money, rejected the proposal.

Today, NASA has Mars manned missions back on the docket, with NASA's next big project - the Artemis program - being the first step towards that goal. NASA's Artemis program intends to change the course of space development - from deepening scientific understanding of the Earth, Moon, and our Solar System, to bolstering economic opportunities with thousands of jobs, and to creating an international commercial operation - through a basecamp on the Moon. Artemis will utilize reusable spacecrafts, docking with a gateway in the Moon's orbit, and use that gateway to transfer astronauts to the Moon where they can carry out various missions from the basecamp. The basecamp will also be powered by nuclear fission - a design made in collaberation with the DOE and being used due to its light weight and reliability, regardless of weather and solar energy. And, using the lessons learned from establishing humans on the Moon will be used to ensure that missions to Mars are both possible and within reach. In addition, with the ability to launch from the Moon, deep space exploration opens up considerably and at significantly reduced costs - fuel and payload alike - including Mars. With the Artemis program underway today, NASA has stated that a Mars manned mission can happen as early as 2030, and with duststorms lasting for months blocking out the sun on Mars and nuclear fission planned to power the Moon, fission reactors have been outlined as essential for Mars missions.

ii. Military Use Cases

In addition to the US Government's involvement in space through NASA, the US Government's Department of Defense - Defense Advanced Research Projects Agency (DARPA) is exploring Nuclear Propulsion for national defense, as well as more practical purposes, citing that the leap in propulsion technology provided by nuclear propulsion is essential for moving larger payloads further into space. This exploration is under the DRACO program, which will be further explored in the section below.

ii. Public Projects

While manned Mars missions are far-off visions for the future with much to be discussed and planned, technological advancements for these missions are taking off through multiple different programs right now.

i. NASA's Concept Awards

In 2021, NASA, in collaboration with the Department of Energy (DOE), announced the Nuclear Thermal Propulsion Reactor Concept Awards. This collaboration aimed to explore three separate reactor design concepts, with the DOE awarding 5 million dollar contracts through their Idaho National Laboratory (INL). This joint effort aimed to advance the nuclear reactor system, hoping to aid future deep space exploration through performance gains. The three contracts were given to BWX Technologies (BWXT), Inc, General Atomics, and Ultra Safe Nuclear Technologies. BWXT partnered with Lockheed Martin, General Atomics partnered with X-energy LLC and Aerojet Rocketdyne, and Ultra Safe Nuclear Technologies partnered with Ultra Safe Nuclear Corporation, Blue Origin, General Electric Hitachi Nuclear Energy, General Electric Research, Framatome, and Materion to accelerate their individual concepts. Today each of these entities are still developing nuclear technology from this program.

ii. DARPA's DRACO

DARPA has also undertaken a project under the name of Demonstration Rocket for Agile Cislunar Operations (DRACO). As mentioned earlier, DARPA indicates that with the space domain being a key player in national defense, as well as modern commerce and scientific discovery, moving increasingly heavy payloads increasingly further into space will require vast advancements in propulsion technology. DARPA is looking to utilize NTP through the DRACO program to tackle this surmounting restriction. DARPA is directing its focus to NTP due to its "high thrust-to-weight ratio around 10,000 times greater than electric propulsion and two-to-five times greater specific impulse … than in-space chemical propulsion". DRACO's aim is to demonstrate this cutting-edge NTP system in low-earth orbit by 2025. On April 12, 2021, DARPA selected Blue Origin and Lockheed Martin to compete in developing spacecraft concepts to demo NTP. General Atomics was also selected to develop the reactor, focusing mainly on a risk reducing nuclear propulsion. Blue Origin and Lockheed Martin will use this reactor design to develop their individual Demonstration Systems (DS) and Operational Systems

(OS) spacecraft concepts. The OS concept is pitched at meeting mission operational objectives, whereas the DC concept is more focused on demonstrating General Atomic's propulsion system.

More recently, on the 24th of January, NASA and DARPA jointly announced that NASA would be coming onto the DRACO project to propel DRACO into the future. With its previous experience from its concept awards, NASA would be responsible for the nuclear propulsion engine, and DARPA would handle the integration of NASA's engine into a spacecraft for launch. In addition, on July 26, the agencies announced that they had reached an agreement with Lockheed Martin, where Lockheed Martin would be developing the spacecraft for DRACO - meaning Lockheed Martin's initial design won out over Blue Origin. Lockheed Martin will also partner with BWXT, where BWXT will provide the nuclear reactor and provide high-assay, low-enriched uranium (HALEU) fuel. Under this agreement, NASA and DARPA will be splitting the 499 million total value of the agreement, with NASA continuing to oversee the reactor design and DARPA handling spacecraft and regulation. In addition, NASA's Space Force will be providing the launch of DRACO, which is planned for no later than 2027.

Priorities for Future Regulatory Regime

Nuclear propulsion, used in applications ranging from naval vessels to spacecraft, must include the principles of resiliency, redundancy, and safety in its foundations.

I. Resiliency

Rensures that the system can withstand and recover from unexpected conditions, thereby maintaining operational integrity under adverse circumstances. Resiliency is akin to the sturdy foundation of a well-built bridge, which withstands the forces of nature like heavy storms or seismic activity while ensuring uninterrupted passage for travelers. Just as the bridge's design incorporates flexible materials and reinforcement techniques to absorb and distribute stress, resilient systems in various fields employ similar strategies to navigate unexpected challenges while maintaining functionality and safety. In nuclear propulsion systems, resiliency is achieved through robust design and operational strategies that allow for continuous function under a variety of stressors. This includes the use of materials and components that can endure high levels of radiation and thermal stress, as well as advanced control systems capable of adapting to changing conditions.[8] For instance, resilient nuclear reactors are designed to automatically adjust control rod positions in response to fluctuating power demands or cooling system variations.[9] This adaptability is crucial for maintaining reactor stability and preventing scenarios that could lead to overheating or radiation leaks, thereby ensuring the system's integrity even in adverse conditions.

II. Redundancy

Redundancy, through the inclusion of backup components, safeguards against system failures, preventing any malfunction from escalating into a catastrophic event. Redundancy operates much like a backup generator in a household, ready to kick in seamlessly during a power outage to ensure continuous electricity supply. Similarly, in complex systems such as data centers or telecommunications networks, redundant servers and network connections are employed to maintain uninterrupted service even if primary components fail. This redundancy ensures that essential functions remain operational, minimizing disruptions and enhancing overall reliability. Redundancy is a critical safety feature in nuclear propulsion, involving the duplication of key components and systems to provide a backup in case of failure. For example, multiple independent cooling systems are installed to prevent reactor overheating, and dual power sources ensure continuous operation of critical systems even if one power source fails.[10] Control systems

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[8] ScienceDirect. "Optimum design of nuclear electric propulsion ...." Accessed October 29, 2023.
[9] Ayoub, Ali, et al. "Resilient Design in Nuclear Energy: Critical Lessons from a Cross-Disciplinary Review of the Fukushima Dai-ichi Nuclear Accident." arXiv.org. Accessed November 2, 2023.
[10] Tandfonline.com. "Reliability Evaluation of Complex Nuclear Energy Redundancy Systems ...." Accessed November 1, 2023.

are also often duplicated, with separate sensor arrays providing concurrent data for cross-verification.[11] This layering of redundancy not only prevents single-point failures from escalating but also provides a safety buffer during maintenance or repair operations, ensuring that the propulsion system remains operational and safe at all times.

