Establishing Safety Zones on the Lunar Surface for Space Nuclear Power

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Honor Pledge

On my honor as a student, I have neither given nor received unauthorized aid on this assignment.

Savannah Horton

Glossary

Artemis Accords: an international agreement created by NASA, signed in 2020, that seeks to promote peaceful use of the Moon, Mars, and other celestial bodies.

Celestial Bodies: any naturally occurring physical object outside of Earth's atmosphere. Includes planets, moons, and asteroids.

Federal Aviation Administration (FAA): federal regulating body responsible for approving launches to space and ensuring that parties are adequately insured.

Harmful Interference: activity by one actor that disrupts or poses a safety hazard to the activity of another actor.

Lunar Night: the 14-day period when night falls on the moon and temperatures can plummet to as low as -280 F.

Mission Operators: the actor(s) involved with the conducting the launch, space activity, and utilization of payloads on a space mission.

Moon Heritage Law: laws that require non-interference of historic landing sites on the Moon.

National Aeronautics and Space Administration (NASA): federal administration that assisted in the creation of the Artemis Accords and has previously been the sole entity in the United States to engage in activity on the Moon.

Non-interference: a principle in the Artemis Accords in which actors agree to not interfere with the environment or the activities of another party.

Outer Space Treaty (OST): an international law completed in 1967 that states that outer space is not subject to national appropriation by claim of sovereignty, use, or occupation.

Planetary Protection Law: legal principles that protect that lunar surface from contamination.

Radioisotope Power Systems (RPS): devices that are powered by spent nuclear fuel that produce electrical and thermal energy as the radioisotopes decay.

Radioisotope Thermal Generators (RTG): devices that convert heat from the decay of radioactive material into electricity that serves as a source of power.

Radioisotope Heater Units (RHU): devices that utilize the heat produced from decaying radioactive material to keep technology from freezing in space exploration missions.

Safety Zones: the area on a celestial body in which the activities of private actors or States could reasonably cause harmful interference to the environment or another party.

Space Nuclear Power: technologies that produce heat and electricity on the lunar surface through radioactive decay or fission that enable missions to continue operations and survive lunar night.

Executive Summary

The rise of private sector space exploration and NASA's commitment to the Artemis Program that will land the first woman and first person of color on the Moon signify a new era of aerospace policy and regulation (Potter, 2020). With the publication of the Artemis Accords in 2020, safety zones on the lunar surface serve as a means of governing activity on the lunar surface and reducing harmful interference between actors as they conduct critical research. Space exploration requires power, which makes the work of my client, Zeno Power, so necessary. Zeno Power's innovations to Radioisotope Power System (RPS) technology is not just poised for novel technological demonstrations, but regulatory demonstrations as well. This report proposes three alternatives that Zeno Power can pursue and advocate for that align their mission with the principles of the Artemis Accords.

Commercial Radioisotope Power Systems provide a unique opportunity to make the Artemis Accords' proposals for safety zones a reality because reducing liability and preventing harmful interference is necessary for the field of space nuclear power. This analysis looks at three alternatives for how safety zone proposals ought to be conducted broadly and evaluates these proposals based on the needs of Zeno Power. As such, the alternatives include:

1. Operator-led proposals for safety zones

2. Safety zones to be assigned and regulated by the FAA

3. Model tiered approaches of space nuclear launch approvals for safety zones

After assessing these methods on their effectiveness, equity, risk-mitigation, and feasibility, it is recommended that Zeno Power advocate for and utilize operator-led proposals for establishing their own safety zones. This recommendation works proactively, as Zeno Power can conduct novel regulatory demonstrations alongside technological demonstrations and use ethical space conducts as a competitive-advantage against other industry competitors. Additionally, this research into various types of safety zone requirements will allow for Zeno Power to preempt federal regulation and have prepared insights on how new policies may affect them and adapt mission proposals as necessary. Implementation of this option will use successful case studies on novel technological demonstrations as a guideline for how to best balance innovation and incremental policy regulations. By using Radioisotope Power Systems as a means to demonstrate successful space policies and norms, Zeno Power will be able to forge a new regulatory pathway that promotes innovation, safety, and reduces harmful interference on the lunar surface.

Problem Statement

Nuclear power on celestial bodies poses new challenges regarding how States ought to regulate land use in space. The Artemis Accords provide guidelines for States to establish safety zones on celestial bodies, yet provide an unclear definition for how these zones will be regulated. Since space nuclear poses novel risks of harmful interference by outside actors, these zones ought to be defined and regulated based on the types of conduct that occurs within them.

Client Relevancy

In order to have safe and successful lunar missions that fulfill the objectives of NASA's Artemis Program, there is a need for power on the lunar surface that provides adequate heat and electricity to rovers, astronaut equipment, and other research infrastructure. The analysis of existing safety zones and property law in space is critical to my client's mission. Zeno Power seeks to develop and implement next-generation radioisotope power systems that convert the heat from recycled nuclear waste into electricity. Their design allows for long-endurance, reliable power to be supplied to critical infrastructure where fuel supply chains are complex or non-existent. Although Zeno's systems are intended for space, deep sea, and Arctic use, this Applied Policy Project will focus on the broader question of cislunar applications and how space nuclear power (SNP) will be governed by a State according to the norms of the current Artemis Accords.

Creating more robust space law and clearly defining safety zones has impacts that extend beyond just Zeno Power. Radioisotope power systems can be an effective use of policy demonstrations for establishing and regulating safety zones. The use of RPS is precedented on the lunar surface and can be used to begin to create regulations for safety zones that contain externalities like radiation on a smaller scale compared to larger scale reactors. The precedent and current existence of RPS on the lunar surface makes this a streamlined regulatory process. Using RPS as a means to demonstrate the feasibility of safety zones on the lunar surface is an efficient way to gauge the overall effectiveness of safety zone proposals. Through researching the efficacy and feasibility of lunar safety zones, Zeno Power aligns itself with its company values that simultaneously promote transparency, sustainable development, and the preservation of space heritage while operating within the private sector. Zeno Power intends to create policies that promote innovation that power critical missions while also engaging in regulatory procedures that result in equitable and safe missions.

