Safety Zones for Lunar Activities under the Artemis Accords

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This paper is a pre-print, having been submitted for peer review.

Abstract

Improving technology could enable new commercial and scientific activities in outer space, including bases, space mining, and advanced science in locations like the Moon or asteroids. To facilitate these and related space exploration activities, the United States has led the development of a new multi-lateral agreement, the Artemis Accords. A key element of the Accords and related soft law is the idea of establishing "safety zones'' surrounding the space operations of participant states and their mission-authorized nationals. Safety zones are controversial because their implementation could violate the non-appropriation principle or other clauses of the Outer Space Treaty. Thus, successfully implementing safety zones is essential to the Artemis Accords' framework to unlock space resources and other activities. This study reviews the history and principles behind safety zones in outer space and other domains. It reviews the requirements such zones place on operators and the obligations they can create for other states and actors. In reviewing three case studies for specific activities on the Moon, it proposes an algorithm for the establishment, alteration, management, and termination of a safety based on operational and other considerations. Finally, it recommends pathways to develop and implement safety zones in an iterative manner consistent with international law and best practices for industry.

Keywords: safety zones, Artemis Accords, space resources, dust management

1. Introduction

Outer space presents the most hazardous operating environments of any domain of human activity. Deep space conditions like extreme temperature swings, vacuum, radiation, microgravity, and exceptionally high velocities pose risks to human crews and spacecraft. On celestial bodies, like the Moon, these risks can be aggravated by low gravity conditions, coarse regolith, and limited energy availability. As costs for space access continue to fall, and space technologies expand to new governments and private sector actors, there are growing interests in conducting NewSpace activities on the Moon, Mars, and even the asteroids. These science, commercial, and potentially security driven missions represent a fundamental shift in how we use space and the value of space. Yet the operating conditions of outer space mean that increased human and robotic activities by one actor can threaten the safety of other actors. Unless lunar actors are able to successfully exchange information to enable proximity operations, the proliferation of space activities could increase the risks of conflict and endanger spacecraft and crews. Successful operations of NewSpace activities on the Moon requires that missions and crews are safe from interference by activities of other entities.

Recognizing these risks, the recently introduced Artemis Accords and other soft international law instruments envision a new type of coordination mechanisms for state and non-state actors: safety zones. Conceived independently from multiple perspectives, the general principle of safety zones is to facilitate proximity operations on the Moon and other locations in outer space. By invoking technology- and hazard-based considerations of space activities, safety zones promise to enable actors to minimize risks to nearby space missions. However, the theory and implementation of safety zones raises concerns in space law about violating core tenets of the Outer Space Treaty, including the prohibition on appropriation of territory on celestial bodies. Although the Artemis Accords are a multi-lateral treaty, they are led by the United States and are generally opposed by Russia and China (1).

Given their relatively novel nature, there is limited existing literature on the basis, scope, and definition of safety zones for outer space activities. Predating modern safety zones, stricter keep-out zones have long been considered for space activities, driven in part by security considerations in orbital space (2). Broadly, modern safety zones are quickly emerging as a potential governance mechanism because NewSpace activities are moving beyond the existing framework for space activities in international law, practice, and standards (3). As the most controversial safety zones are likely to be related to resource activities, recent national decisions to enact laws enabling extraction of space resources inherently tie safety zones and space resources together (4). Perhaps the most comprehensive recent treatment is by Stubbs (5) who examined the legal basis for security-driven keep out zones and commercial-driven safety zones for outer space activities. As part of a general critique of the Artemis Accords, Boley and Byers (6) criticize safety zones as akin to national appropriation and preventing access to the Moon for non-Artemis countries (an interpretation that is disputed). In contextualizing the Artemis Accords in broader space law debates, Vazhapully (7) notes that if safety zones did prevent access they would violate provisions of the Outer Space Treaty.

