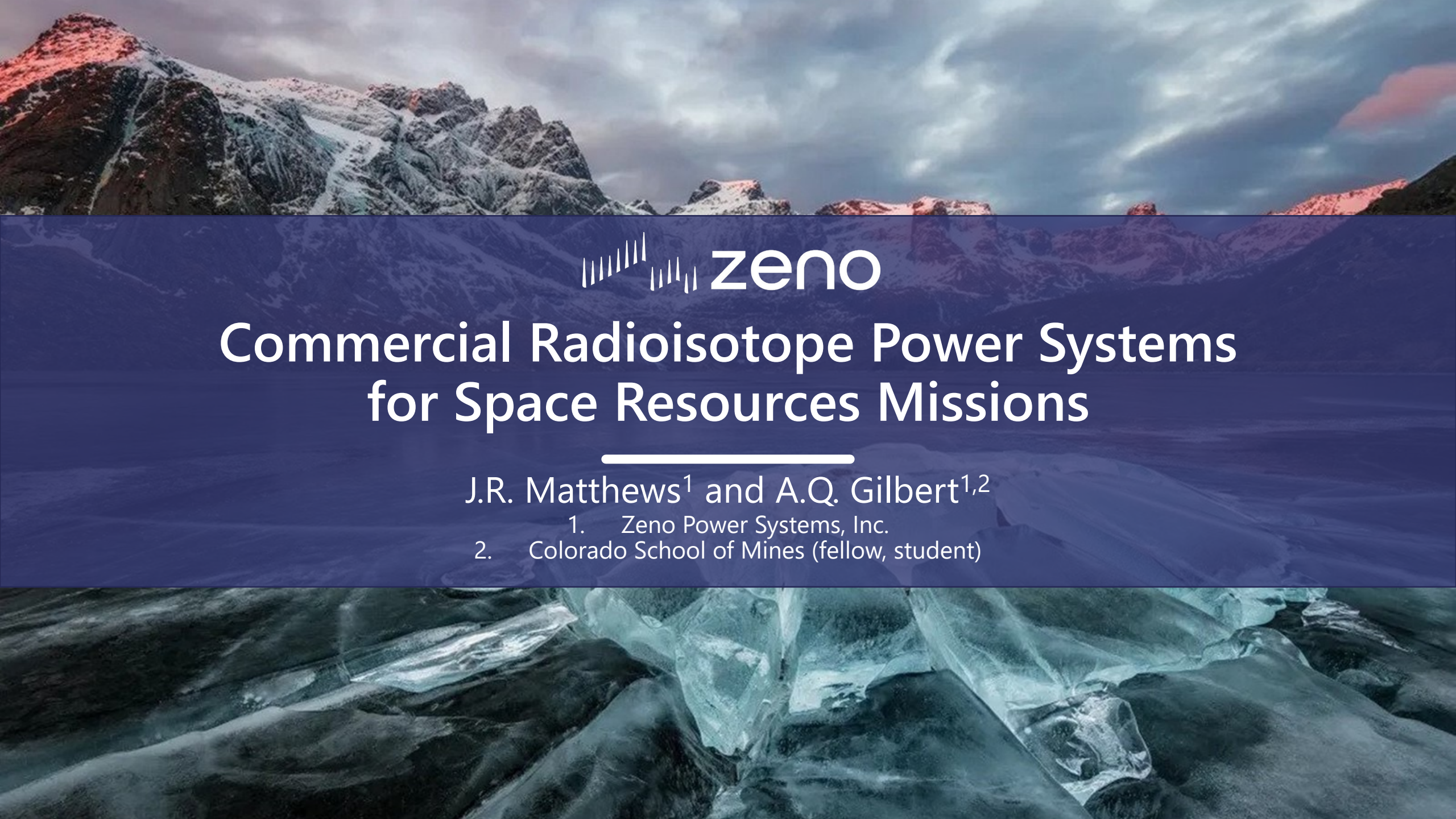