III. Safety Measures

Above all, safety measures that encompass rigorous protocols and protective mechanisms are crucial to prevent accidents and contain hazardous materials, thereby securing the wellbeing of the crew and the environment. Safety measures are similar to the seat belts and airbags in a car, designed to protect occupants in the event of a collision by minimizing the impact and reducing the risk of injury. Similarly, in industrial settings like manufacturing plants or laboratories, safety protocols such as hazard assessments, personal protective equipment (PPE), and emergency evacuation procedures are implemented to safeguard workers from potential accidents or exposure to harmful substances. These measures serve as a crucial line of defense, ensuring the wellbeing of personnel and minimizing the impact of unforeseen incidents on both individuals and the surrounding environment. Safety in nuclear propulsion encompasses a complex set of protocols and engineering controls designed to mitigate risks associated with nuclear materials and radiation. This includes containment structures capable of withstanding extreme conditions, radiation shielding to protect crew and environment, and emergency response systems for quick intervention in case of an incident. Strict operational guidelines and regular safety drills ensure that personnel are well-prepared to handle potential emergencies. Additionally, continuous monitoring systems track radiation levels, reactor core temperature, and structural integrity, providing early warning signals for preventive action. These safety measures are not only essential for preventing accidents but also crucial for ensuring long-term reliability and public trust in nuclear propulsion technologies.

These three principles form the bedrock of reliable and secure nuclear propulsion systems, addressing the unique challenges and risks associated with nuclear technology.

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[11] ResearchGate. "Reliability and redundancy allocation analysis applied to a nuclear protection system." Accessed November 2, 2023.

Risks

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The development of NTP and NEP systems offer exciting prospects for the coming decades of space travel. These systems offer a more efficient method to travel across varying lengths of distances as designed to reduce travel time, energy costs, and are more reliable than past propulsion systems used in rockets. However, these technologies involve the use of nuclear materials and reactors, making them susceptible to catastrophic disasters if they are not maintained and observed with the utmost care.

The government, space agencies, and organizations involved in space exploration must exercise meticulous oversight to ensure the safety, security, and reliability of these powerful systems as they venture into the final frontier. The main challenges that the government and constituents are going to face as the decades progress is balancing the ability of allowing technology to flourish and explore the universe without constraints while still understanding and preventing potentially disastrous events like Kosmos 954 from happening again.

I. Risks of Nuclear Electric Propulsion

A. Kosmos 954

Mid-December, the North American Aerospace Defense Command noticed that Kosmos 954, a Soviet nuclear satellite powered by a nuclear thermal propulsion system, changed its altitude of orbit by 50 miles. After realizing the miscalculation, the Soviets fought a long and hard battle to attempt to steer the satellite back onto its orbit. On the dawn of January 24, 1978, the Soviets lost the fight and Kosmos 954 re-entered the Earth's atmosphere, crashing into the icy terrain of the Northwest Territories in Canada. The crash spanned almost 48,000 sq miles and debris covered areas from the Great Slave Lake to Baker Lake, which included portions of the Northwest Territories, present day Alberta, Saskatchewan, and Nunavut (1). The Canadian and U.S Departments of Defense and the U.S Department of Energy, spent nearly $14 million Canadian dollars in eight months attempting to clean up the remains of Kosmos 954 (or more commonly known as Operation Morning Light) (2).

During the collection and assessment of recovered debris found by the Canadian Atomic Energy Control Board (AECB), they realized that there were two different quantities of radioactive debris that survived the re-entry into the atmosphere. The first quantity of debris was around 65 kg, which included large objects like cylinders, steel plates, and Be rods which has a radioactive contact rate as high as 5 Gy (4). The measurement of gray (Gy) describes the level or amount of radiation that can be absorbed by a person or object. According to the official Occupational Exposure risk measurement from the Massachusetts Government, if a person is in contact with 5 Gy of radiation within a short period of time (which they define as a few hours), it can cause the mass death of the body's cells. The extreme loss of cells in a rapid period of time can be attributed to diarrhea, vomiting, loss of hair and weight, and a fever (3). It is important to note that the person must come into whole body contact for the symptoms described above. The second quantity of debris was around 4000 small radioactive particles with a mGy of 0.1-1.0. This level of radiation is not harmful for a person (4). It is also imperative to note that after eight months, the AECB only recovered about one fourth of the total project debris that still exists in the Northwest Territories of Canada.

While the extent of damage caused by Kronos 954's crash was remarkably limited, particularly due to the satellite fortuitously crashing into a sparsely populated area, the burning of radiation from the satellite's descent into the Earth's atmosphere, and that the pieces that remained did not contain much radiation, we cannot ignore the potential catastrophic event if the conditions were different. What if enough radiation was not absorbed from the satellite during its entry into the atmosphere? What if the satellite crashed into a highly densely populated metropolitan area like Los Angeles or New York? What if the satellite was unfortunate enough to collide into one of the 54 commercially operating nuclear power plants or the 93 power reactors in the U.S? What if there is a more powerful and dangerous rocket that could cause unimaginable and irreparable damage on the people of today and for the coming generations? These ill-fated questions could've become our horrific reality with the launch of the spacecraft, Galileo.

B. Galileo

On October 18, 1989, the Galileo spacecraft was launched from the John F. Kennedy Space Center in Florida with the primary mission of analyzing Jupiter and its moons. Instead of following the traditional path of heading straight towards Jupiter, Galileo made a series of stops at Venus and Earth. It was also tasked at gathering information on any subsequent asteroids it encountered. The spacecraft was equipped with a near-infrared mapping spectrometer to study the chemical, thermal, and structural composition of Jupiter's moons and its atmosphere, an integrated photopolarimeter and radiometer to gather data on thermal energy distribution and atmospheric composition, and an ultraviolet spectrometer for measuring gases, aerosoles, and its ability to detect complex molecules.

C. Mission and Findings

After the fourteen year mission to explore our solar system, Galileo supplied scientists and the world with valuable information on our solar neighbors. Galileo established the presence of lightning on Venus, gathered information on the Earth's Moon's north polar regions, and created a more in depth mapping of the surface of the Moon. Galileo was also the first spacecraft ever to observe and document an asteroid (later named Gaspra) and two years later, it encountered the asteroid Ida. Documenting Ida revealed the first asteroid known to have a strong enough magnetic field to have a natural moon (satellite). The spacecraft documented the breaking of Comet Shoemaker-Levy as it plummeted into Jupiter's atmosphere. Galileo was the first spacecraft to orbit another planet than Earth and after thirty-five trips around Jupiter, Galileo contributed scientists with data on Jupiter's cloud layers, auroras, strom systems, and close up images of the Gas Giant's moons Io, Europa, Ganymede, and Callisto (5).