Implementing safety zones under the Artemis Accords or related instruments can form the basis for long-term peaceful lunar missions for civil and commercial missions. To date, the definition and purpose of a safety zone are not universally defined; understanding of the purposes of safety zones vary from actor to actor. This article examines the policy and theory behind safety zones in outer space to chart a pathway towards their successful, and fair, implementation. It does so through five contributions. First, it reviews the legal basis for safety zones in space law, highlighting how it complements or contrasts with the history of safety and other zones in terrestrial domains. Second, based on contemporary legal instruments like the Artemis Accords, this article defines safety zones as an implementation of the harmful interference provision of the Outer Space Treaty. Third, it develops, identifies, and evaluates principles for implementing safety zones, or alternative methods, under emerging instruments of space law. Fourth, the article proposes a general qualitative algorithm for the establishment and management of safety zones, evaluating how the algorithm works in three case studies: a lunar base with mining, a nuclear reactor, and a radio quiet zone. Finally, the article proposes an iterative approach to move forward with policy demonstration to implement the algorithm and ensure safety zones are effective operational and deconfliction tools.

2. Defining a "Safety Zone"

Prerequisite to designing and implementing a safety zone is defining the objectives and intent of a safety zone. Safety zones as currently described lack a clear definition and purpose, leading to various definitions by multiple actors that can exacerbate legal concerns or lead to mistaken assumptions about the effectiveness of a zone. Depending on the point of view of a particular actor, safety zones can variously be described as:

- "Keep-out" areas to protect security or economic interests
- Operational health and safety areas around certain activities
- "Notice-and-deconfliction" zones to prevent conflict
- Registration of activity and dangers it presents

To determine what is meant by contemporary usage of "safety zone" in legal instruments or texts, this section reviews relevant multi-lateral treaties, national laws, and other consensus-based processes to develop a working definition of a safety zone. This definition does not necessarily represent a consensus across all stakeholders, but rather intends to identify the definition of safety zone with the strongest basis in international and national law (both hard and soft). Considering the wide ranges of views described above, establishing a coherent definition is essential to evaluating principles for safety zones and operationalizing implementation.

2.1. Precedents for Safety Zones in Outer Space and International Space Law

As with other space governance analyses, an examination of terrestrial analogs provides a foundation for consideration of safety zones in outer space. There are multiple domains on Earth where states lack territorial jurisdiction yet have economic, scientific, and military interests. Generally termed "global commons," these locations include the High Seas, Antarctica, and the atmosphere (8). In these areas, interactions between governments or citizens of multiple states can cause tensions and raise novel legal questions over competing rights. Recent conflicts over whaling and aggressive activist protests of whaling practices has led to substantial debate over the tension between freedom of navigation and expression for multiple parties on the high seas (9). Other types of territory with limited jurisdiction, like Exclusive Economic Zones for international waters or conflict zones lacking a state asserting sovereignty, can lead to special area-based considerations that may restrict or otherwise modify activities of a third-party state or its nationals.

Newsome (10) and Stubbs (5) both explore how "keep out" or security-based zones could work for outer space activities. Newsome identified three general principles: "(1) transparency in creating and maintaining a zone; (2) establishment of a zone does not grant sovereign rights; and (3) the law that applies outside a zone, also applies inside the zone." To the degree that the basis for zones is based on security, Stubbs notes that the legal basis extends from a state's right to self defense. This basis makes sense as most historic discussion of such zones in outer space focused on maintaining the security of satellites, and the related potential need for pre-emptive action to prevent a kinetic anti satellite attack (11).

The Outer Space Treaty (OST) is the primary governing treaty for state activities in outer space (12). Along with three other widely accepted space treaties, the OST contains the key legal principles that determine the legality of state declarations of safety zones (3). Notably, OST and international law are focused on governing the relationships between different states, not private entities. Thus, implementing safety zones in international law requires coordination and relationships between states on behalf of government or private activities, as well as potential implementation within the laws of an individual state. The key relevant provisions in the OST that will shape safety zones are:

- Article 1 outlining the freedom of exploration and use to outer space and celestial bodies
- Article 2 enacting the non-appropriation principle, preventing states from claiming territorial sovereignty over the Moon or other celestial bodies (13)
- Article 9 requiring avoidance harmful contamination of the Moon or celestial bodies
- Article 9 requiring a state to commence consultations with other states to avoid harmful interference
- Article 9 also requires due regard of the interests of other states
- Article 12 allowing state inspections of outer space activities

Of these the most important are freedom of exploration and use (Stubbs calls this “the fundamental principle” in regard to space zones), non-appropriation, and consultations regarding potential harmful interference.