Background

Artemis Accords

Historically, space exploration has only been conducted by international agencies like NASA, Russia's State Corporation for Space Activities, and the European Space Agency. However, the rise of private sector space exploration has broadened the scope and magnitude of the problems that arise from a lack of legal and regulatory consensus. Although space has been traditionally governed by international treaties like the Outer Space Treaty of 1967, they lack enforcement mechanisms. The laws established under the Outer Space Treaty (OST) state that outer space is not subject to national appropriation by claim of sovereignty, use, or occupation. Three relevant laws from the Outer Space Treaty for this analysis are that States shall be responsible for national space activities whether carried out by governmental or non-governmental entities; States shall be liable for damage caused by their space objects; and that States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner (UNOOSA, n.d.). Further, the OST makes space an area beyond national jurisdiction, meaning that hard law constraints from other treaties apply in space to the same degree as they are applied on Earth. In this context, it means that state obligations under the nuclear non-proliferation treaty also apply in space (A. Gilbert, personal communication, April 1, 2022).

Most recently, the Artemis Accords are an international agreement created under the guidance of NASA and the US State Department that establishes norms for space conduct in novel exploration activities in deep space. As of completion of this report, the Accords have been signed by 18 different countries and remain indefinitely open for signature (Potter, 2020). Unlike the Outer Space Treaty, the Artemis Accords operate under soft law and provide guiding principles rather than creating international laws Signed in 2020, the Artemis Accords seek to promote peaceful use of the Moon, Mars, and other celestial bodies. The Artemis Accords are a government-to-government agreement that affirms the importance of the 1967 Outer Space Treaty and other supporting international commitments such as the 1972 Convention on International Liability for Damage Caused by Space Objects, and the 1975 Convention on Registration of Objects Launched into Outer Space. The Artemis Accords also aligns with the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), which intends to further efforts toward a global consensus on critical issues regarding space exploration and use (NASA, 2020). One way that the Artemis Accords promotes this goal is through "non-interference" mechanisms like safety zones. Safety zones are areas in which the activities of private actors or States could reasonably cause harmful interference to another party. The text from the Artemis Accords that describes safety zones is as follows:

> In order to implement their obligations under the Outer Space Treaty, the Signatories intend to provide notification of their activities and commit to coordinating with any relevant actor to avoid harmful interference. The area wherein this notification and coordination will be implemented to avoid harmful interference is referred to as a 'safety zone'. A safety zone should be the area in which nominal operations of a relevant activity or an anomalous event could reasonably cause harmful interference. The Signatories intend to observe the following principles related to safety zones:
>
> (a) The size and scope of the safety zone, as well as the notice and coordination, should reflect the nature of the operations being conducted and the environment that such operations are conducted in;
>
> (b) The size and scope of the safety zone should be determined in a reasonable manner leveraging commonly accepted scientific and engineering principles;
>
> (c) The nature and existence of safety zones is expected to change over time reflecting the status of the relevant operation. If the nature of an operation changes, the operating Signatory should alter the size and scope of the corresponding safety zone as appropriate. Safety zones will ultimately be temporary, ending when the relevant operation ceases; and

(d) The Signatories should promptly notify each other as well as the Secretary-General of the United Nations of the establishment, alteration, or end of any safety zone, consistent with Article XI of the Outer Space Treaty (NASA, 2020).

As one measure to regulate conduct, the Artemis Accords enable states to establish safety zones on celestial bodies, orbit, and space. According to the Accords, a safety zone is the area in which the activities of private actors or States could reasonably cause harmful interference to the environment or another party (NASA, 2020). However, these safety zones are not clearly defined. It is important then to determine the appropriate size of a safety zone in relation to the conduct occurring within the boundaries. Moreover, the nature of regulation of these zones needs to be clarified (Schingler, 2020). Adequately regulating safety zones requires that the area of the zone is defined by the scope of the activities conducted and not merely the size of a landing site or object. The implementation of space nuclear power challenges the way that these zones are defined because the risks of harmful interference by an external party could have greater consequences with a space nuclear system. Further, the particular nature of and risks associated with a space nuclear system could change the extent and nature of a safety zone (Gilbert, 2021). Although one cannot claim property on the moon, safety zones can be used to govern the nature or type of activity in a specific area of the moon. The Outer Space Treaty's non-appropriation provisions mean that staking a claim on the moon, be it placing a flag or constructing a base, doesn't confer any binding rights to individuals, companies or States (Parkinson, 2019).

Space Nuclear

Space nuclear power systems are traditionally small fission systems or systems that utilize radioactive decay to generate electricity or heat in orbit, on the surfaces of celestial bodies, and in deep space. Space nuclear prompts a need to define and regulate safety zones because the Artemis Accords seek to use these zones as a means to prevent hazards to a spacecraft or technological development. Space nuclear power systems vary in size, power generation, and longevity. Radioisotope power systems (RPS) for instance, do not rely on fission. Instead, these devices are powered by spent nuclear fuel that produces energy as the radioisotopes decay. As such, regulations on the size of safety zones ought to vary for smaller, less radioactive systems like radioisotope power systems compared to other space nuclear systems or nuclear reactors. Interference from an outside actor will vary in its degree of harm based on the level of interference from the actor but also the nature of the object they interfere with.

Precedent

Radioisotope power systems are already on the lunar surface. Therefore, it is critical to parse out how the government has historically governed them in comparison to the future laws that will be needed to govern the conduct of commercial RPS producers. The radioisotope thermoelectric generators from the Apollo missions in the 1960s are still under government authority, yet private companies typically have shorter lifetimes than the time in which it takes for the fuel in radioisotope power systems to decay. The United States uses laws outlined within the One Small Step to Protect Human Heritage in Space Act as a mechanism that protects Apollo mission heritage sites, but they also operate similar to safety zones (Smith, 2021). Radioisotope thermal generators are present on those protected locations. This provides analogous protections to what the Artemis Accords envision for safety zones. The precedent of lunar heritage protections provide a basis that eases the implementation process for establishing and governing safety zones.