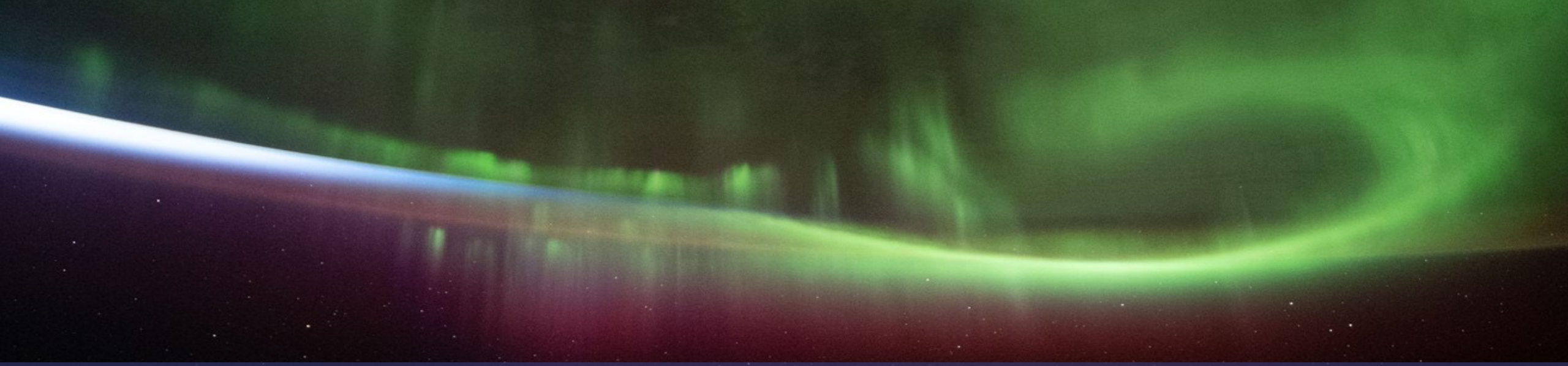