2.2. Emergence of Safety Zones in Space Law

As far as the author could tell, the first contemporary concept of an outer space “safety zone” in the context of commercial or civil activity came from Bigelow Aerospace (14). Alternatively termed “non-interference zones,” this concept was driven primarily by occupation health and safety considerations, and related commercial interests, in protecting space investments and crews. In submitting its payload review request to federal regulators, Bigelow specifically asked for non-interference provisions to limit other actors from threatening the safety of Bigelow’s operations. While the regulator’s approval of the payload review did not expressly create a zone, it recognized the potential need for such zones (15).

Legislation in the U.S. Congress built upon this early concept of preventing non-interference. In 2015, Congress passed the Commercial Space Launch Competitiveness Act which, among other things, recognized the property rights of U.S. citizens who extract resources from celestial bodies. Although ultimately stripped from the bill, an early version of the bill (16) contained elements related to preventing harmful interference:

"(b) Safety of Operations.--A United States commercial space resource utilization entity shall avoid causing harmful interference in outer space.

(c) Civil Action for Relief From Harmful Interference.--A United States commercial space resource utilization entity may bring a civil action for appropriate legal or equitable relief, or both, under this chapter for any action by another entity subject to United States jurisdiction causing harmful interference to its operations with respect to an asteroid resource utilization activity in outer space.

(d) Rule of Decision.--In a civil action brought pursuant to subsection (c) with respect to an asteroid resource utilization activity in outer space, a court shall enter judgment in favor of the plaintiff if the court finds—

(1) the plaintiff--

(A) acted in accordance with all existing

international obligations of the United States; and

(B) was first in time to conduct the activity; and

(2) the activity is reasonable for the exploration and utilization of asteroid resources."

Ultimately, this provision was dropped for several reasons, including its focus narrowly on asteroid mining, the general lack of maturity of these types of space activities, questions about international implementation of these provisions, and the de facto favoring of entities that are first in time to do something.

Nevertheless, space resources continued to be a primary driver of thought regarding harmful interference and safety zones, becoming a Building Block of the Hague Space Resources Working Group (HSRWG) (17). An international group intending to develop soft law for space resources activities, the HSRWG evaluated how to permit space resource activities in a manner consistent with existing international statutory law, especially the OST. Adopting its Building Blocks approach in 2019, the HSRWG's output informs states as they seek international and national approaches to governing NewSpace activities. Building Block 11, "Technical standards for, prior review of, and safety zones around space resource activities," contains the first widely reviewed conception of safety zones. The block requires a state to review a space resource activity prior to the activity to ensure it "is carried out in a safe manner to avoid harmful impacts." It envisions an international framework that encourages procedures, methodologies, and technical standards to support safe operations of space resources activities. Block 11.3. contains specific details for implementing a safety zone, acknowledging the restrictions from the non-appropriation principle. An area-based safety zone should be based on the need to assure safety and prevent third party harmful interference. Although the block notes that a safety zone shall not impede free access, it does give a state the ability to restrict access for temporary activities. Finally, Block 11.4. allows for international consultations in the case of overlapping safety zones or conflicts regarding freedom of access. Generally, the Building Blocks have been well received as an incremental approach to space resource activities, particularly as they envision an international (global not multilateral) framework for governance (18).