D. Catastrophic Disaster Avoided

Galileo operated in two different phases. The first phase was to gather data on Venus and Earth's atmosphere, then use the gravitational assist from Venus to loop around Earth and launch itself into Jupiter's orbital system. The second phase was to explore Jupiter and its moons to find possible forms of life. Within the first phase itself, NASA split the mission into five phases: Prelaunch (0), SRB Ascent, 2nd Stage, On Orbit, Payload Deploy, and VEEGA (5). According to the Final Environmental Impact Statement for the Galileo Mission (Tier 2), conducted by NASA, they found that Phase 0 and Phase 5 had the most probable and devastating effects on the environment and people.

a. Phase 0, 1 and 5

NASA defined the probable accidents are "Inadvertent Range Safety System destruct, Fire/explosion" for Phase 0 and Phase 1 and "High-speed reentry of the spacecraft" for Phase 5. In the situation for Phase 0 and Phase 1, if the spacecraft were to explode on the launch pad/a few seconds after the spacecraft launched, the area primarily affected would be the surrounding area of the Kennedy Space Center property as most of the effects will be contained "within 10 km of the accident location". If the plutonium is exposed to the soil, 95% of the plutonium will remain at the top 2 inches of surface soil for at least 10 to 20 years. The vegetation that comes in contact with plutonium and possible vegetation that is produced from the soil is no longer edible for animal or human consumption. While tangerines could be washed and be safe to consume if the plutonium was on the fruit, it is not safe once the fruit grows in soil contaminated by the chemical. The loss of habitable vegetation will not only severely impact the 48 endangered species living in the area, it will also irreparably damage the Orange Country tangerine based economy as none of the produced tangerines would be safe to consume. NASA provided multiple methods of dealing with the environmental fallout, and the estimated cost of cleanup ranged from 0.2 million to 36 million as a cleanup level of 25 mrem/year (The level of 25 mrem/yr is based on the acceptable range of radiation from the National Council on Radiation Protection and Space Measurement(6)). Furthermore, the actual cost of cleanup might be much higher as the Risk Analysis did not consider secondary costs with decontamination plan as: temporary/long term loss of employment, relocation of residents, quarantine/loss of agricultural products, and restrictions on commercial fishing, tourism, real estate, and medical care (source). For Phase 5, the Risk Analysis cited that it would be difficult to calculate the scope of damage from an accident as Galileo retendered Earth. However, they assessed that the impacts would be similar to Phase 0 and 1's effects to the Kennedy Space Center, but to a larger extent. For example, if the accident were to occur over an urban area, the it could force the relocation and displacement of millions of people, the wind could cause plutonium particles to travel and contaminate a larger area, and all land development, tourism, and agricultural work would have to come to an immediate halt until it is deemed safe. The effects of plutonium dioxide are much more severe when considering its interaction with the environment.

b. Impact of Plutonium Dioxide on the Environment

Phase 0, 1, and 5 all share the risk of plutonium interacting with the water supply, one of the most detrimental effects. The magnitude of damage and environmental impact caused by plutonium dioxide is dependent of the availability of the chemical and the mobility, which is directly controlled by a variety of physical and chemical parameters like: "particle size, potential for suspension, and resuspension, solubility, and oxidation state of any dissolved PuO2" (6). Furthermore, the different methods plutonium is exposed: surface contact, ingestion, and inhalation, determines the impact on aquatic and terrestrial ecosystems.

Particle size is incredibly important in considering the impact to environmental resources as the size of the particle affects the rate of dissolution of PuO2 in water and the initial suspension and resuspension (the dissolving of particles from the ground by wind, rain, etc) in aquatic systems and the atmosphere. The rate of dissolution and suspension/resuspension potential dictates the mobility and availability of PuO2 for plants and animals (man included). As the particle size decreases, the easier it is for particles to be easily kept in suspension as facts like gravity and turbulence like wind can cause the particles to persist and remain suspended for long stretches of time. The particle size of plutonium dioxide is also closely correlated with deposition range. Due to the smaller particle's ability to stay suspended within the atmosphere, the smaller particles also are able to travel a much further distance than larger particles. For example, according to the Risk Analysis, the fireball accident from Phase 0 would have the highest deposition of larger particles in the 0 to 10 km range from the accident site while the smallest particles would travel more than 50 km due to the winds.

In aquatic systems, the larger particles will settle at the bottom as sediments. The smaller particles will remain in suspension or they might not even break the surface tension of water. Instead, it will form a thin film on top of the water surface (just as how oil interacts with water) and the film can be transported to the shoreline, which could lead to the destruction of an entirely different ecosystem that is nowhere close to the accident site. Furthermore, the concentration of dissolved plutonium dioxide in water can lead to an increase in pH levels, oxidizing conditions, dissolved organic carbon (DOC concentrations, carbonate concentrations, nitrate concentrations, and sulfate concentrations (6). The increasing or decreasing of the different concentrations can easily cause algae to bloom uncontrollably in bodies of water and completely kill entire ecosystems. Moreover, plutonium dissolves more readily in freshwater and at cooler temperatures(6). Meaning, if there was ever an accident and if plutonium dioxide affected the glaciers or vital fresh water sources like the Great Lakes or water reservoirs, the scope and damages to humans, animals, and entire ecosystems would be incalculable.

Plutonium dioxide particles could also permeate the soil and potentially reach groundwater aquifers (drinking water supplies) through rainfall, animal activity, leaching of particles into the soil, or other disturbance to the soil by man. While aquatic fauna retains higher levels of plutonium contaminated sediment than terrestrial fauna and can cause the unmeasured toxicity to aquatic and land organisms, inhalation is a greater danger for terrestrial fauna. If plutonium dioxide is inhaled, the smaller particles have a high chance of living deep within the lungs. While definitive research has not been conducted to exactly understand the immediate reactions and effects of plutonium dioxide on plants and animals, there are three general types of physical effects organisms experience from the radiation exposure:

1. Somatic injury (damage to the function of exposed organism)
2. Carcinogenic injury (increase of cancers)
3. Generic injury (affects reproductive cells and causes abnormalities in the organism's offspring).

All three effects cause the shortening of lifespan (6).