Stakeholders

This policy has impacts that extend beyond the manufacturers of radioisotope power systems. This work on establishing space law will affect private space exploration companies, all international signatories, and any group that works on putting a payload on to a spacecraft bound for the Moon. According to Forbes, the space industry has over 10,000 companies engaged and a valuation of nearly $4 trillion (Koetsier, 2021). Below, Figure 1 illustrates the sharp rise in private space investment in contrast to the declining percentage share of federal spending on NASA's budget (Cordelle, 2017).

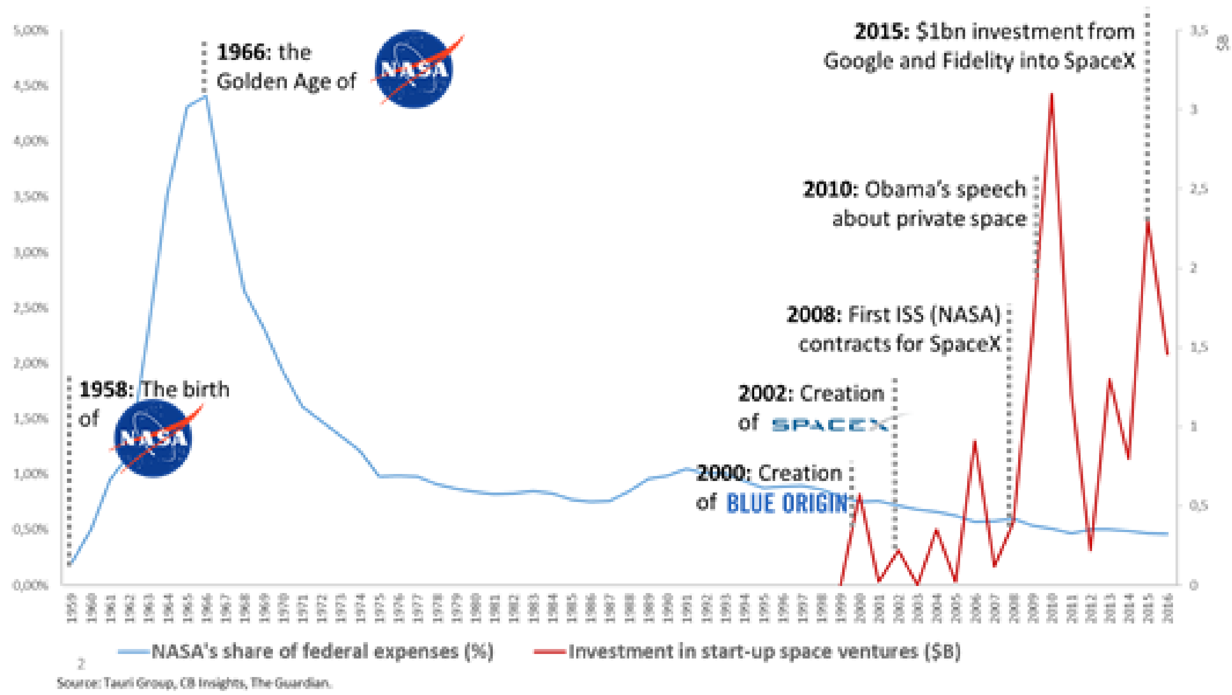

Figure 1: Graph showing investment in start-up space ventures and NASA's share of federal expenses.

The space industry is also international so stakeholders for this policy problem span space industry workers, nuclear energy stakeholders, and financial investors. Provided that there are unclear definitions, minimal precedent, and no private company has yet to engage in lunar development, it is imperative that companies engage in policy advocacy. By having private actors involved in the policy development process, public-private partnerships can pioneer industry norms for space activity and engage with legislators so that laws that govern space are proactive and not implemented retroactively after there is already substantial activity on the lunar surface. Space nuclear demonstrations and private launches are expected for the near future; therefore, policymaking must be engaged sooner rather than later so that companies can practice ethical, lawful conduct on the surface and orbits of celestial bodies.

As space exploration has shifted from a federally funded enterprise to one where private companies dominate, many scholars have been critical of the so-called "billionaire space race" (Obeidallah, 2021). Despite the salient wealth gap, space nuclear power is an issue that affects all actors in the aerospace industry. Technological setbacks caused by inadequate power supplies in space do not just affect billionaires and governments. Loss of research caused by technology failures during the frigid lunar night impacts stakeholders worldwide: from NASA interns, to astrobiologists, to appropriations staffers in Congress. Providing power in space is critical to advancing space missions for all of humanity, not just professional astronauts or billionaires.

Political Salience

Given that international law provides limited guidance on how to enforce norms in space for private companies, it is imperative that international agreements convey jurisdiction and governance obligations to the launching State. Having comprehensive and agreed upon norms will reduce the likelihood of harmful interference between operators on celestial bodies. Documents like the Artemis Accords must be more concretely defined as more private companies begin to take up space. Although this has been recognized in the political arena, there have yet to be concrete policies as to how land governance may be enforced in space. The Subcommittee on Space and Science under the Senate Commerce, Science, and Technology Committee has begun to hold meetings on various space problems like orbital debris and private-public partnerships (Smith, 2021). However, the notion of safety zones has existed primarily in international law and now merits domestic, regulatory attention.

Causes and Consequences

Lunar Night

Without space nuclear systems, technology on the lunar surface will become defunct with each passing lunar night. Non-nuclear technologies are not equipped to handle the 14 days when night falls on the moon. Temperatures can plummet to as low as -280 F. Even projects like the Chinese moon rover, "Yutu," have ended abruptly as technology fails in the sub-zero temperatures (David, 2014). During the Apollo program, the United States spent approximately $280 billion to land men on the Moon between 1960 and 1973, when adjusted for modern inflation (Planetary Society, 2020). Inadequate power on the lunar surface could result in technology failures that amount to several billion dollars in lost materials and data.

Diplomacy

Even without incorporating space nuclear into safety zones, the lack of a clear definition of zones and no international consensus could pose problems for diplomacy. If the size and scope of safety zones are not defined, crowding of the lunar surface could occur. Rovers by one nation could venture on a path that goes through the regolith experiments of another. Undefined property boundaries, even in space, can result in international disputes caused by interference of objects. In the context of space nuclear power, one object may block a power grid in a way that impedes the power from a nuclear system from reaching a landing site or even a lunar habitat.