The multilateral Artemis Accords represented the next step in safety zones, their first appearance in a hard law multi-lateral agreement. Released in 2020, the Accords were developed to help guide upcoming lunar activities and establish principles for cooperation among multiple governments (19). As of mid-2021, thirteen nations have officially signed the Accords (or announced intent to do so):

- Australia
- Brazil
- Canada
- Italy
- Japan
- South Korea
- Luxembourg
- New Zealand
- Ukraine
- United Arab Emirates
- United Kingdom
- United States
- Isle of Man

Section 11 of the Accords, "Deconfliction of Space Activities," envisions how safety zones could be used to limit harmful interference and otherwise facilitate multi-national uses of the Moon. Reflecting the important nature of safety zones, Section 11 is the largest section of the accords in terms of text and subsections. Specifically acknowledging the provisions related to due regard and harmful interference, Section 11 commits the signatories to not conduct intentional actions to cause harmful interference, provide information sharing to avoid harmful interference, and to use their experience under the accords to contribute to later multilateral efforts regarding safety zones.

Subsection 11.7. prescribes the specific action mechanisms of a safety zone, consisting of notification of the potential of harmful interference and coordination to avoid harmful interference. The subsection describes four principles for 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.”

Beyond these specific implementation principles, the signatories commit in Subsection 11.11. to using safety zones to encourage scientific discovery, safe and efficient utilization of space resources, and sustainable space exploration.

Second to the explicit recognition of rights to extract and use space resources, safety zones are one of the most contentious portions of the Artemis Accords. The area-based nature of a safety zone inherently raises questions about the non-appropriation provision of the OST, especially to the degree that a state views its declaration of a safety zone as creating obligations for other states (20). Even temporary restrictions on activities in a safety zone, such as described in Building Block 11.3., could limit a state’s rights to free access. In a critique of the Artemis Accords, Wang (21) distinguishes the Accords from the HSRWG by noting that the Accords focus on “the interests of the party which establishes the safety zone” as opposed to HSWRG, which “pays more attention to balance the rights and interests between the state that establishes the safety zone and the successor states.” Wang also notes that sensitivities around safety zones are not just based on concerns about appropriation but also whether they create “de facto ‘spheres of influence’”. Boley and Byers (6) were more pointed in their critique, claiming that the Accords, including implementation of safety zones, put the safe development of space at risk by making U.S. interpretation of international law prevail and making the U.S. the de facto gatekeeper to outer space activities. This characterization was hotly debated as a misreading of the multilateral nature of the Accords, their iterative nature on the way to a broad multilateral treaty, and as an overstatement of the use of safety zones in practices (22, 23). Ultimately, ensuring that safety zones are consistent with international law is more about how they are implemented in practice as opposed to general theory.

2.3.A. Working Definition for a Safety Zone

Interestingly, neither the Artemis Accords nor HSRWG's Building Blocks fully define what a safety zone is, as opposed to what it does and how a state uses it. Accordingly, I propose the following definition of a safety zone:

> "a safety zone is one method to meet state obligations under the Outer Space Treaty that defines a geographic, temporal, and/or other delimited circumstance under which a mission operator believes their operational safety requires third parties to commence consultations to avoid harmful interference and related risks."

This definition is largely based on the idea that safety zones must be grounded in the harmful interference provision of the OST, and their implementation must otherwise be consistent with international space law. My definition differs from past discussions of safety zones in that it does not necessarily require that safety zones be area-based. Rather, safety zones may not necessarily be zones. They can be multi-dimensional:

- One-dimensional. The safety zone is delimited solely by a space object or an astronaut.
- Two-dimensional. A safety zone is a line constituting a space object trajectory or a pathway between an astronaut and their spacecraft.
- Three-dimensional. A three-dimensional area around a space object.
- Four-dimensional. A four-dimensional area around a space object bound for an area that varies in time.

The primary reason for this delimitation, which adds the one-dimensional and two-dimensional zones and fleshes out the four-dimensional zone, is to recognize the bilateral nature of safety zones. As commonly described, envisioning safety zones as solely area-based measures would involve an operator determined safety zone based on their perceptions of activities that may impact them. However, they may not be fully aware of the design and operations of other space missions and so may not be in the best position to define an area to protect against risk (see section 4.b.). Adding one-dimensional and two-dimensional safety zones would define an operator's activities or intentions, providing information for other space missions to determine if they would impact those activities. In such an analysis, "safety zones" may more accurately be considered "safety conditions" which are fundamentally tied to the nature of the space activity.