Commercial Radioisotope Power Systems for Space Resources Missions

J.R. Matthews[1] and A.Q. Gilbert[1,2]

1. Zeno Power Systems, Inc.
2. Colorado School of Mines (fellow, student)

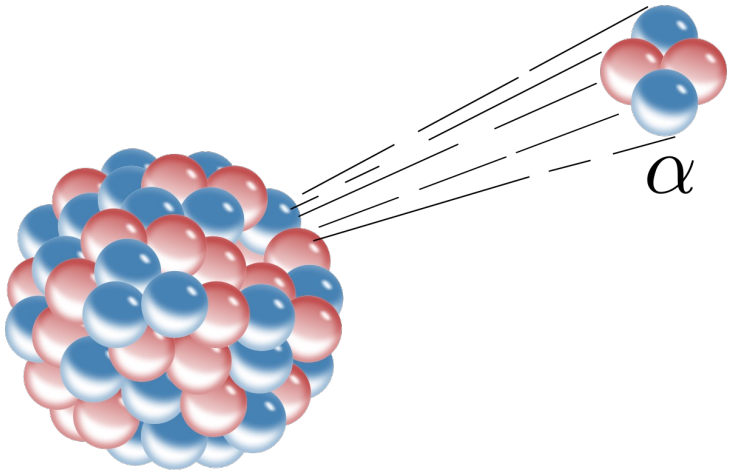


RPS Technology

Characteristics of radioisotope power

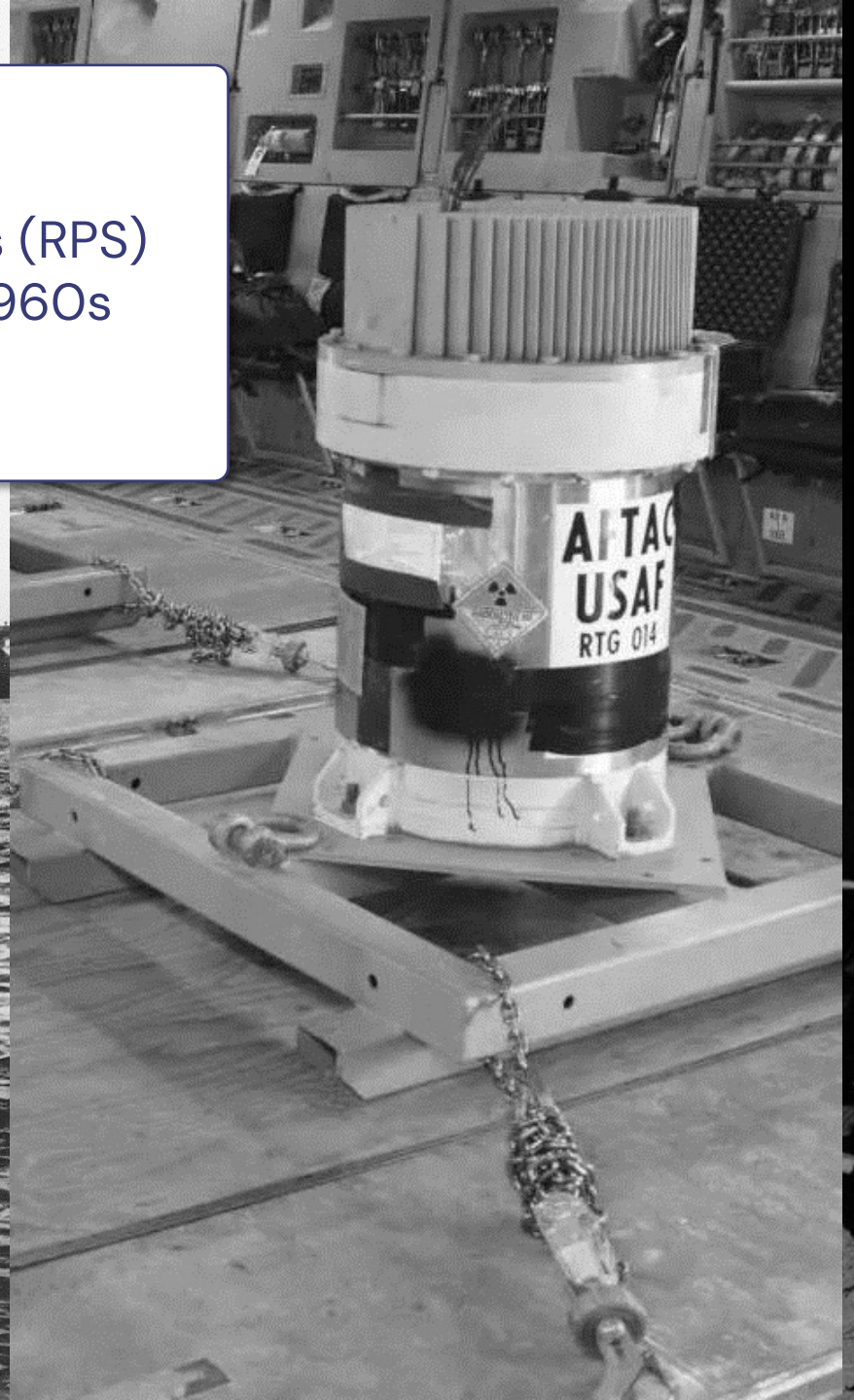
High-reliability power

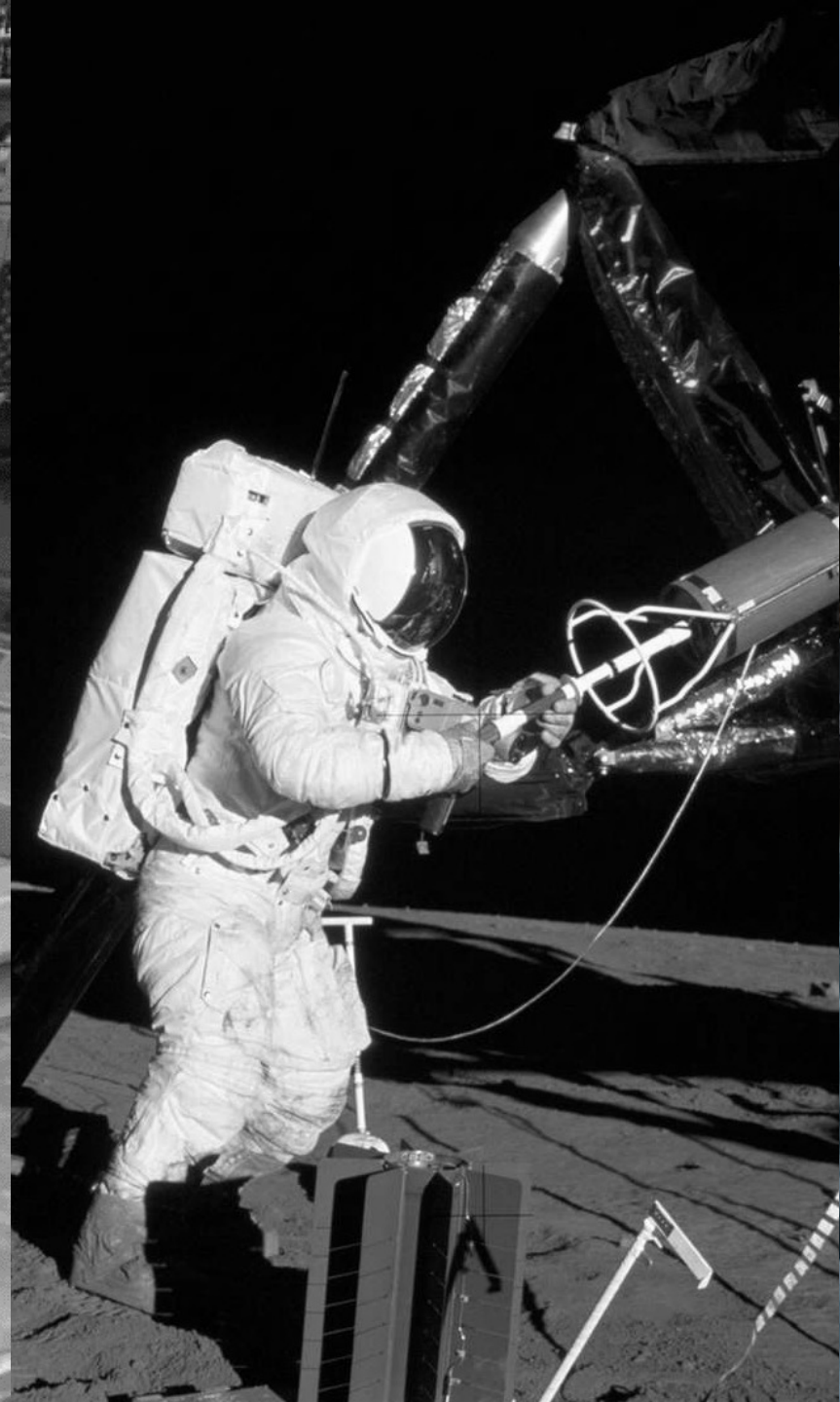
- Radioisotope power systems (RPS) use the predictable decay of certain unstable isotopes to produce heat
- Can provide heat from <1 watt-thermal to >1 kilowatt-thermal
- With thermoelectric or Stirling power conversion, can provide electricity at 5-25% efficiency, leading to power outputs from <1 watt-electric to 100s of watts-electric
- Heat and/or power can be provided to a spacecraft with very high reliability, for decades