Liability

Finally, unregulated zones can lead to consequences that make it difficult to establish at fault liability. If a space nuclear site experiences leakage or unacceptable levels of radiation exposure, there are currently no laws or policies that hold private companies liable. Presently, only the launching State is liable for harmful interference. Establishing safety zones will provide clearer norms and guidelines that apply to private actors that prohibit harmful interference between operators. With more comprehensive guidelines on lunar activity through safety zones, it will be easier to discern when violations have been made and actors who engage in harmful interference will be more likely to be held liable and found to be at fault.

Existing Evidence on Defining Safety Zones

Maritime Law

One existing solution for defining safety zones in space is to model definitions of maritime law on Earth. According to the US Coast Guard, a Maritime Safety Zone is a, "water area, shore area, or water and shore area combined to which, for safety or environmental purposes, access is limited to authorized persons, vehicles, or vessels. A Maritime Safety Zone is established to prevent interference with safe navigation and tug maneuvers, to exclude third party access in order to reduce ignition probability, to aid in emergency preparation, and to protect the public from being exposed to potential harm" (Le et al., 2015). This definition meets certain elements on prohibiting harmful interference outlined in the Artemis Accords.

Planetary Protection

Despite the fact that the Artemis Accords were written decades after the last mission involving activities on the lunar surface, planetary protection laws and moon heritage laws have been in place since the signing of the Outer Space Treaty in 1967. Planetary protection has historically been used as a basis of laws to protect that lunar surface from contamination, and radioactive waste is another type of activity that warrants protection from harmful interference. A salient example of a contaminating externality is oftentimes referred to as the Tardigrade Incident. In April of 2019, an Israeli spacecraft crash-landed on the lunar surface. When spacecraft leave Earth, they are bound by the Outer Space Treaty not to contaminate their environment (Virk, 2019). Yet this crash inadvertently released tardigrades, micro-animals known as water bears. As a result of this accident, it could be argued that the release of tardigrades could have resulted in harmful contamination of the pristine environment of the lunar surface. Although no fines were imposed, there was substantial international backlash against Israel and a push for more robust space regulations.

Planetary protection laws operate similar to safety zones but advocate for non-interference of historic landing sites on the moon. President Trump signed legislation into law in 2020 that included a bill to protect lunar heritage sites such as the Apollo 11 landing site. Presently, the One Small Step to Protect Human Heritage bill within the Space Act applies only to companies that have partnership agreements with NASA to conduct lunar activities (Smith, 2021). Because protections currently exist only for companies who have explicit partnerships with NASA, safety zones will be able to protect public and private personnel, equipment, and operations from harmful interference regardless of the nature of their partnerships with space agencies.

Space Nuclear Precedent

In regards to what precedent exists for nuclear power on the lunar surface, it is important to bear in mind the radioisotope thermoelectric generators were part of numerous Apollo missions. Radioisotope power systems that have been sitting on the lunar surface since the 1960's. Although they are not actively powering missions, they still have several half-lives remaining. Moreover, the continued power and heat provided by radioisotope thermal generators and heater units have led to rovers that utilize this technology to survive longer than their initially expected mission timelines (NASA, n.d.). NASA has already detailed policies on how to regulate their radioisotope thermal generators from the Apollo mission in both their environmental impact assessments and mission operations. As the radioisotopes decay, aspects of the mission are phased out. This process is detailed in NASA's Voyager mission (Natha & Espinoza, n.d.). Table A in the Appendix lists out the history of radioisotope power systems that have been used in space exploration missions. The table also denotes whether the device was a radioisotope thermal generator or radioisotope thermal heater unit.

Space Insurance Policies

One parallel to safety zones lies in existing law surrounding space insurance. Current space law makes the launching state potentially liable for their conduct upon launch, activity in space, and re-entry. Insurance relates to safety zones by assessing how third parties can be held accountable for harms they cause or interference with other actor's conduct. Company risk can therefore be counterbalanced by expanding space insurance policies and using safety zones to enforce liability (Harrington, 2020). In order to determine when companies are at fault for harms, safety zones can be used to determine the scope of liability.

The Federal Aviation Administration is the only institution that has required a compulsory insurance cover for space vehicles flying from the United States. Such cover will also likely be required for vehicles flying from other countries within the license/authorization framework as for traditional rocket launches (Conn et al., 2020). According to legal scholars, the amount of this compulsory cover may vary depending on the licensing authority assessment of the risk and the determination of the 'Maximum Probable Loss' which is the greatest dollar amount of loss for bodily injury or property damage that is reasonably expected to result from a licensed or permitted activity. However, the required amount cannot exceed $500,000,000 given that third party claims in excess of this amount will be paid by the United States Government up to $1.5 billion (Bensoussan, 2010). Due to the cap on insurance claims for space exploration, there are gaps that leave private companies underinsured.

Alternatives

According to the Artemis Accords, "the Signatories should, as appropriate, make relevant information regarding such safety zones, including the extent and general nature of operations taking place within them, available to the public as soon as practicable and feasible, while taking into account appropriate protections for proprietary and export-controlled information" (NASA, 2020). The following policy options describe the methods of which space actors define and govern their respective safety zones. In order to achieve these policy outcomes, the actors would abide by a registration and coordination process that mitigates instances of harmful interference while promoting norms of transparency. The public availability of information about safety zones outlined in the Accords is analogous to the registration of orbital slots through the International Telecommunications Union (Gangestad, 2017).

As a result of the increased prominence of private companies in the new age of space exploration, it is crucial to create policies that establish ethical norms of conduct. Moreover, having a concrete process for notifying Artemis signatories about active safety zones will reduce risk and liability on companies that engage in space activity. As such, the below policy alternatives will analyze the degree in which proposals for safety zones will be private or public led processes.

