SPACE NUCLEAR SAFETY AND REGULATION FOR SPACE RESOURCES ACTIVITIES. A. Q. Gilbert[1] and J. R. Matthews[2]; [1] Zeno Power Systems, Inc., 709 G St NW, Suite 300, Washington, D.C. 20001; Colorado School of Mines. alex@zenopower.com; [2] Zeno Power Systems, Inc., 709 G St NW, Suite 300, Washington, D.C. 20001. jmatthews@zenopower.com

Introduction: Space nuclear power systems can provide enabling capabilities for a wide range of space resources activities. Radioisotope power systems (RPS) can provide heat for survivability and electricity for operations throughout the lunar night and in permanently shadowed regions. Fission reactors can support high power applications, such as molten regolith electrolysis or crewed mining. Notably, NASA's Fission Surface Power project is nominally intended to support the first In-Situ Resource Utilization pilot plant. Together, space nuclear power systems can support large-scale and distributed space mining architectures with enabling capabilities that greatly improve access to emplaced resources.

Utilizing space nuclear power systems for space resources requires successful navigation of regulatory pathways, which in large part depend on developing strong safety cases. In some cases, like a single lunar rover powered by RPS, existing launch safety and regulatory paradigms based on NASA practice are straightforward to adapt. Other applications, like large scale mining operations involving proximity to astronauts, may raise novel questions of safety risks and regulatory pathways. The Mission Safety Framework described in [1] provides an analytical tool that can identify nuclear safety considerations across a space resources mission lifecycle, providing an essential input to any regulatory approvals.

This paper provides two novel contributions to support the use of nuclear energy for space resources missions. First, it applies the Mission Safety Framework to space resources plans, identifying nuclear safety considerations specific to space resources across the mission lifecycle. Second, it proposes a regulatory pathway for using nuclear energy for space resources missions launched from the United States, derived from the mission safety framework and reflecting recent regulatory developments. Such a pathway can inform designation of a future mission authorization regulatory authority in the United States and guide space nuclear regulation internationally.

Mission Safety for Space Resources: Recent nuclear launch safety practice has been dominated by robotic NASA missions heading beyond cislunar space. The primary risks from such a mission profile occur at the spaceport and during launch activities, up until an interplanetary trajectory is reached. After that trajectory is reached, there are no significant safety concerns about nuclear systems on robotic spacecraft heading to Mars or to orbit gas giants. Accordingly, this has led to the "Launch Safety" paradigm for space nuclear safety.

Comparably, the Mission Safety Framework is designed to handle innovative applications of space nuclear energy, including commercial and space resources activities. Established in [1], the framework expands nuclear safety across a mission lifecycle, including operations and end-of-life. It also identifies the many different actors and potential regulators involved across a novel mission lifecycle, in order to guide safety practices and regulatory strategy. Applying the framework to proposed space resources mission architectures can identify any novel safety issues associated with planned space mines, as well as provide guidance and input for subsequent regulatory processes.

The framework breaks a mission into six phases. The following subsections describe each and their application to space resources.

Phase 1: Design. The design of the mission is essential to all subsequent steps, as it entails establishing design requirements and mission planning that shape overall safety outcomes. For a space resources mission, the two primary entities in the design phase are the space resources entity and the nuclear technology provider.

Phase 2: Supply Chain. This phase consists of the nuclear technology supply chain, including fuels, facilities, and radiological transportation, used to provide a space nuclear system. Generally, this phase is primarily the concern of the nuclear technology provider but, in certain circumstances, the space resources entity may desire to do ground integration and related testing with live nuclear systems before spaceport operations.

Phase 3: Spaceport. This phase consists of all activities before launch, including receipt of transportation, storage, nuclear system integration to spacecraft, and spacecraft integration to launch vehicle. In some cases, a large dedicated nuclear system like a fission reactor will be a separate mission, to be delivered to a space mining site in space. In others, the space nuclear system, like an RPS, would need to be integrated to space resources spacecraft at the spaceport. This phase involves a significant number of entities and processes, including the launch site, launch provider, mission lead, nuclear technology developer and more.

Phase 4: Launch. This phase composes the traditional Launch Safety paradigm. The primary delta for a space resources mission is that the interplanetary transportation phase may need to be included in launch safety analysis and approvals if there is a risk of an Earth reentry. Most lunar trajectories have Earth return risks in the event of failures, so lunar space resources missions would generally require the in-space transportation and/or lander be included in this phase.

Phase 5: Operations. Once a space nuclear system has arrived at an operational site, this phase covers any potential safety considerations. These will vary considerably, depending on: the specific systems (especially RPS versus fission); the current or future presence of astronauts; policy considerations like planetary protection, science objectives, or human heritage; and the space resources mining concept of operations. The space resources entity is in the lead role here, though multi-operator bases may have unique considerations. Radiation dose from systems is likely to be a large driver and could require space resources solutions such as berms or shielding bricks. For an example of safety analysis, see [2].

Phase 6: End-of-life (EOL). All space nuclear systems will require dedicated end-of-life plans due to the long-lived nature of spent fission fuel or RPS radionuclides. Generally, this will be in-situ, with action to decommission the nuclear system and some registration requirement to notify the EOL state. For a space resource plan, this can either be incorporated for individual nuclear systems or as part of an overall site decommissioning and remediation plan.

A Regulatory Pathway for Commerical Space Nuclear for Space Resources Missions: In 2019, the U.S. federal government issued National Security Presidential Memorandum-20 (NSPM-20), which modernized space nuclear launch authorization. It created a commercial launch approval pathway via the Federal Aviation Administration (FAA) and established clear, achievable safety guidelines. The guidelines are technology-inclusive and performance-based, a best practice to facilitate technological innovation.

Based on NSPM-20 and other applicable laws, each phase of the mission safety framework will have a specific regulator. Generally, the Nuclear Regulatory Commission will be responsible for terrestrial regulation such as testing and spaceport integration (Phases 2 and 3). The FAA would handle Phase 4, including launch safety and transportation to the Moon (to the degree that there is risk of Earth reentry). The payload review process by FAA would also include evaluation of relevant policy questions associated with the specific proposed activity. Finally, lunar operations and end-of-life would be covered by a future mission authorizer (Phases 5 and 6). Beyond the specific regulatory framework developed, the development of future standards specific to space resources, similar to the gaps identified in [3], can be informed by the mission safety framework, regulatory pathways, and early missions.

As described in more depth in [4], Article VI of the Outer Space Treaty requires that states provide authorization and continuing supervision of the space activities of their nationals and commercial entities. Current U.S. law does not provide for a clear commercial regulatory pathway for meeting authorization and supervision requirements for certain novel space applications, such as lunar mining or non-governmental deep space use of nuclear energy. Multiple legislative proposals seek to address these gaps by assigning relevant authorities to a responsible regulatory agency, such as the FAA or Department of Commerce. The scope and nature of mission authorization and supervision for a commercial space resources mission using space nuclear systems would be defined in future rulemakings after the statutory designation. In certain instances, particularly for near-term activities, NASA and/or FAA can serve as an authorizer or supervisor.

Conclusion: In 2023, two major developments illustrated significant progress towards establishing a regulatory pathway for commercial space nuclear missions. First, FAA accepted for review its first ever payload review application for a commercial space nuclear launch from Zeno Power [5]. The review is ongoing and could lead to launch approval as soon as 2025. Second, the FAA released long awaited guidance on space nuclear launch approval, document in Advisory Circular 450.45-1. Together, these two developments lay the foundation for regulatory approvals for near-term space missions, greatly de-risking space nuclear technology options for space resources missions.

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