Space Nuclear Safety and Regulation for Space Resources Activities

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Space Nuclear for Space Resources

Nuclear Energy in Context

Enabling technology for space operations

- Long duration
- Location independence and flexibility
- High reliability
- Energy-density
- Does not drive system or mission architecture

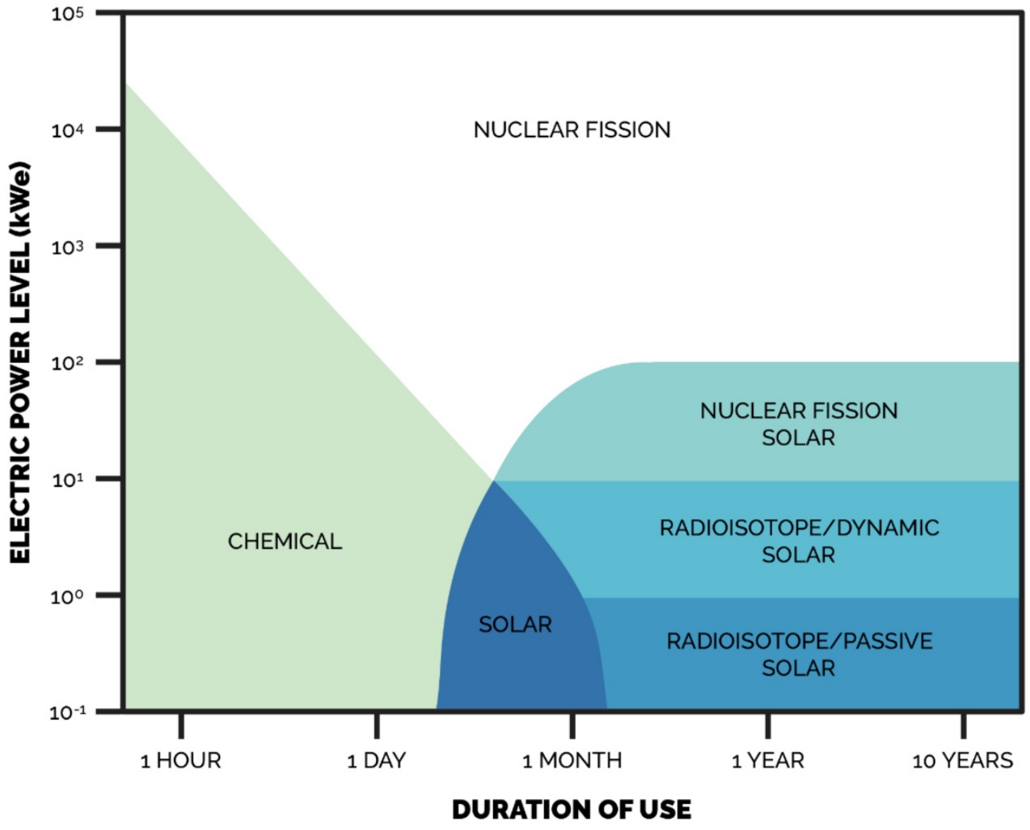


Image: CLPA/NASA

>$650 million in commercial space nuclear funding since 2021

Company	Technology	Contracts
Avalanche Energy	Fusion power	DOD: DIU
BWX Technologies, Inc.	Nuclear thermal propulsion	DOD/NASA: DRACO NASA: FSP, NTP
General Atomics	Nuclear thermal propulsion	DOD: DRACO NASA: NTP
Space Nukes	Fission power	DOD: JETSON High
USNC	Nuclear thermal propulsion, fission power, radioisotopes	DOD: DIU NASA: NTP
Westinghouse	Fission power	DOD: JETSON High NASA: FSP
X-Energy	Fission power	NASA: FSP
Zeno Power	Radioisotopes	DOD: LENS NASA: Tipping Point “Harmonia”

- DIU: Defense Innovation Unit
- DRACO: Demonstration Rocket for Agile Cislunar Operations
- JETSON: Joint Emergent Technology Supplying On-orbit Nuclear Power
- FSP: Fission Surface Power
- NTP: Nuclear Thermal Propulsion