1. Operator-led proposals for safety zones

This process would entail mission operators requesting safety zones as part of their launch approval or future regulatory processes. Because mission operators have technology-specific knowledge about the nature of the activity, they can request for safety zone designations. Under this alternative, operators will present safety zone requests to regulatory authorities that traditionally administer launch approvals such as the Federal Aviation Administration (FAA, 2022). Operators have information specific to the nature of their technology that provides them with a deeper understanding of the size, scope, and timeline of which they need a safety zone to protect their activity. This gives operators a foundation that makes it easier to determine when another actor has breached their safety zone and caused undue harm. This creates a process in which demonstrations of novel technologies by the operator can also serve as a means to test the effectiveness of their zoning they proposed to be tailored to their unique technology.

2. Safety zones to be assigned and regulated by the FAA

In this alternative, safety zones will be designated by the Federal Aviation Administration in addition to their current launch approval process. Under current federal law, the launching actor must adhere to safety guidelines and present a safety analysis outlined by the FAA in order to receive launch approval. In addition to payload reviews, safety approvals are a separate authorization for launch approvals, reentry, and site licenses (FAA, 2020). This proposal will add mission conduct to the list of authorizations. A safety zone would be included as part of the review process that protects the area of activity on the celestial body from harmful interference. The FAA will use their regulatory expertise and existing approval processes for launch approvals to determine the scope and nature of the safety zone based upon the proposed activity of the mission operator.

3. Model tiered approaches of space nuclear launch approvals for safety zones

This alternative will be modeled after the 2019 Presidential Memorandum regarding the Launch of Spacecraft Containing Space Nuclear Systems. Under the current launch approval process, "authorization for launches of spacecraft containing space nuclear systems shall follow a three-tiered process based upon the characteristics of the system, the level of potential hazard, and national security considerations." Tier I requires authorization from the head of the sponsoring agency, Tier II requires the aforementioned authorization as well as additional safety reviews, and Tier III missions require launch approval from the President of the United States (Piazza, 2019). This alternative will expand the existing tier system beyond launches and include the establishment of a safety zone based on the risk-level of the mission activity. This alternative is similar to the alternative of having the FAA assign safety zones, but instead designates safety zones into different categories based on the types of criteria a mission's conduct would meet.

Criteria

The criteria that I will use to evaluate my proposed alternatives are effectiveness, equity, cost, and feasibility. These criteria are relevant to both Zeno Power's mission as well as the overarching goals of the Artemis Accords. Safety zone proposals must be effective at reducing harmful interference between actors; promote transparency and interoperability through equitable policy; mitigate risks placed on companies and regulators; and be able to be feasibly implemented within current and future regulatory environments. The criteria of the proposed alternatives will be weighted based on their importance in the existing regulatory framework and the alternatives will be evaluated on a scale of 1 (fulfills the criteria the least) to 5 (fulfills the criteria the most).

Effectiveness

In this context, effectiveness as a criteria will assess the extent to which private companies can continue to innovate. In order to create effective safety zones that fulfill the Accords' mission of preventing harmful interference, the scope of the zones must be robust enough to hold actors liable for interference but not too restrictive as to inhibit private activity. Because there are unclear definitions of safety zones, minimal precedent, and no private company has yet to break ground on lunar development, it is imperative that companies like Zeno Power engage in policy development and demonstrations. Alternatives that are spearheaded by mission operators or encourage collaboration allow for innovation and more effective regulation over zones.

Because of information asymmetry between regulators and mission operators, private companies may have the most knowledge about their own type of conduct and internal safety assessments but do not necessarily have substantial information about the conduct of other governments or States. In the context of space nuclear power, "a national regulatory authority may not have sufficient technical capabilities to determine the specific operational risks to a space reactor or to quantify the impacts of accident scenarios. However, the mission operator would be in the best position to identify and manage risks to and from the reactor" (Gilbert, 2022). The disparities in technology, information, and size of conduct would then justify that safety zones be tailored to the needs of the operator. For example, a lunar launch site will need a much larger zone than an RPS on a small rover simply due to the amount of dust that could interfere with nearby actors.

Equity

This criteria will assess equity in the context of space norms and accessibility. The signatories of the Artemis Accords pledge themselves to both transparency and interoperability. In the text of the Accords, signatories affirm their commitment "to transparency in the broad dissemination of information regarding their national space policies and… to share scientific information resulting from their activities pursuant to these Accords with the public and the international scientific community on a good-faith basis, and consistent with Article XI of the Outer Space Treaty" (Dunbar, 2021).

Without robust safety zones, harmful interference could result in a loss of research that restricts equitable access of the lunar surface and discourages the Artemis Accords' principle of interoperability. Moreover, space nuclear technology has enabled spillover benefits that can improve life on Earth. Developing regulations that encourage nuclear power in space also can allow for development of new technologies on Earth. Every dollar spent on space nuclear development is also spent towards critical research and development that can address failing power grids in Arctic communities, provide heat to researchers in Antarctica's winters, and maintain power connectivity for naval missions (NASA, 2019). If safety zones are regulated too strictly, the benefits of technology demonstrations on the lunar surface may never materialize due to regulatory hurdles.

Risk Mitigation

The risk level of each proposal is another key criteria in determining the best alternative for registering safety zones. The risk of different safety zone proposals is difficult to quantify because the financial losses incurred by harmful interference will vary wildly based upon the initial cost of the mission and the degree of damage caused by an outside actor. Without well defined safety zones, harmful interference between actors can jeopardize missions and incur staggeringly high financial costs. For instance, the proposed Artemis Missions to the moon will cost approximately $28 billion dollars (Carter, 2020). As such, risk in this sense evaluates the amount of losses that could result from non-existent or weak safety zones.

Alternatively, risk also accounts for regulatory costs. The manner in which actors are required to abide by safety zones can be costly for internal operations. For alternatives that give actors more autonomy in their requests for safety zones, there is a lessened cost because governance could be incremental or tailored to the actor's specific needs. Conversely, if safety zone requirements are instilled by a regulator or State entity, this could disrupt mission timelines and lead to increased operating costs.

Feasibility

Finally, feasibility is an important criteria, particularly in assessing enforcement mechanisms. Although space has been traditionally governed by international treaties like the Outer Space Treaty of 1967, the Artemis Accords differ in that it is not hard law and lacks enforcement mechanisms. While the Artemis Accords have been signed by 18 international parties, there are no explicit sanctions or punishments for violating commitments in the Accords (U.S. Dept. of State, 2022). As such, the alternatives will be assessed on their feasibility of implementation and enforcement. This criteria accounts for aspects of political feasibility, but primarily focuses on whether or not the alternative will be able to be efficiently implemented in the current regulatory climate.