Another critical element of this definition is that it one based on international law and state obligations to other states. In practice, however, the easiest way to implement and enforce safety zones is amongst government and private actors within the jurisdiction of one state. Hence, while safety zones are a creation of international law, states are also responsible for making them an aspect of national law and can use them as tools to minimize domestic conflicts over national outer space activities. As states look at how they can create and use safety zones, they must answer the question of the roles and responsibilities of government entities to create safety zones for their activities, handle any international diplomatic activity required, and assign regulatory authorities oversight over commercial activities. For commercial activities, including safety zones as part of mission authorization or licensing seems a natural implementation method.

3. Principles for Safety Zones and Outstanding Questions

This section reviews the general principles inherited from space law, the physical and engineering basis, and outstanding questions for implementing my definition of safety zones.

3.1. Compliance with international and national laws

In order to facilitate broad recognition and adoption, safety zone standards or regulations must be compatible with international space law. In practice, safety zones should not be created with an intent of denying access to a location because of economic, scientific, security, or other similar concerns. Rather, the intent of safety zones should be narrowly limited to safety considerations for a states' space objects and astronauts and the space objects and astronauts of other states. Beyond intent, the practice of safety zones should not have the effect of going beyond safety, except to the degree that states agree such activities are highly likely to constitute harmful interference unrelated to safety. Similarly, an actor should not treat safety zones as a means of appropriation. If a space mine has declared a safety zone for its operations, it should only treat that zone as relevant for bilateral safety consultations. It should not, for example, count resources within that safety zone as part of its resource base for financial purposes. Nor should an actor unilaterally enforce its safety zone by physically preventing access or removing a third party's space mission from the zone. The harmful interference provision is primarily about consultations to avoid harmful interference and creation of a safety zone does not constitute jurisdictional enforcement rights between two states.

3.2. Grounding in Physical and Engineering Reality

Safety for proximity operations is fundamentally derived from physical reality and the performance of engineered systems. Thus a safety zone needs to be based on the characteristics of activities undertaken by multiple actors in a specific environment. On the Moon, the low gravity and lack of an atmosphere create two readily identifiable safety risks:

- Lunar dust from landing, launching, and surface operations can harm other spacecraft indiscriminately at long distances (24)
- Embedded energy in spacecraft fuel and energy systems can create an explosion hazard that could likewise have long distance impacts

The other readily identifiable risk is a direct collision between two space objects. As national space agencies, national regulators, and private actors evaluate how to define a space zone, the extent and characteristics of the zone should be grounded in analyses of these (and emergent) risks.

In practice, this creates an information asymmetry problem that safety zones can address: while an individual actor may be aware of the specific risks that their operations create, they are not aware of the specific risks related to activities of other actors. The specific lunar dust pollution, embedded energy, operations, and other risks associated with a third-party spacecraft are not necessarily known to the entity declaring a safety zone. Thus, while a safety zone can be easily defined by the risks associated with the declarant's activities, the actual physical extent of the zone depends in part on the characteristics and plans of third parties. Correctly implemented, safety zones can overcome this information asymmetry by creating forums for parties to exchange information about their activities to mutually assess risk. Nevertheless, recent experience with space traffic management suggests that actors' analysis of and thresholds regarding risk may defer – in such instances, consultations invoked by safety zones become even more important for mitigating potential disputes (25).

3.3.Relationship between Safety Zones, Environmental Governance, and Heritage

While beyond the scope of the definition and algorithm described in this paper, there are open questions about how safety zones related to environmental governance and heritage sites. As currently constituted, safety zones are primarily about managing contemporaneous proximity operations between actors. In implementing the harmful interference provision of the outer space treaty, they do not necessarily address the provision that prohibits harmful contamination (i.e. environmental pollution) nor does it address planetary protection. In managing deep sea mining on the High Seas, the UN Convention on Law of the Sea requires that mining plots are accompanied by reference areas so that miners can monitor baseline environmental conditions and to support conservation (26). Similar concepts could apply to outer space safety zones but raise boundary questions (i.e. at what point does environmental or scientific monitoring of an area constitute a state's space activity versus a less restrictive zone of interest to the state).