Source: Gilbert, Desai, and Matthews, 2024 zeno

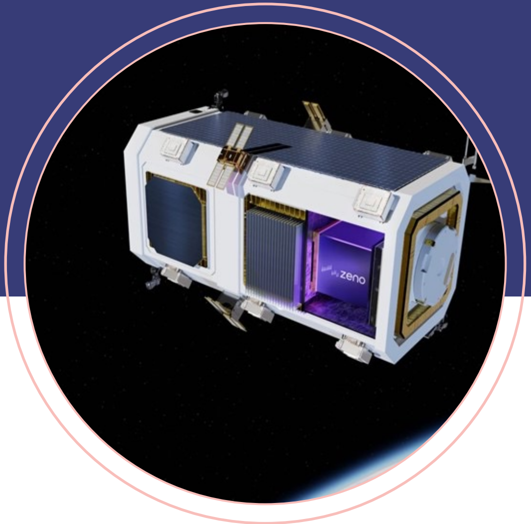
Upcoming RPS Missions

Dragonfly

NASA

Rosalind Franklin

ESA



LENS/Harmonia

Commercial - Zeno

Images: NASA, Zeno

Space Fission Projects

DRACO

Nuclear Thermal Propulsion

FSP

Fission Surface Power

JETSON High Power

Nuclear Electric Propulsion

Images: NASA

Space Nuclear for Space Resources

- RPS
  - Rovers, landers, distributed architectures
  - Survive and operate in the lunar night
  - Sustained PSR operations
- Fission surface
  - High power ISRU
- Fission propulsion
  - Astronauts
  - Deep space material return