II. Risks of Nuclear Thermal Propulsion

- What elements are used for NEP? Main one is xenon
    - Noble gas
- Was chosen as a propellant because of the high molecular weight and convenient handling properties
    - It's relatively really safe as according to the research, if the engine was to fall apart in decent, there would not be much of an impact as the levels are not high enough to to cause any problems
        - https://electricrocket.org/IEPC/74_1.pdf
            - Lockheed Martin study on the impact of nep systems, conclusion was that there isn't much of an environmental impact
    - However, most people concur that they are not exactly sure if that will be the case if it ever happens as xenon is highly reactive to oxygen
        - Meaning, if xenon was released in an enclosed room, the oxygen particles would "disappear"
            - https://pubs.aip.org/aip/rsi/article/91/6/061101/957865/Ion-thrusters-for-electric-propulsion-Scientific
                - Study on how xenon acts in different situations and its nature
    - Furthermore, the element is highly reactive so there's scientists are saying there is no telling what would happen if large quantities of it were released at once in the atmosphere
            - But also to this point, the impact might not be large enough for people to be affected by it
    - Scientists are also saying that theoretically, it is not that much of a problem if the system fails in re-entry as the emergency systems would neutralize the xenon
        - Could lead to a bunch of horrible health complications
            - This situation is the most likely and most dangerous during launch
            - https://electricrocket.org/IEPC/IEPC-2007-257.pdf
                - Environmental study by the eclectic rocket propulsion society

What is the big takeaway?

- We do not have enough information on how xenon would react to the atmospheric elements if there was ever a catastrophic event, but that does not mean we should not take the utmost care to ensure that we are prepared for every single worst case scenario.

Current Regulatory Regime

Introduction:

With the ongoing development of next generation nuclear propulsion technology, current regulations and governance need to be analyzed to point out weaknesses and potential threats. That being said, necessary in understanding next generation nuclear propulsion is its nuanced regulations in domestic and international governance, as well as space policy.

I. Domestic Regime

The United States' Code of Federal Regulations grants the Federal Aviation Administration (FAA) the authority to oversee licensing of commercial aircraft, which might include nuclear payloads. *Title 14, Aeronautics and Space*, and *Title 51, National Commercial Space Programs*, outline the specifics of this process and the power that the FAA, as well as the other agencies it collaborates with, have. In order to obtain a license from the FAA to launch, there is a detailed application process, including safety reviews and inspections of aircrafts and their payloads. For the sake of what these authors aim to consider in terms of nuclear propulsion as well as sufficient background, outlined below are existing regulations regarding United States national and commercial nuclear energy, both through legislation and non-legislative bodies.

I. The Commercial Space Launch Act of 1984 (CSLA):

The Commercial Space Launch Act outlines various regulations when it comes to nuclear payloads in the commercial sector. It designates that the "facilitating [of] commercial launches and reentries" is to be overseen by the general authority of the Secretary of Transportation.[12] Broadly speaking, the act designates the Secretary with the role of promoting "public-private partnerships involving the United States Government, State governments, and the private sector to build, expand, modernize, or operate a space launch and reentry infrastructure," while also ensuring safety and working in tandem with missions of the National Aeronautics and Space Administration (NASA).[13]

II. The National Environmental Protection Act of 1970 (NEPA):

The first major environmental law, NEPA, requires government agencies to review the environmental effects and any possible threats that are posed by different actions. The Act mandates that federal agencies provide (1) a detailed review of the environmental impact of proposed actions, (2) unavoidable adverse effects of the action, (3) potential alternatives, (4) short-term and long-term productivity details, and (5) any irreversible commitments that the

[12] The Commercial Space Launch Act of 1984, §50903, 1994.
[13] The Commercial Space Launch Act of 1984, §50902, 1994.

action involves.[14] The Nuclear Regulatory Commission (NRC) works closely with NEPA with regard to nuclear payloads. With the exception of those that are eligible for a categorical exclusion (CATEX), all licensing requires NEPA environmental assessments.[15] According to the NRC, these evaluations cover a broad range of concerns, including "land use, visual resources, air quality, noise levels, aesthetics, geology and soils, surface and groundwater, terrestrial and aquatic ecology, human health, historic and cultural resources, socioeconomics, transportation, environmental justice, postulated accidents, decommissioning, and waste management." Furthermore the NRC works closely with NEPA regulations for reactor decommissioning, renewals of reactor licenses, storage of spent nuclear fuel, in-situ leach uranium milling, as well as license termination. Finally, in its NEPA reviews, the NRC accounts for other environmental legislation like the National Historic Preservation Act, Endangered Species Act, Magnuson-Stevens Act, as well as collaborate with other agencies (more to be discussed later in this section) regarding the Coastal Zone Management Act and the Clean Water and Air Acts.[16]

To ensure that agencies, like the NRC, are abiding by NEPA regulations, the Council of Environmental Quality exists to review the procedures of these agencies and recommend alternative approaches.[17]

While legislative regulations like the CLSA and NEPA outline broad standards and enforcement, governmental agencies play a more active role in the specific regulating processes.

III. The Federal Aviation Agency (FAA) and the Nuclear Regulatory Commission (NRC):

Penal Code 413.7 of the Code of Federal Regulations requires that those seeking to launch payloads must file an application with the FAA including all relevant data including an updated description of the type of payload.[18] While this is a federal requirement that must be done in order to obtain a license, the FAA's Advisory Circular outlines steps that applicants can take in order to obtain more efficient approval, however, it is not legally binding and conformity of these steps is voluntary – an issue later to be brought up in this section. A pre-application process can prepare applicants with potential issues and concerns that might arise during the actual application process.[19] By outlining these concerns or potential failures, applicants can fix them prior to the formal application. Details regarding the payload should be included in a pre-application, which as new information arises, is encouraged to be continually updated.

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[14] "NEPA: National Environmental Policy Act." *NEPA | National Environmental Policy Act.* Accessed November 9, 2023. https://ceq.doe.gov/.

[15] "National Environmental Policy Act at the NRC." *NRC Web* October 20, 2021. Accessed November 9, 2023. https://www.nrc.gov/about-nrc/regulatory/licensing/nepa.html

[16] "National Environmental Policy Act at the NRC." *NRC Web* October 20, 2021. Accessed November 9, 2023. https://www.nrc.gov/about-nrc/regulatory/licensing/nepa.html

[17] "NEPA: National Environmental Policy Act." *NEPA | National Environmental Policy Act.* Accessed November 9, 2023. https://ceq.doe.gov/.

[18] Federal Aviation Administration. (August 10, 2023). *Applying for FAA Determination on Policy or Payload Reviews* (Advisory Circular 450.31-1). Kelvin B. Coleman.

[19] Federal Aviation Administration. (August 10, 2023). *Applying for FAA Determination on Policy or Payload Reviews* (Advisory Circular 450.31-1). Kelvin B. Coleman.

Finally, the FAA oversees the type of payload which includes: satellites, cargo, or those on spacecraft.[20]

The most important aspect of the application process is obtaining launch licenses; of which are distributed by the FAA upon the completion of others being acquired prior. Once this is done, the license is sent to the Secretary of Transportation for overall approval. It should be noted that the previously mentioned Title 14 and 51 of the Code of Federal Regulations include, in much more detail than these authors can cover, the various steps needed to be taken and the types of licenses obtained. However, in terms of next-generation nuclear propulsion and the concerns it raises for national security, those of particular interest are: the commercial space vehicle licenses and nuclear payload licenses.