Alternatives Evaluated

1. Operator-led proposals for safety zones

Effectiveness

Having operator-led proposals for safety zones promotes incrementalism on regulation. Due to the advantage that operators have in their technical knowledge about their activity, operators will be able to tailor regulatory policies to align with their technological demonstrations. The effectiveness of operator-led proposals is benefitted through operator-knowledge, but it could make the safety zone proposal process on the needs of the operator rather than for the sake of preventing harmful interference writ-large. Since operator-led proposals may lose efficacy when bad actors undermine their own need for more thorough safety zones, this criteria receives a score of 4.

Equity

Without robust safety zones and enforcement of zone violations, harmful interference could result in a loss of research that restricts equitable access of the lunar surface and discourages the Artemis Accords' principle of interoperability. Operator-led proposals could be beneficial for interoperability but ultimately lack enforceable punishments for violations and harm caused by interference due to the weakness of norms. However, if safety zones are regulated too strictly, the benefits of technology demonstrations on the lunar surface may never materialize due to regulatory hurdles. Interoperability is a core tenant of the Artemis Accords and without adequate safety zones that promote non-interference then there will not be equitable protection of research and mission operations. Due to the tension between placing burdens on private actors and the fear of weak norms, this criteria also receives a score of 3.

Risk Mitigation

Without well defined safety zones, harmful interference between actors can jeopardize missions and incur staggeringly high financial and environmental costs. Interference by outside actors on the lunar surface could damage sensitive instruments or corrupt research experiments. In order to mitigate interference, operator-led proposals would be established across the public and private sector to ensure that there is sufficient buy-in of norms and regulations. The success of risk-mitigation is dependent upon how proactive operators are. Operator-led proposals may run the risk of businesses not engaging in proactive regulatory procedures which could result in becoming noncompliant with changing federal regulations or loss in business from investors due to weak policies regarding safety zones. Companies could actually increase their own risk by not implementing their own safety zones because it opens them to vulnerabilities of other actors damaging their objects. As such, risk mitigation of operator-led proposals receives a score of 4.

Feasibility

Rather than having private actors comply with top-down federal regulations, this alternative allows for federal regulations to adapt based on the needs of the private sector and evaluate the successes and failures of incremental regulations created by operators. This proposal is the most likely to be feasibly implemented because the safety zone proposal process must be initiated by the operators under this alternative. This alleviates the issues that are associated with bureaucratic rollouts of regulatory changes. Under this alternative, companies will be able to engage in their own proposal processes through incremental policy demonstrations. Furthermore, there is accountability that ensures operators engage in safety zone proposals because it will enable them to have a competitive advantage by demonstrating not just technological demonstrations of space exploration, but policy demonstrations as well. Because operator-proposals can exist outside of enforced mandates and still encourage more regulation than the status quo, the criteria for feasibility receives a 5.

2. Safety zones to be assigned and regulated by the FAA

Effectiveness

Presently, the FAA only has enforcement authority over launches and information reviewed during launch risk and safety assessments. Making safety zones part of the launch approval process will promote their establishment and adherence. Under this proposed alternative, the FAA would also have the authority to impose punishments and fines upon those who violate federally-allocated safety zones. However, having top-down guidelines for the creation and establishment of safety zones may place regulatory divisions at private companies in a place of uncertainty and makes it difficult to preempt permanent changes in the regulatory process, giving this criteria a 4.

Equity

Having safety zones designated and enforced by a state entity allows for uniform implementation. Expanding safety zones into launch approval processes closes the mission authorization gap and allows for increased federal oversight for equitable space missions. Including safety zones in this regulatory process will make the requirement uniform across the public and private sectors. Due to the uniformity in how this policy will roll out, this criteria receives a 4 for equity.

Risk Mitigation

Safety zones are not established in existing FAA authorization of space launches. This leads to a mission authorization gap. Under this new alternative, launch approval would also require conduct approval within safety zones. In essence, both the launch and the mission conducted on the lunar surface would double the work of the operator to conduct safety analysis reports. Additionally, top-down safety zone proposals lack the technological expertise from Alternative 1 that could make this policy regulation too risky for private space actors. As a result, this criteria receives a 2.

Feasibility

Granting the FAA authority to regulate and define safety zones has the potential to change upcoming mission timelines and compliance with regulations. This makes it difficult to discern when the FAA would receive this authority and how long would it take for mission operators to be mandated to comply with new regulations. In order for this alternative to be feasible, there must be adequate fair warning from the regulator and a clear timeline of when the

FAA would assume this authority and detail how long mission operators would have until the new approval process goes into effect. This alternative's feasibility is therefore dependent on the timeliness of the regulation's implementation and whether or not the changes happen incrementally or immediately, giving this criteria a 3 in evaluation.

3. Model tiered approaches of space nuclear launch approvals for safety zones

Effectiveness

By using tiered launch approval processes as an analogy to safety zones, there will be substantial regulatory burdens on operators. This is because private actors will have to alter their internal regulatory divisions to account not just for a categorical launch approval but mission conduct approval. Moreover, converting existing launch guidelines into safety zone requirements could result in a less effective outcome because launch approvals do not have the same temporal components that long-term lunar activity would have. As such, this criteria receives a 2.

Equity

This alternative promotes equity by standardizing approval processes. This gives each mission operator clearly codified guidelines regarding safety zone allocations. While this leads to an equitable process, it may lead to some inequities in outcomes for companies who may have original mission proposals that are no longer able to meet new standards depending on when the policy change is implemented. This alternative substantially differs from the traditional case-by-case launch approval process that may benefit equity by being more holistic, and therefore receives a 3.

Risk Mitigation

Similar to Alternative 2, risk is mitigated because operators will be disincentivized to engage in conduct outside of their approved safety zone. In order to ensure that future projects will continue to receive approval, operators are incentivized to be good space actors and avoid actions that result in harmful interference. However, if one aspect of the proposed lunar activity does not meet the requirements of a specific approval category, the mission could change from a standard mission to one that is more expensive and has more time-consuming regulatory hurdles for the operator. This criteria has a risk-mitigation score of 3.