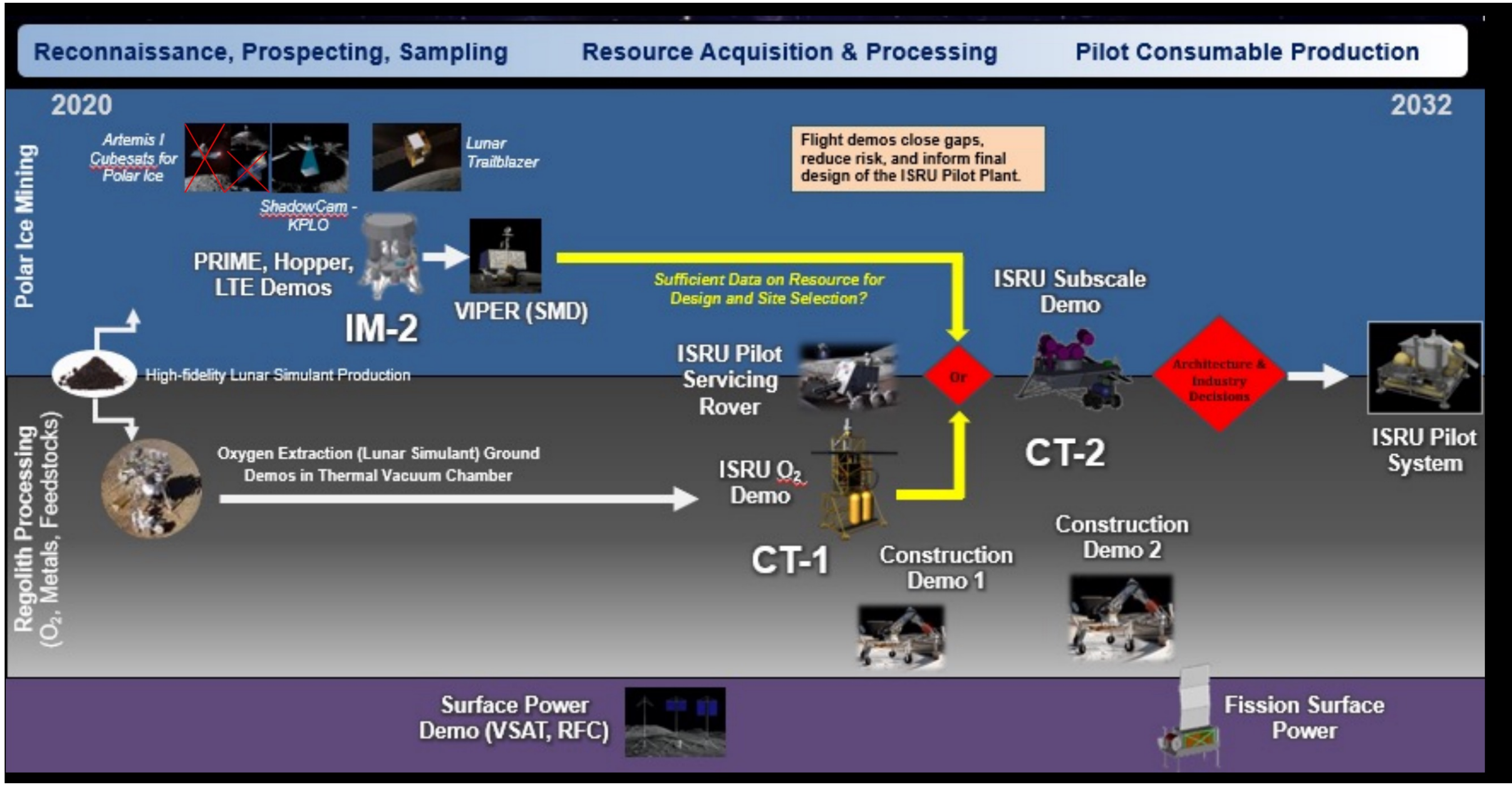
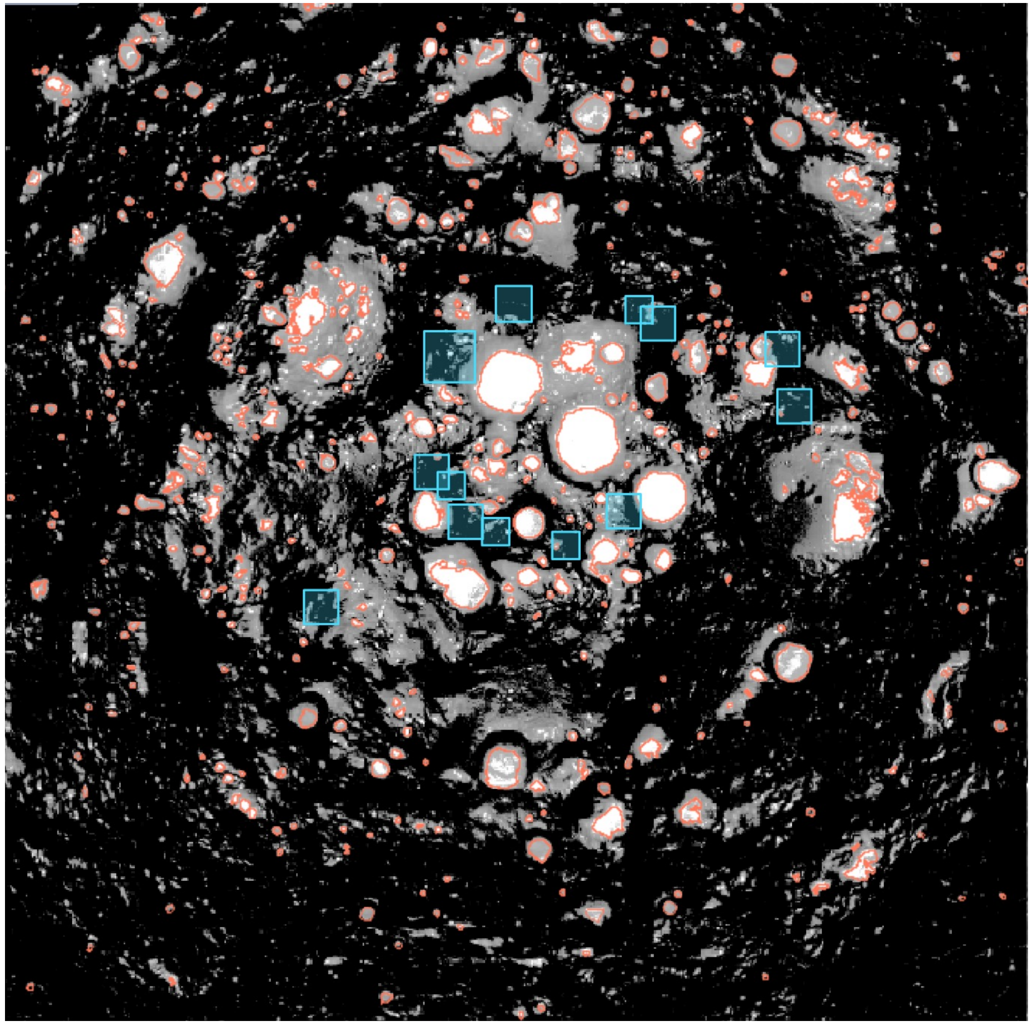