The FAA oversees the distribution of commercial space licenses. To obtain these the FAA determines the training qualifications of the aircraft crew as well as the distribution of launch and reentry, site-specific, and operation licenses.[21] In addition to this, the NRC, in alignment with the previously discussed regulations put in place by NEPA, issues licenses specific to the use of nuclear material. With this in mind, prior to issuing a license for the launch of aircraft, the NRC conducts payload reviews, requiring that:

a. The payload is named and its function identified;
b. A physical description is given (i.e., weight, composition, and dimensions);
c. The owner of the payload is separate from the individual requesting the review;
d. If the payload is owned by a foreign entity, they must be specified.
e. The types and amounts of hazardous materials are defined;
f. Explosive and other materials found on the payload are identified;
g. Both the orbits, if applicable, are listed and the times of transit are as well;
h. Identification of when the payload will no longer be under the licensee's control;
i. Lifespan and plan of disposal are outlined;
j. Whether encryption associated data is on the payload;
k. Additional information regarding health, safety, and national security is given.

The NRC requires similar, only slightly more limited, regulations for the reentry of nuclear payloads.[22] That being said, once a license is obtained it is up to the discretion of the Secretary of Transportation whether the payload is capable of launch or reentry (taking into consideration safety and national security).[23]

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[20] Federal Aviation Administration. (August 10, 2023). *Applying for FAA Determination on Policy or Payload Reviews* (Advisory Circular 450.31-1). Kelvin B. Coleman.
[21] "Getting Started with Licensing." *Federal Aviation Administration* June 21, 2023. Accessed October 28, 2023. https://www.faa.gov/space/licenses/licensing_process/
[22] "Licensing of Medical, Industrial, and Academic Uses of Nuclear Materials" *NRC Web* December 2, 2020. Accessed October 28, 2023. https://www.nrc.gov/materials/miau/licensing.html.
[23] The Commercial Space Launch Act of 1984, §50902, 1998.

In terms of space, the NRC works with other agencies – as is the case for most domestic regulations – to review the safety of nuclear payloads on spacecraft. The Department of Energy (DoE), Department of Defense (DoD), and NASA have established requirements for the construction and operation of nuclear propulsion systems, of which are informed through international entities like the United Nations and the International Atomic Agency.[24] The NRC's Interagency Nuclear Safety Review Board (INSRB), oversees nuclear system launches directed to space and their safety. It includes experts from various different agencies and representatives from the DoE, DoD, Department of State, Department of Transportation, and Environmental Protection Agency.[25]

Particularly important when it comes to nuclear payloads and next generation nuclear propulsion is the potential threats it can pose to national security both domestically and abroad. Because of this, in adherence with Title 51 of the Federal Code of Regulations, the FAA is responsible for determining whether the desired launch poses United States national security threats or disregards foreign policy.[26] To do this, it collaborates with other agencies.

IV. Interagency Regulation:

While the FAA, NRC, and Secretary of Transportation dominate most of the regulation regarding aircraft systems – both space-ferring and not – as well as nuclear payloads, there are a plethora of other agencies that all have a hand in oversight.[27]

a. The Department of Defense oversees "issues to U.S. national security" and works with the FAA to consider whether or not launches or reentries pose threats to national security or international obligations.
b. The Department of State oversees "issues related to U.S. foreign policy or international obligations."
c. The National Aeronautics and Space Administration who oversees "the effects of commercial space activities on NASA interests."
d. The National Nuclear Security Administration who "checks to see if material in the system poses a nuclear proliferation concern for payloads containing exposure levels of nuclear materials."
e. The Nuclear Regulatory Commission responsible for "examin[ing] commercial use or possession of nuclear material for payloads containing exposure levels of nuclear materials."

[24] "Navigating Space Nuclear Safety: The Role of the Nuclear Regulatory Commission." *NRC Web* October 20, 2023. Accessed November 9, 2023. https://www.nrc.gov/about-nrc/regulatory/research/space-nuclear-safety.html

[25] "Navigating Space Nuclear Safety: The Role of the Nuclear Regulatory Commission." *NRC Web* October 20, 2023. Accessed November 9, 2023. https://www.nrc.gov/about-nrc/regulatory/research/space-nuclear-safety.html

[26] Federal Aviation Administration. (August 10, 2023). *Applying for FAA Determination on Policy or Payload Reviews* (Advisory Circular 450.31-1). Kelvin B. Coleman.

[27] Federal Aviation Administration. (August 10, 2023). *Applying for FAA Determination on Policy or Payload Reviews* (Advisory Circular 450.31-1). Kelvin B. Coleman.

f. The Office of the Director of National Intelligence that oversees "issues related to U.S. national security" as well.

II. International Regime

Much more difficult to regulate, for geopolitical challenges and interests, is the international regulation of nuclear propulsion systems. The United States' regulation offers multi agency and legislative oversight, however because of these difficulties, international regulation remains broad and nearly impossible to enforce.

I. Agencies with Relevant Interests:

The International Atomic Energy Agency (IAEA) oversees the safety of nuclear installations through safety standards. The IAEA provides the Integrated Regulatory Review Service (IRRS) to member states with nuclear installations.[28] However, this is not applicable to the use of nuclear as a propulsion mechanism and their jurisdiction is limited to nuclear plants.

II. International Collaboration and Treaties:

The International Atomic Energy Agency (IAEA) oversees the safety of nuclear installations through safety standards. The IAEA provides the Integrated Regulatory Review Service (IRRS) to member states with nuclear installations.[29] However, this is not applicable to the use of nuclear as a propulsion mechanism and their jurisdiction is limited to nuclear plants.

International collaboration on nuclear energy and space is done through the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS).[30] It oversees five international treaties that govern space law as well as issues resolutions that uplift the peaceful use of space. Also relevant here is the United Nations First Committee which concerns itself with disarmament and international security, with special attention to nuclear energy.[31]

Following the end of the Cold War, in 1967 the United States, United Kingdom, and Soviet Union, aware of the potential threats and instability nuclear technology proposed, signed the Outer Space Treaty, aiming to maintain space as a realm for peaceful relations and scientific investigations, while not entirely stunting their technological growth. Article I emphasizes that

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[28] "Nuclear installations." 2016. *IAEA* June 8, 2016. Accessed October 28, 2023. https://www.iaea.org/topics/nuclear-installations
[29] "Nuclear installations." 2016. *IAEA* June 8, 2016. Accessed October 28, 2023. https://www.iaea.org/topics/nuclear-installations
[30] Space Foundation Editorial Team. 2023. "International Space Law." *Space Foundation* September 27, 2023. Accessed October 30, 2023. https://www.spacefoundation.org/space_brief/international-space-law/#:~:text=There%20are%20five%20international%20treaties,of%20Outer%20Space%20(UNCOPUOS).
[31] Foye, Heather, and Gabriela R. Hernández. December 2022. "UN First Committee Calls for ASAT Test Ban." Arms Control Association. Accessed October 31, 2023. https://www.armscontrol.org/act/2022-12/news/un-first-committee-calls-asat-test-ban#:~:text=The%20United%20States%20launched%20its,of%20debris%20to%20litter%20space.