Further, analysis and planning safety zones may feed into extraterrestrial environmental impact assessments (27). In the United States, it is not yet clear whether the National Environmental Policy Act applies to lunar activities but, if it does, safety zone analysis could constitute a large portion of the required consideration of significant effects (28).

Finally, there are recent efforts to protect lunar heritage sites on the Moon. The United States recently passed the "One Small Step to Protect Human Heritage in Space Act" which directs NASA to ensure that its contractors do not interfere with heritage sites on the Moon (29). Practically speaking, there is no clear prohibition on states declaring safety zones retroactively to apply to heritage sites to enhance their inherent protections as state space objects.

4. Formulating an Algorithm for Safety Zones with Three Test Cases

I propose an algorithm for creating, defining, sharing, maintaining, and extinguishing a safety zone that meets the above principles. Under this formulation, a single mission could consist of one or a set of safety zones at different points in the mission lifecycle. Physical or temporal overlapping of safety zones can lead to different responsibilities for an operator and for a consultant depending on the actions involved. In this section, I formulate the constituents of a generic algorithm and then test it against three case studies: a lunar base with in-situ mining, a nuclear reactor, and a radio quiet zone. As these cases demonstrate, the generic algorithm can be adapted to a wide variety of use cases depending on the specific activities involved.

4.1.An algorithm for a safety zone

A safety zone algorithm is composed of relevant technical, operational, and related information relevant to each step or factor of a safety zone. For purposes of this paper, the algorithm is defined qualitatively – in practice, risk analysis would provide quantitative information to inform relevant distances and timeframes. The algorithm could be operationalized by a private mission operator, by a government entity, or as a condition of an activity license. An algorithm has base *characteristics* (definitions that describe the activity and operator), *functions* of a safety zone, and *zonal formulation* (inputs to determine the size and nature of a safety zone).

Characteristics of a safety zone are derived from the mission itself and could be considered 'biographical' features of a zone. They include:

- **Mission operator.** The most important part of a safety zone is the identity of a mission operator. All other characteristics and functions derive from or are the responsibility of the operator.
- **Type of mission.** Derived from the mission operator are the type of mission, whether private, public, or hybrid.
- **Crewed or uncrewed.** The intended or actual presence of a crew can enhance the importance of a safety zone by elevating it to human operational health and safety, as opposed to just equipment.
- **Launching state(s).** Missions are authorized and overseen by one or more launching states, who bear ultimate responsibility for activities related to safety zones.

When a mission features multiple activities that require different safety zones, characteristics would generally be shared across multiple zones.

Safety zones have functions. Functions are specific actions that mission operators must take to operate a safety zone. They also create requirements for consultation for missions that may enter a safety zone. Proposed base functions, in part inspired by the textual requirements for deconfliction activities in the Artemis Accords, include:

Table 1. Functions of a Safety Zone

Function	Description	Actor(s)
Establishment and/or alteration.	A distinct event where a safety zone goes into effect or when circumstances require a significant alteration to the safety zone that changes its nature. Prerequisite to this, the safety zone creator must conduct the zonal formulation analysis described below to characterize the extent and nature of the zone, as well as to provide the justification for the formulation.	Mission operator and/or regulating launching state
Registration, announcement, and/or communication.	A safety zone creator must register, announce, or otherwise communicate their safety zone. This step must contain sufficient information based on the zonal formulation for other actors to understand their obligations related to the safety zone. This step could be one-time (registration or announcement), periodic, or quasi-continual (i.e. a broadcast regarding the zone).	Depends on prevailing systems, whether industry-led, single government, or multi-national. Could be the mission operator or its sponsoring launching state