Image: NASA

Lunar ice mining example and paired technology development

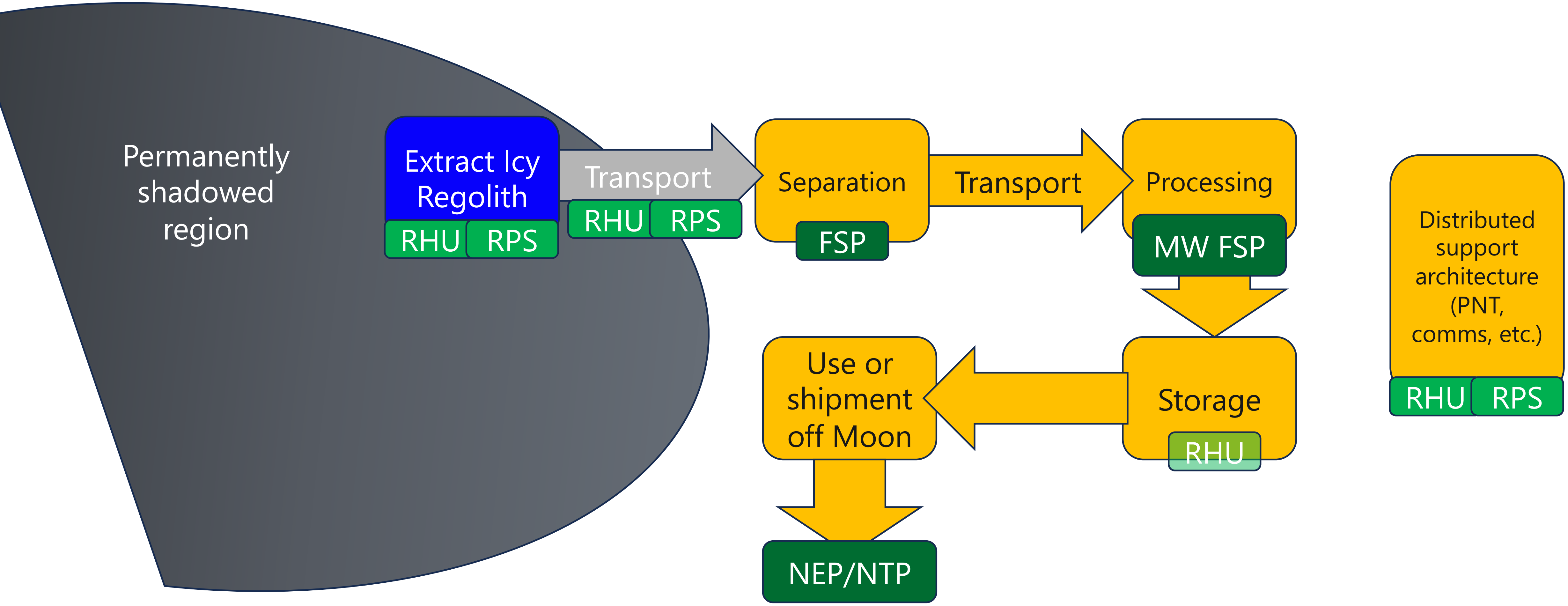


- Science
- Prospecting
- Demonstration
- Artisanal/Pilot
- Industrial-Scale

- RPS - Survive
- Low Power RPS
- Higher Power RPS (100s We)
- Early Fission
- Industrial Fission