the exploration of outer space be for all countries "irrespective of their degree of economic or scientific development," making it open for all countries, regardless of their international dominance, to explore.[32] It is important for its application of the international targeting law.[33] Thus, overall, weapons in space are regulated by three broad classifications: how enemies are injured, the scale of injury caused, and whether or not they are indiscriminate.[34] The Outer Space Treaty is likely most important, however, for its limitations on nuclear technology in space, to which it prohibits the placement of nuclear weapons and those of mass destruction both in outer space and on celestial bodies.[35]

The Nuclear Non-Proliferation Treaty concerns itself with the peaceful use of nuclear energy and the right of party nations to develop and research nuclear energy technologies so long as they adhere to the treaty's limitations.[36] Article IV.1 of the treaty extends the right to all party nations 'without discrimination.'[37]

The Nuclear Test Ban has never been formally passed by all United Nations members, however, it is introduced to the UN First Committee annually. With 91 nations having signed the treaty, and 68 ratifying it, the treaty attempts to have nations commit to not participate in nuclear weapons technology.[38] That being said, the nine countries believed to possess the nuclear technology for weapons – China, France, India, Israel, North Korea, Pakistan, Russia, the UK, and the United States – have not signed it as of October 6, 2021.[39]

III. United Nations Resolutions and the United Nations Office for Outer Space Affairs (UNOOSA):

The United Nations General Assembly Resolution 47/68. Principles Relevant to the Use of Nuclear Power Sources In Outer Space as well as the Resolution 75/36. Reducing Space threats through norms, rules and principles of responsible behaviors recognize and establish the technological advancement being made overall, as well as in nuclear energy. They attempt to outline goals and concerns all nations should bear in mind when launching technology into space. Resolution 47/68 specifically details international law, criteria of safe use, and

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[32] The Outer Space Treaty of 1966
[33] Boothby, Bill. 2017. "Space Weapons and the Law." International Law Studies vol 93:180-214.
[34] Boothby, Bill. 2017. "Space Weapons and the Law." International Law Studies vol 93:180-214.
[35] "Outer Space." *United Nations Office for Disarmament Affairs.* Accessed October 16, 2023.https://disarmament.unoda.org/topics/outerspace/#:~:text=This%20includes%20that%20the%20exploration,appropriation%20or%20claims%20of%20sovereignty.
[36] ElBardei, Mohamed, Edwin Nwogugu, and John Rames. 1995. "International law and nuclear energy: Overview of the legal framework." *International Atomic Energy Agency Bulletin (Austria)* 37(3): 16-25.
[37] ElBardei, Mohamed, Edwin Nwogugu, and John Rames. 1995. "International law and nuclear energy: Overview of the legal framework." *International Atomic Energy Agency Bulletin (Austria)* 37(3): 16-25.
[38] Foye, Heather, and Gabriela R. Hernández. December 2022. "UN First Committee Calls for ASAT Test Ban." *Arms Control Association*. Accessed October 31, 2023. https://www.armscontrol.org/act/2022-12/news/un-first-committee-calls-asat-test-ban#:~:text=The%20United%20States%20launched%20its,of%20debris%20to%20litter%20space.
[39] Foye, Heather, and Gabriela R. Hernández. December 2022. "UN First Committee Calls for ASAT Test Ban." *Arms Control Association*. Accessed October 31, 2023. https://www.armscontrol.org/act/2022-12/news/un-first-committee-calls-asat-test-ban#:~:text=The%20United%20States%20launched%20its,of%20debris%20to%20litter%20space.

open-communication,[40] while Resolution 75/36 establishes international norms to avoid threats from the ever-developing technological world.[41]

Limitations and Loopholes:

I. Domestic Regulation:

With the exception of the acquisition of the launch license (and the steps taken to obtain one), the steps listed in the FAA's Circular Advisory are not required, nor are they legally enforceable by any means. Nuclear proliferation is inevitable, especially in the context of space exploration, thus perhaps what is needed is for the processes to be made more strict and for things like pre-application processes, to be enforced. For private companies, things like FAA safety standards and requirements, are obstacles that they would rather avoid or entirely ignore. Consider SpaceX and its launch of the Falcon 9 in August 2022. The company "did not submit launch collision avoidance analysis trajectory data to the FAA prior to the launch."[42] Though subject to a proposed civil penalty of $175,000, because SpaceX is spending its own money – and this is the presumed case for many other private companies – the fine they incur is an afterthought to the information they gain. In many ways, private companies who finance their own research have no obligation to take FAA advice into consideration. This raises questions as to how effective current policies are.

While there is relatively cohesive oversight from agencies when it comes to licensing, the consideration of space and the safety challenges it might present go fairly unconsidered. One example of this is that although the FAA sets specific training qualifications, Congress has placed limitations on their ability to regulate in space and they, therefore, are limited in their capacity to protect the safety of individuals on board spacecraft. Furthermore, the FAA's nuclear propulsion regulations are applied to aircraft, not specifically spacecraft, thus stricter wording might be in order. The NRC's regulation capacity is similarly limited in terms of space given that it has focused substantially on terrestrial pursuits making nuclear propulsion's application to spacecraft a concern.

II. International Regulation:

The language within these treaties is problematically vague when it comes to the possibilities of next-generation nuclear propulsion. Both the Outer Space Treaty and the Nuclear Non-Proliferation Treaty reference the right to use nuclear energy for "peaceful purposes." Though, the two fail to further define what this means. Definitions of what aligns with a peaceful use of nuclear technology might perhaps increase international security as the technology

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[40] *Principles Relevant to the Use of Nuclear Power Sources In Outer Space*, GA Res 47/68, UN GAOR, 35th session, Agenda Item 72, Supp No. 20 A/Res/47/68.

[41] *Reducing space threats through norms, rules and principles of responsible behaviours*," GA Res 75/36, UN GAOR, 75th session, Agenda Item 101(b), Supp No. 20 A/Res/75/36.

[42] Armstead, D. Eden, *Notice of Proposed Civil Penalty*. Letter. Washington DC. From Federal Aviation Administration. https://www.faa.gov/sites/faa.gov/files/afn-20230217-spacex-2022WA990004-notice-of-proposed-civil-penalty.pdf. Accessed October 28.

continues to advance, so there is more international agreement as to what is a peaceful use of a technology. Similarly, lacking in these international regulations are clear definitions of weaponry. The new age of technology has blurred the lines of what constitutes a weapon, and nuclear propulsion further complicates it. The United States' Department of Security does determine whether or not launches and reentries within the United States adhere to international law outlined in Article IX of the Outer Space Treaty.[43] However, nowhere in The Outer Space Treaty does it mention the use of nuclear propulsion and its limitations as a weapon or on spacecraft. The same can be said for Article IV of the Outer Space Treaty – that of which deals with the prohibition of nuclear weapons in space.