Feasibility

Mission operators are already familiar with tiered approaches to launch approval regulations since the adoption of the Presidential Memorandum of Launch of Spacecraft Containing Space Nuclear Systems. This process will be most similar to a status quo that regulators and operators are both familiar with. Codifying and classifying the nature of safety zones in rigid categories for an approval process has trade-offs for effectiveness and risk, but it does provide increased transparency into the regulatory approval process. Due to its analogous precedents for launch approvals, creating tiered safety zone approval procedures would be smoother than other top-down alternatives. As such, this criteria receives a 4.

Outcomes Matrix

The outcome matrix below rates each alternative against the evaluative criteria. For this matrix, each criteria ranking is rated on a scale of 1-5. Additionally, the criteria are weighted based on the immediate interests and implementable policy goals of Zeno Power. As such, the most weight is given to effectiveness, then risk mitigation, followed by feasibility, and then equity. As the regulatory climate changes and different categories take precedence over others, the outcomes matrix and ensuing recommendations will be adaptable for future use. Based upon regulatory precedent and the current needs of safety zones, the following criteria have been used to quantify which alternative is the most appropriate for Zeno Power to pursue.

	Effectiveness (.4)	Equity (.1)	Risk Mitigation (.3)	Feasibility (.2)	Total
Operator-Led	4	3	4	5	4.1
FAA Regulation	4	4	2	3	3.2
Model Tiered Approach	2	3	3	4	2.8

Recommendation

It is recommended that Zeno Power pursue operator-led proposals for safety zones. Per the above outcome matrix, having operators design and implement safety zones as part of their mission operators scored the highest overall with and without ranking criteria based on their urgency. Operator-led initiatives for safety zone development scored the highest on feasibility because it can be implemented without changes in regulatory agencies, executive orders, or federal legislation. Moreover, operator-led proposals promote risk mitigation because it does not require top-down regulatory orders that alter mission timelines or launch approval processes. While there is no federal intervention under this alternative, there is still reduced risk to mission safety and interoperability due to private companies using safety zones as a competitive advantage that illustrates robustness of safety and ethical space exploration to their clients.

The lowest scores for this alternative was in equity. It is important to note that operator-led proposals for safety zones are only as effective as the operators themselves. While safety zones created by mission operators may be more effective at promoting interoperability or reducing externalities, this alternative does not have the same level of federal oversight as others so there are few enforcement mechanisms to be used when violations occur. This is relevant to the score in equity because while too rigid of regulations can make safety zones a barrier that makes space exploration too prohibitive, the lack of enforcement mechanisms could allow for more harmful interference that disrupts equity.

Implementation

The recommended policy proposal that lunar safety zones be defined and regulated through operator-led initiatives aligns with technology regulatory theories of permissionless innovation. The premise contradicts the precautionary principle in which regulators preempt potential harms with proactive analysis in order to avoid having to reactively use regulations after the harm has already occured (Belt, 2003). While unregulated technology poses clear problems to concerns of health and safety, rigid regulations suppress innovation and hinder technology.

Opponents of sweeping adoption of the precautionary principle instead look towards "permissionless innovation." This theory for technological regulation advocates for experimentation, calculated risk-taking, and less top-down regulation (Yonk & Smith, 2021). Permissionless innovation still permits appropriate levels of caution, particularly when the technology poses risk of "tangible, immediate, irreversible, catastrophic harm" (Thierer, 2016). Operator-led safety zone designations, particularly in the case of radioisotope power systems, balances caution and innovation. While missions relating to space exploration are frequently cited as an opportunity to demonstrate technological advancement, it also can serve as a venue to demonstrate new policy implementations. In this section, case studies that highlight the successes and failures of permissionless innovation will be used to assess the effectiveness of operator-led models for safety zones.

Case 1: Drone Regulation

The success of relaxed drone regulation affirms the benefits of permissionless innovation as a framework for advancing technological innovation. Japan has the largest number of commercial drone operators globally and farmers have been allowed to use drones to inspect crops and monitor field conditions since the early 2000s. In Canada, police use drones for search-and-rescue operations while in the U.K., drones are used for commercial photography (Chen, 2017). However, commercial drones usage is still relatively uncommon in the United States due to rigid regulatory barriers imposed by the FAA. The global differences in drone regulation reflect that relaxed regulation can lead to improved agricultural production methods and can save human lives in search and rescue missions. By implementing top-down regulations quickly, the US has slowed economic growth and delayed technology that has had proven benefits to health and safety in other countries (Murray, 2015). The endurance of relaxed drone policies abroad signals that there has not yet been substantial harm by commercial drones that would warrant retroactive policies that curtail usage.

Case 2: Reusable Rockets

Reusable rockets illustrate a technology where the United States has seen success with less regulation. According to a Congressional Research Service report from 2018, the Office of Commercial Space Transportation "can grant permits rather than full licenses for experimental reusable launch vehicles that are suborbital (in other words, that launch into space but not high enough or fast enough to orbit the Earth before returning). To encourage the development of the industry, the permitting process has fewer requirements and a faster approval timeline than the licensing process." The report notes that the first permitted launch took place in 2006. Between the first launch and October 2016 there had been a total of 44 permitted launches of reusable launch vehicles (Morgan, 2018). Reducing barriers to access to foster the experimentation and innovation of reusable rockets in suborbital space paved the way for reusable rockets to be used in orbit. In September of 2021, SpaceX was successfully able to launch, land, and reuse their Falcon 9 booster during their Inspiration4 mission (Clark, 2021). Deferring to operators to assess risk in the context of reusable rockets enabled space missions like Inspiration4 which marked the first all-civilian crew to orbit the Earth. The crew did so for 3 days at an altitude higher than the Hubble Space Telescope. Additionally, the mission advanced equitable aerospace initiatives by including a crew composed of all civilians, including Hayley Arceneaux, the youngest person in space and the first astronaut with a prosthesis (Gohd, 2021).