Image: Lunar Quick Maps, Diagram: Gilbert 2024

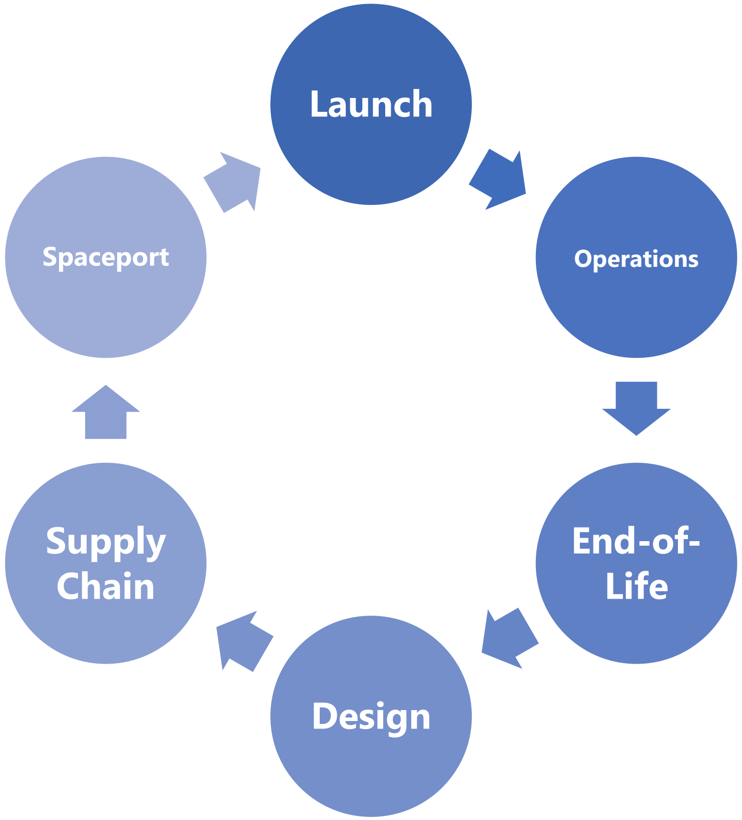
Nominal nuclear-powered ice mining architecture



Mission Safety for Space Resources

Mission Safety and Defense-in-Depth

Mission Safety Framework to guides safety approach for novel space nuclear technologies



See: Gilbert. "Lifecycle Mission Safety for Space Nuclear Power Systems." *Journal of Space Safety Engineering* 2023.

Zeno developed novel nuclear safety defense-in-depth principles for RPS

- Level 1. Operations
- Level 2. Containment
- Level 3. Radioisotope
- Level 4. Contingency

See: Gilbert and Matthews. "Defense in Depth for Radioisotope Power Systems for Space Applications." *ANS NETS* 2024.

Mission Safety for Space Resources

Mission Phases	Issues important for Space Resources mission planners
Design	• Understand mission planning and engineering requirements/limitations
Supply chain	• Testing requirements
Spaceport	• Spacecraft integration • Worker dose • Spaceport hazards
Launch	• Primary overall driver of risk • “Good neighbors” for payloads