Because of these gaps mentioned above, the enforcement of international nuclear regulation is challenging, if at all, ever effective. Competing countries have no incentive to communicate with one another if it means falling behind in nuclear technology development. Following the Cold War, the United States and the Soviet Union decided against Anti-satellite weapons (ASATs) because of the intense danger they posed.[44] Up until 2005, 2006, and then 2010 there had been zero ASATs tested, until China performed what they referred to as a "missile defense test," intercepting a ballistic missile from the atmosphere.[45] Despite this false label, the technologies and methods used have been recognized to heavily resemble those of ASAT tests. This was the direct result of the lack of definitions of what constitutes a weapon and the strict enforcement of what is sent to space that permits nations to deliver dangerous weapons into orbit under a false goal. It should be noted that the United States responded to this by shooting down a satellite of their own, however, made it clear internationally what they were doing.[46] More recently, Russia conducted an ASAT test in November 2021, targeting a Russian satellite that had been in orbit since 1982.[47] Missiles carry with them and deliver nuclear payloads to whatever they are targeted at, thus, although they are not powered by nuclear propulsion, they provide an ample case study of the dangers that nuclear technologies in space can pose to international security. As of April 2022, the United States led an initiative to ban ASATs in the ASAT Test Ban, with seven other countries following suit (New Zealand, Japan, Germany, the United Kingdom, Switzerland, Australia, and South Korea). That being said, however, neither the Soviet Union nor China have joined the initiative – the only two other nations to participate in ASAT tests – and the current legal framework is not capable of ensuring adherence to the regulation.

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[43] Federal Aviation Administration. (August 10, 2023). *Applying for FAA Determination on Policy or Payload Reviews* (Advisory Circular 450.31-1). Kelvin B. Coleman.
[44] Samson, Victoria. 2014. "Space Technology Cooperation and Its Effect on National Security and International Stability." In *Space Technology Development*, edited by Park Jiyoung, 10-32.
[45] Samson, Victoria. 2014. "Space Technology Cooperation and Its Effect on National Security and International Stability." In *Space Technology Development*, edited by Park Jiyoung, 10-32.
[46] Samson, Victoria. 2014. "Space Technology Cooperation and Its Effect on National Security and International Stability." In *Space Technology Development*, edited by Park Jiyoung, 10-32.
[47] Foye, Heather, and Gabriela R. Hernández. December 2022. "UN First Committee Calls for ASAT Test Ban." *Arms Control Association*. Accessed October 31, 2023. https://www.armscontrol.org/act/2022-12/news/un-first-committee-calls-asat-test-ban#:~:text=The%20United%20States%20launched%20its,of%20debris%20to%20litter%20space.

International treaties and and United Nations resolutions, although with well-intent and expressed peaceful sentiment between nations, in terms of nuclear propulsion, do little to effectively regulate launches. United Nations resolutions, specifically, hold no legal enforcement, but are rather "formal expressions of the opinion or will of UN organs" and thus carry with them no enforceable consequence for violating them.[48] Treaties, though signed by countries with the expectation that they abide by them, too, carry no legal enforceability. For the sake of national security and internal safety, the increasing use of and desire for nuclear propulsion, especially developments in the private sector, prompt a need for more direct and enforceable international regulations.

[48] "About UN Documents." *United Nations*, United Nations, Accessed 16 Oct. 2023. https://research.un.org/en/docs/resolutions#:~:text=UN%20 resolutions,in%20annual%20 or%20 sessional%20 compilations.

Limitations of Current Regulatory Regime

The sudden surge of nuclear propulsion technology in space has developed so quickly that it has outpaced the development of corresponding regulating policies. As nuclear space technology advances, we will likely see a growing number of experiments and deployment of rockets containing nuclear reactors, raising safety concerns in the absence of regulatory oversight. Current policies are simply insufficient for the regulation of the in-space nuclear propulsion happening today. In this section, we present a detailed overview of the insufficiencies of current domestic and international regimes, and the shortcomings of especially the current major space and nuclear power regulators: FAA, NRC, IAEA, and UNOOSA (United Nations Office for Outer Space Affairs).

DOMESTIC REGIME

I. Limitations of Domestic Regime

In the United States, a company or entity must adhere to strict standards, apply for and receive multiple approvals from different agencies, and document financial health in order to send an object into space. They must also understand the international rules and regulations of outer space in addition to the United States.

i. FAA

The FAA is a branch governing federal aviation and is a main player in space regulation in the U.S.. The FAA has also incorporated policies regarding human space flight and the commercial sector of space operation. In these regulations, the FAA requires rocket launchers to obtain a vehicle operator's license and subsequent rocket case-based approvals. The FAA grants these licenses for commercial space operations, conducts safety inspections, ensures vehicles designed for human space transport during launches or reentries meet their intended requirements, and regulates the qualifications and training of flight crews.

While the FAA has a clear concern for space activities, Congress has placed limitations on their authority in space. For example, the FAA is prohibited from regulating the safety of the individuals on board the spacecraft. So, for example, in the event of a nuclear reactor emergency, the individuals are not protected by the FAA (4). Moreover, they do not mention regulations around nuclear propulsion technology at all for spacecraft, only aircraft. The FAA has nuclear regulations for aircraft vehicles around the following: 1) Avoidance of areas of nuclear radiation 2) Notification of unusual aircraft activities in the vicinity of nuclear power plant sites and 3) Obtainment of a general license is for the export of nuclear reactor components (5). As you can see, these nuclear regulations are not extremely applicable to spacecraft and space. If an entity wishes to send an object with a nuclear reactor to space, all they would need to do in addition to the regular process is have the reactor verified by the NRC (Nuclear Regulatory Commission). However, this agency typically handles terristrial matters.

ii. NRC

The NRC licenses and regulates the use of nuclear reactors, materials, and waste in the U.S.. However, as mentioned above, the NRC has predominately terrestrial pursuits. Therefore, the NRC may only be involved if there are concerns related to the handling, transportation, or use of nuclear materials on the ground. Given the unique scientific properties of a space environment including microgravity and radiation, regulating nuclear technology in space requires a certain degree of space-science knowledge the NRC may be unfamiliar with. In other words, if the NRC deems a reactor “safe” on Earth, it does not mean that it would be safe in space. So, while the NRC may also be consulted to ensure nuclear material compliance, we question the sufficiency of its application to nuclear technology in space. Understanding the intricacy of a space environment is essential when regulating nuclear technology in space, and falls out of the NRC’s usual scope.