Case 3: Boeing 737 MAX

Regulations that are too weak can result in catastrophic failures, as was warned about by even the biggest advocates of permissionless innovation. The innovations taken by Boeing to streamline their training process for their 737 Max line resulted in shortcuts that led to hundreds of deaths. While the changes in computing systems resulting in reduced training may have reduced costs, the issues arose due to a lack of oversight of continued safety and were not a reasonable innovation. While the Max planes had successfully flown over 42,000 flights in their first year, there are evident cracks caused by insufficient regulation. Namely, that the first Max plane to crash had been giving out the "incorrect speed and altitude readings on a previous trip, but was kept in service anyway" (Slotnik, 2020). The continued service when technological errors were occurring, coupled with the brief 2 day inspection and continued flights of Boeing 737 Max planes illustrates the point where productivity and innovation begin to jeopardize safety (Slotnik, 2020). When errors initially began to occur, more thorough inspections or grounding plans ought to have been implemented. While these measures may have slowed down success, it would not have been nearly as costly or as halting as the regulatory sanctions that were imposed after the second crash.

Ultimately, these cases serve as a guidance for how operator-led missions can be implemented as an effective regulatory tool. The permissionless innovation theory makes it the role of regulators and authorities to "wait and watch" to assess when intervention is truly necessary when health and safety are jeopardized such as in the Boeing case. However, it is also up to private actors to understand the importance of safety and self-regulation. Internal regulatory processes and robust safety protocols ought to be wielded as a source of power for private sector actors. Investors may be more inclined to buy into companies that can implement ethical policies and reduce both safety and financial risk. As such, innovation and operator-led proposals are critical for advancing technological demonstrations. Additionally, operator-led innovations serve as an avenue for determining adequate levels of regulation through demonstrations of effective and efficient policymaking.

Conclusion

Zeno Power is in a unique position to be able to demonstrate both novel technological applications as well as new regulatory demonstrations for the private sector. This report serves as a forward-looking framework that informs Zeno Power of their potential policy options. Particularly under the recommendation of operator-led proposals, Zeno Power is able to curate any future safety proposals of theirs based upon their unique patented fuel and shielding design that differentiates their technology from traditional Radioisotope Power Systems like thermal generators and heating units (Conca, 2021). This assessment also provides Zeno Power with an implementation framework that highlights the successes of novel technology regulations and an example that illustrates the problems with non-incremental, unreasonable advances without the safeguards of diligent safety oversight.

Continued analysis of safety zones and operations that promote interoperability and reduce harmful interference can extend beyond lunar applications. While lunar safety zones are relevant to the Artemis Program and future lunar missions, the principles of the Artemis Accords and Outer Space Treaty are intended also intended for Mars, comets, asteroid surfaces and subsurfaces, the orbits of the Moon and Mars, the Lagrangian points for the Earth-Moon system, and transit between these celestial bodies and locations (NASA, 2020). This report uses relevant analyses of lunar safety zones, but can also be used as a baseline for continuing work that extends to other celestial bodies and points in space. Outside of space exploration, establishing clear norms and regulatory intentions is practical for Zeno Power's non-space activities as well. While maritime and terrestrial applications operate under vastly different laws and regulatory frameworks, the undergirding purpose of this report can be useful for advocating for permissionless innovation in some contexts and to prepare for the rollout of top-down regulations in other aspects.

Appendix

Mission	Objective	Type of RPS	Duration
Mars 2020 “Perseverance” Rover	To conduct a geological assessment of the Martian surface by assessing habitability.	Powered by RTG.	Feb. 2021 - Present
Mars Science Laboratory “Curiosity” Rover	To characterize the planet's climate and geology in the Gale Crater.	Powered by RTG.	Aug. 2012 - Present
New Horizons	To conduct the first close-up study of Pluto and other celestial bodies in the Kuiper Belt.	Powered by RTG.	Jan. 2006 - Present
Voyager 1	Analyzed Jupiter and Saturn and was the first spacecraft to reach interstellar space.	Powered by RTG and heated by RHU.	Sept. 1977 - Present
Voyager 2	Only spacecraft to visit Jupiter, Saturn, Uranus and Neptune.	Powered by RTG and heated by RHU.	Aug. 1977 - Present
Mars Exploration “Opportunity” Rover	Discovered evidence that part of Mars had remained wet in the past with conditions that could have hosted microbial life.	Heated by RHU.	Jan. 2004 - Present
Mars Exploration “Spirit” Rover	Revealed that Mars could have produced water by hot springs or steam vents.	Heated by RHU.	Jan. 2004 - Mar. 2010
Cassini-Huygens	To explore Saturn’s atmosphere, moons, and neighboring icy satellites.	Powered by RTG and heated by RHU.	Oct. 1997 - Sept. 2017

Mars Pathfinder	Successfully deployed the first rover to land on Mars and study its surface.	Heated by RHU.	Dec. 1996 — Sept. 1997
Ulysses	To study the heliosphere of the sun.	Powered by RTG.	Oct. 1990 -
Galileo	To analyze Jupiter and its moons.	Powered by RTG and heated by RHU.	Oct. 1989 - Sept. 2003
Viking Mars Lander 1	First mission to land on Mars.	Powered by RTG.	Aug. 1975 - Nov. 1982
Viking Mars Lander 2	Assisted Viking 1 with imaging Mars.	Powered by RTG.	Sept. 1975 - April 1980
Pioneer 10	First object to pass the asteroid belt and leave the solar system.	Heated by RHU.	March 1972 - March 1997
Pioneer 11	Made the first direct observations of Saturn and studied energetic particles in the heliosphere.	Heated by RHU.	April 1973 - Sept. 1995
Apollo Surface Experiments	Landed humans on the moon and safely returned them to Earth.	Powered by RTG and heated by RHU.	July 1969 - Dec. 1972
Nimbus III	NASA's first successful launch and use of space nuclear power.	Powered by RTG.	April 1969 - Jan. 1972
Transit IV-A	First satellite to carry a radioisotope power supply into space	Powered by RTG.	June 1961- 1970s

Note. Adapted from NASA. (n.d.). Missions – NASA RPS: Radioisotope Power Systems. NASA. (https://rps.nasa.gov/missions/?page=0&per_page=40&order=date%2Bdesc&search=)

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