Safety Concern Matrix

Nominal Lunar Mission Sub-phases

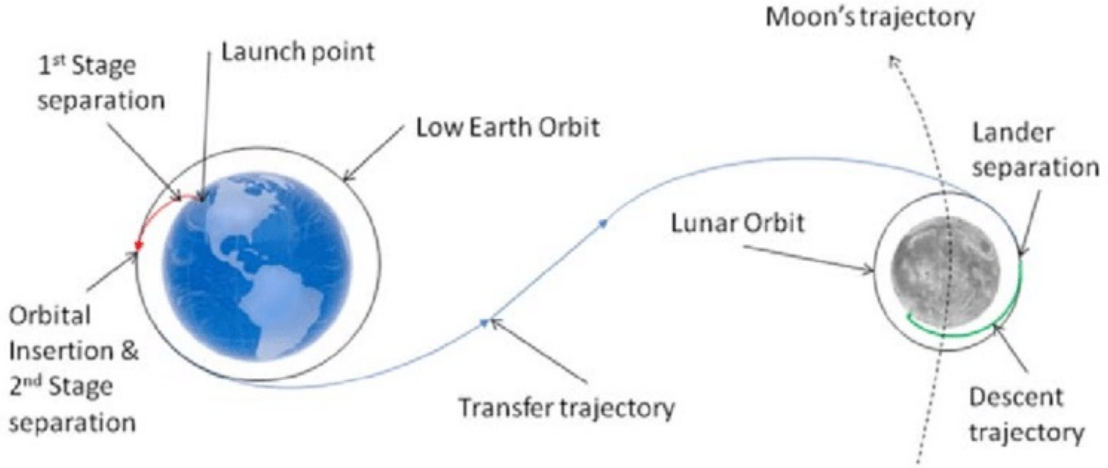
Sub-phases 3-7 new to space nuclear safety analyses

1. Pre-Launch
2. Launch
3. Orbit Circularization
4. Lunar Transfer Orbit
5. Lunar Circularization
6. Lunar Orbit
7. Landing Operations
8. Lunar Operations
9. End-of-Life

Risk of Earth return (sub-phases 3–6)

Lunar global/ regional risk (sub-phase 7)

Lunar site risk (sub-phases 8–9)