Consultation.	When an actor determines they will enter a safety zone, or otherwise determine there is a potential for harmful interference as defined by the safety zone, they should notify the mission operator and launching state as soon as possible. Consultations would then take place under the jurisdiction of one or more launching states to minimize risks to both missions.	Entity entering a safety zone, subsequently operator-to-operator or launching state to launching state consultations
Monitoring.	Monitoring of the territorial or other characteristics of the safety zones is needed to ensure the integrity of a safety zone, to monitor for potential risks, and identify violators. During early lunar activities, monitoring capabilities may be limited and thus actors may have to rely on 'good faith.'	Mission operator most likely.
Enforcement.	If a safety zone is violated without proper consultation, or in a manner that constitutes potential or actual harmful interference, enforcement may be required. If the relevant actors are both under the jurisdiction of a single launching state, this can be handled through national regulatory or judicial systems. However, if there are two or more launching states involved, bilateral or multi-lateral dispute resolution may be necessary.	Launching state of the mission operator

Termination.	When the activity that requires a safety zone ceases, mission operators and/or regulators have an obligation to end that safety zone. Termination of a safety is a distinct event that likely requires communication and potentially modification to mission registries.	Mission operator or launching state

These general functions are not necessarily an exhaustive list of the potential functions of a safety zone. Specific activities may lead to different functions (such as a moving activity causing continual alterations of a zone). Further, more detailed functions may be required (i.e. to manage overlapping safety zones from different missions).

Zonal formulation is the core algorithmic portion of a safety zone:

Safety zone = activity + risks from activity + risks to activity

This straightforward formulation would likely be the most controversial portion of the algorithm. In effect, the safety zone is derived from a specific activity or set of activities. This activity or set is then analyzed to identify what risks it poses to other space missions, such as ejecting lunar dust upon landing. With sufficient operating experience and analysis, these risks can be relatively well defined and quantified, establishing the basis for the size of a physical zone where the operator's activity poses risk to other entities in the area. Next, based on the activity or set, the operator can identify what it perceives as the risks to its operations. Whereas determining risks from their own activity can include existing tools like probabilistic risk assessment or related precise methods, this step is inherently more speculative. An operator can identify potential risks to their spacecraft, such as dust damage, and potentially define thresholds.

After conducting this analysis, the operator (or launching state) would establish the safety zone with a public statement of the zone. Ideally, this statement would include documentation supporting the safety analysis used for the operator-related physical zone and a list of identified external risks to operations. Together, these would enable third-party missions to understand the risks from the operator's activities and determine which of their activities may pose a risk to the operator. Notably, disclosure of risks from an operator establishes reciprocity and can incentivize the exchange of information between two operators in creating mutual safety zones.

4.2.Case Studies for the Algorithm

Three specific cases detailed in Table 2 were chosen to test the algorithm. They represent near-term (within 15 year) activities on the Moon and each feature unique characteristics that test different functions or formulation inputs for safety zones.

Table 2. Applying Safety Zone Algorithm to Case Studies

Activity	Description	Dimensions	Risks from activity	Risks to activity
Lunar base with water mine	As commonly envisioned by many space agencies and private companies, a crewed lunar base that features complex operations including water mining of regolith	1D – Crew 2D – Crew extravehicular activities, spacecraft landing and launching 4D – base and water mining	Lunar dust from operations, including spacecraft launches and landing	Threat to crew or equipment from dust or collision
Surface nuclear reactor	To provide power for a base or other activity, a small space reactor could be deployed to the lunar surface	1D – Reactor 3D – radiation risk zone	Risk of radiation exposure from normal operations, radiation release from accident,	Threat to reactor operations from external activities, especially to degree it causes

		4D – reactor decommissioning and spent fuel	long-term risks from spent fuel	accidental release
Radio telescope in radio quiet zone (30, 31)	Taking advantage of the Moon's 'radio shadow,' such a telescope would make observations from the dark side of the Moon	4D – Observation zone	Limited	Radio interference from missions travelling through quiet zone

These case studies indicate that the general algorithm provides a sufficient basis upon which to begin initial safety zone policy demonstration missions. Nevertheless, each reveals specific questions that future states and actors will need to address.

The lunar base reveals differences between crew-related operations and mining activities. Whereas safety zones without crews would only be in danger of damage or destruction of a spacecraft, crews escalate safety zones to a tool for human health and safety. The example thus reveals how multiple safety zones with different considerations could apply to one overall mission. Considering that the greatest near-term environmental issue related to proximity operations is likely to be dust emissions from landings, launches, or operations, the expected extent of these activities would make management of acute safety zones (i.e. larger safety zones tied to a landing or launch that only lasts for a short period of time) a central part of such a base.