The issue with these organizations is that they are limited to U.S. operations and therefore lack the ability to regulate internationally. However, if the FAA and NRC can incorporate better nuclear policy, including policy related to nuclear propulsion for spacecraft, we have the power to lead by example with hopes that other space-faring countries will follow our lead.

II. Limitations of International Regime

i. IAEA

The IAEA is responsible for promoting the safe and responsible use of nuclear technology. An important note is official regulation is the responsibility of individual national authorities rather than the IAEA. While they are the leading agency for atomic energy regulation on Earth, only a small sector of the IAEA is dedicated to policing the use in space. Currently, the IAEA adresses advancements regarding nuclear technology and even has a platform (Unified System for Information Exchange - USIE) for countries to exchange urgent communication during a nuclear emergency. In such an emergency, there is some regulatory framework from the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN) on coordinated actions. However, their regulations are only suggestions, and official regulation falls back onto the entity or individual’s national authority.

ii. UNOOSA

As the primary United Nations entity responsible for space-related matters, the United Nations Office for Outer Space Affairs (UNOOSA) holds distinct obligations outlined in the JPLAN. UNOOSA also maintains a registry of objects launched into space, however, only 86% of flight elements launched in space have been registered with UNOOSA. This means that 14% of satellites, probes, landers, crewed spacecraft or space station flight elements would not use the

platform for nuclear emergency communication or the framework from JPLAN on coordinated actions in the event a nuclear emergency occurred. (1).
The Outer Space Treaty, adopted by the United Nations General Assembly in 1966 and including some of the key spacefaring nations (U.S., Russia, and China) aims to promote the peaceful use and exploration of outer space and prevent its militarization. However, it falls short when comprehensively addressing nuclear technology in space. Currently, it prohibits the placement of nuclear weapons in outer space and on celestial bodies. However, defining what constitutes a weapon has been proven to be extremely tricky, and therefore difficult to regulate. Nuclear propulsion certainly has the potential to be used as a weapon and the United Nations holds no legal enforcement on this matter (3). So, in the absence of clear regulations on space weaponry, entities have the freedom to launch objects into space without significant repercussions, potentially harming astronauts, other nations with fewer space capabilities, and Earth.

Recommendations and Implementation

Given the critical importance of resiliency, redundancy, and safety in nuclear propulsion, it becomes evident that these principles must be at the forefront of any policy discussions and decisions in this field. The intricate balance of ensuring operational stability, preventing system failures, and maintaining the highest safety standards calls for comprehensive and forward-thinking policies. Implemented policies should not only reinforce current practices but also anticipate future challenges, integrating advancements in technology and evolving safety protocols. As we move towards framing these policy recommendations, it is crucial to recognize that the effectiveness of nuclear propulsion systems is deeply intertwined with these foundational principles. The upcoming recommendations aim to further strengthen these aspects, ensuring that nuclear propulsion remains a safe, reliable, and resilient technology in both civilian and military applications. This proactive approach in policy-making is not just a matter of regulatory compliance, but a commitment to upholding the highest standards of safety and performance in the realm of nuclear propulsion.

I. *Recommendation One:* Tracking and Safeguarding

Nuclear propulsion necessitates the implementation of robust tracking systems, akin to those utilized within terrestrial nuclear power facilities, to ensure the utmost safety and performance. These advanced monitoring frameworks are indispensable for real-time surveillance of critical parameters, including radiation levels, core temperatures, and the structural integrity of the system.[49] Such vigilance is pivotal for proactive maintenance, facilitating timely repairs and

[49] "Design of a Nuclear Monitoring System Based on a Multi-Sensor Network." MDPI. Accessed November 6, 2023.

preempting system failures. Furthermore, tracking systems play a crucial role in emergency management by detecting early signs of malfunction, thereby enabling prompt activation of safety measures and preserving detailed operational records for future analysis and system refinement. Drawing parallels to terrestrial counterparts, these systems mirror the stringent protocols mandated by regulatory entities such as the International Atomic Energy Agency (IAEA), which emphasizes the need for continuous monitoring and control to uphold safety standards.

Safety protocols within the realm of nuclear propulsion encompass meticulously crafted plans and procedures that are foundational to operational security and emergency responsiveness. These protocols dictate the standardization of operating procedures, ensure a uniform approach to the reactor's operation, delineate comprehensive emergency action plans, and mandate extensive training and regular drills to ensure crew readiness. Such regimented preparedness is critical for aligning with rigorous international and national regulations governing nuclear technology applications, as embodied by oversight bodies like the U.S. Nuclear Regulatory Commission (NRC). In crafting a regulatory framework for nuclear propulsion, a balance is extremely important; it should be stringent enough to enforce safety and protect public and environmental health, yet flexible to adapt to the technological nuances and novel challenges posed by nuclear propulsion.[50] Moreover, the framework must be resistant to the pitfalls of over-regulation and bureaucracy that could hinder innovation or diminish effectiveness, underscoring the need for a dynamic, transparent, and accountable regulatory architecture that evolves in tandem with advancements in propulsion technology.

Recommendation Two: Nuclear Propulsion for Civilian Purposes vs. Military Purposes

I. Differentiate the regulatory needs for civilian and military contexts.

The regulatory frameworks governing civilian and military nuclear propulsion are distinct, shaped by their differing operational contexts and objectives. Civilian applications, such as commercial shipping or space exploration, require regulations that emphasize public safety, environmental protection, international standards compliance, liability considerations, and transparency to foster public trust. These are overseen by various international and national bodies and entail rigorous public and environmental oversight.[51] Military nuclear propulsion, on the other hand, is guided by national security imperatives, prioritizing operational security, flexibility, and self-sufficiency. The oversight is typically internal and classified, focused on the unique needs of defense operations and is less transparent due to the sensitive nature of national security. Both sectors, however, uniformly adhere to the overarching principles of safety and

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[50] Adkisson, Kelsey, and Pnnl. "Real-time monitoring tool speeds up advanced nuclear reactor development." Phys.org. Accessed November 12, 2023.
[51] International Atomic Energy Agency. "Regulatory framework for nuclear installations." Accessed November 6, 2023.

non-proliferation, albeit through different regulatory mechanisms and with varying degrees of public disclosure.

II.The potential dual-use nature of nuclear propulsion technologies.

Nuclear propulsion technologies exhibit a dual-use character with applications spanning civilian and military domains, offering benefits such as enhanced maritime mobility with reduced environmental impact, and prolonged, fuel-independent space exploration. However, this same technology underpins military assets like submarines and aircraft carriers, granting them formidable operational advantages. This duality raises significant proliferation concerns, as advancements in peaceful applications could inadvertently bolster military capabilities or vice versa, especially if materials like highly enriched uranium are misdirected. Consequently, this necessitates stringent international regulatory frameworks and non-proliferation treaties to mitigate risks, ensure transparent use, and maintain a clear demarcation between peaceful and military endeavors, while also allowing for the cross-pollination of beneficial technological innovations across both sectors.