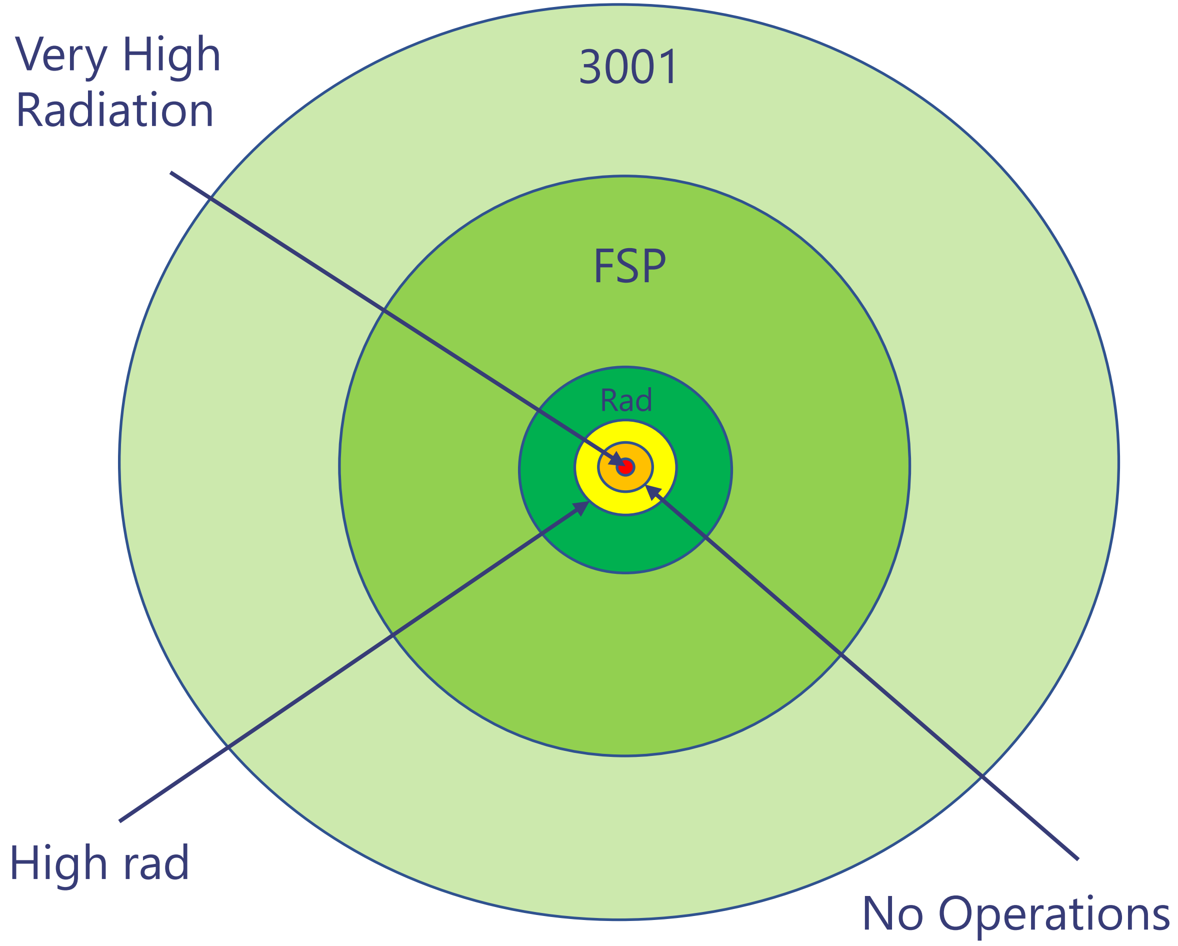


Simplified diagram of lunar mission trajectory.
Source: University of Hawai'i at Mānoa

Radiation Fields ($1/r^2$)

Fission Surface Power Example

Lunar surface natural dose estimate (Zhang 2020): ~6 mrem/hour



Area	Dose (mrem/h)	Distance (meters)	Footprint (km^2)
Very High Radiation	>500,000	1	0.00
No Operations	>2,000	17	0.00
High rad	>100	76	0.02
Rad area	>5	338	0.36
FSP	>0.6	1,000	3.14
3001	>0.2	1,581	7.85

Figure not to scale; source: Gilbert 2023

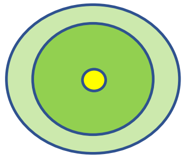
Implications of Radiation Fields

Siting multi-national and multi-user bases, astronauts

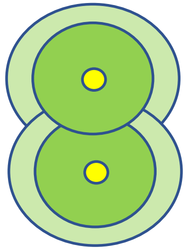
- Large implications for astronaut activities*
- No existing regulatory framework, standards, or guidance
- Safety zones identified in Artemis Accords can be tool for radiation field safety