Comparably, a nuclear reactor illustrates how safety zones can be used to handle more exotic use cases (32). Depending on the shielding employed, a reactor could create significant radiation for crew and equipment in a large area around the reactor. An essential component of a reactor safety zone (or a specific safety zone designed within a larger set) would be a declaration of quantitative details surrounding this risk. This example further underscores how a safety zone is as much about communicating risks from a primary actors' activities as it is about assessing risks from a third party spacecraft. The reactor also raises important questions regarding the decommissioning of the reactor and storage of spent fuel. In-situ storage would require a long-term (1,000-10,000 year) safety zone derived from the risks of the nuclear waste. Given the long-term nature of storage, questions about de facto appropriation or exclusion could be especially high for such an application. Indeed, the Building Blocks and Artemis Accords generally emphasize the short-term nature of a safety zone, which may not be applicable here.

Unique among these case studies, the radio telescope provides a case study where the primary risk to the activity, radio interference from passing satellites, constitutes temporary and reversible interference. Whereas kinetic damages in the other case studies can cause severe consequences, including to crew health and safety, this interference is of a much lower severity. It reduces the potential usefulness of the asset but, so long as interference is temporary, does not permanently damage the objectives of the space mission. In this case, the safety zone is relatively large (the observation zone) and the goal of the safety zone would be to commence consultations so that radio interference is minimized and operator observations are maximized.

Importantly, these different case studies indicate the wide range of activities that could implicate safety zones and the central role of the operator in identifying risks from and to their activities. Imposing obligations on mission operators to provide a technical basis for safety zone extent ensures a high level of technical competency for the zones. The reactor example demonstrates this most clearly – 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.

5. Conclusion and policy pathways

Safety zones are an emergent, important area of international space law. Yet they are relatively underdeveloped from an operational perspective. Safety zones are likely to vary considerably depending on the type of activity being conducted and may have temporal elements as well. Key results from this study are the strong legal basis for a harmful interference-based definition of safety zones, the bilateral nature of safety zones, the information asymmetry derived from that nature, and the algorithm. Further, although it may be too late, the study's analysis supports the use of the term "safety conditions" as it may be more accurate than safety zones, particularly as it pertains to 1-dimensional and 2-dimensional zones. This alternative term that goes beyond zoning or other area-constrained definitions is consistent with the text of the

Artemis Accords, whose section on safety zones is notably titled "Deconfliction of Space Activities."

Looking forward, policy demonstration missions are likely necessary to begin trying approaches to safety zones in an iterative manner. Operationalizing safety zones in such a progressive sequence can allow for states to experiment with them to handle diverse activities while ensuring compliance with prevailing international law. Near-term commercial and scientific missions provide opportunities for such experimentation, as do retroactive declarations of safety zones for heritage sites. Further, using multiple missions can enable establishing government systems such as regulatory consideration, diplomatic activities, and more.

This article's conclusions also indicate areas for future research and pathways. While the Artemis Accords provide a multilateral pathway, there are also opportunities for implementing safety zones or equivalents through industry practice, standards, or other forums of international law. Greater research is likely needed in evaluating the legal relationship between specific safety zone cases (like a nuclear reactor) and appropriation concerns. Further policy development can explore more "radical" derivations of safety zones, such as using them for environmental protection, scientific observation, or lunar settlement coordination. Regardless, the ultimate test for safety zones is not whether they guarantee safety but rather that they provide the impetus to begin the interstate and private sector dialogues needed to establish the technical and political consensus necessary for long-term lunar sustainability.

Acknowledgements

The author would like to thank the Open Lunar Foundation, Chelsea Robinson, Chelsea McMahon, Ethan Hudgins, Maria Rhimbassen, Lukas Kuhn, Chris Hearsey, and Gabriel Swiney for their feedback and input to the research and analysis presented in this article.

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