*See ongoing ASTM standard development on in-space safety fission reactors

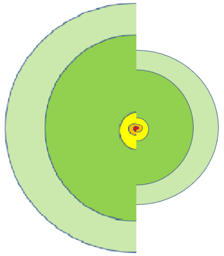
RPS



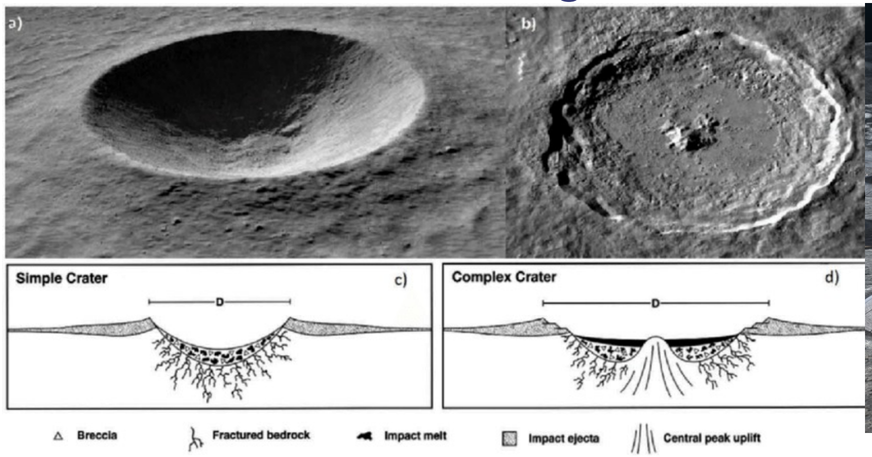
Multiple Systems



Directional Shielding



Crater Siting



Shielding Berms

Images: NASA, ICON

Regulation

Regulatory Authorities

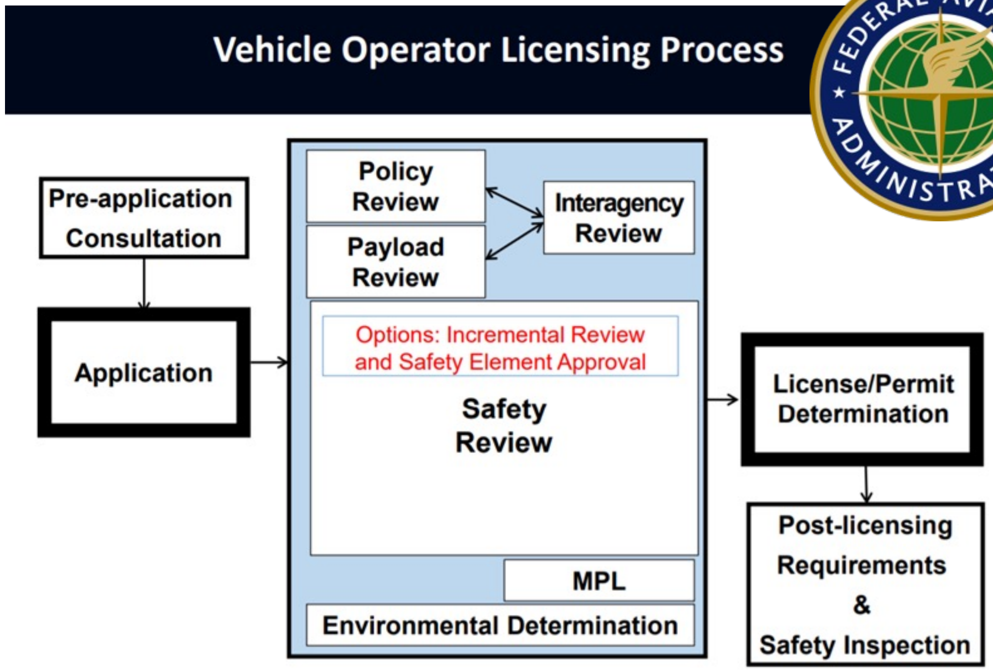
NRC	Spaceport Authorities	FAA	Future mission authorizer
Terrestrial	*Spaceport*	*Launch*	*Mission*

NSPM-20 – *guiding document*

Launch Approval

Zeno on track for commercial approval for 2026 launches

NSPM-20 Tier Criteria and Requirements			
Tier	Material Quantity	Risk Criteria	Special Requirements
I	<100,000 times A2;	<1:1,000,000 probability of public exposure between 5-25 REM TED	None
II	>100,000 times A2;	>1:1,000,000 probability of public exposure between 5-25 REM TED	Interagency Nuclear Safety Review Board (INSRB) required
III		>1:1,000,000 probability of public exposure exceeding 25 REM TED	INSRB required Presidential authorization for government missions



Zeno's Initial FAA Progress

- 2022: Pre-application discussions with AST
- 2023: Payload review submitted, accepted for review
- H1 2024: Preliminary safety analysis complete, indicates Tier 1
- H2 2024: Safety Analysis Report started, launch safety testing
- 2025: Safety Analysis Report submitted
- 2025: Payload Determination expected

Mission authorization

General space regulatory uncertainty

- Article VI of Outer Space Treaty
- Proposals from White House, House of Representatives, Senate
  - Generally either NOAA or NOAA/FAA
- Regulatory agencies expect space nuclear will be a top priority for future regulator
- Unclear about how it works for a space resources and space nuclear mission – ex. who gets a license?

Potential policy issues

- Safety zones
- End-of-life
- Mission registration
- Lunar surface sustainability
- Liability
- International users

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