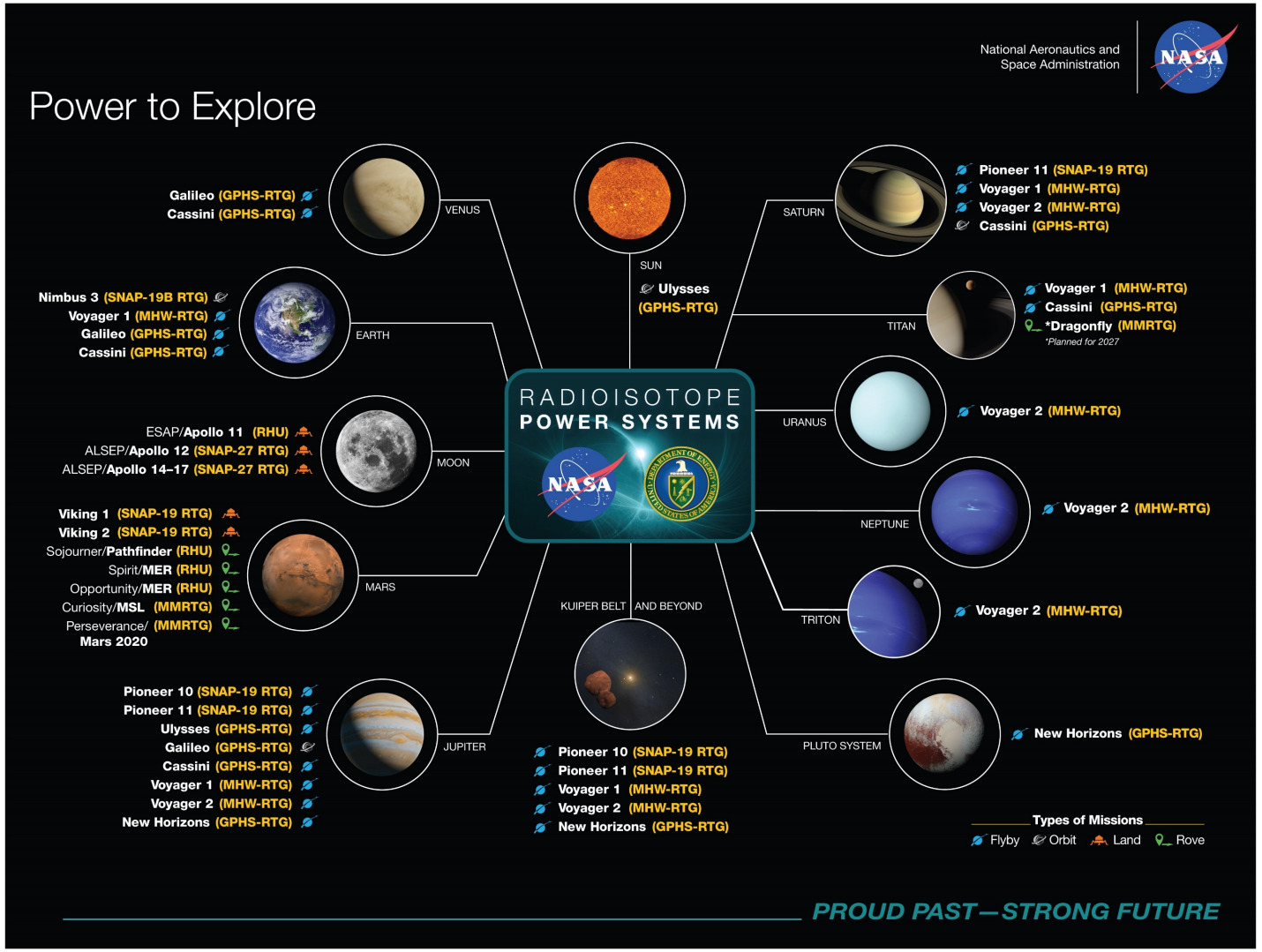
Example alpha decay

Radioisotope Power Systems (RPS) have been used since the 1960s



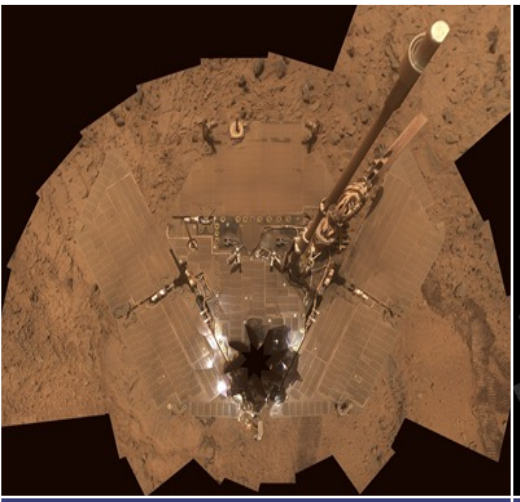


NASA's Plutonium-238 RPS



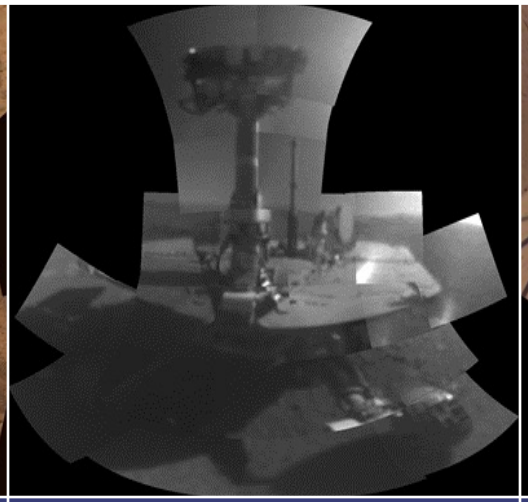
www.nasa.gov

Mars Rovers and Landers



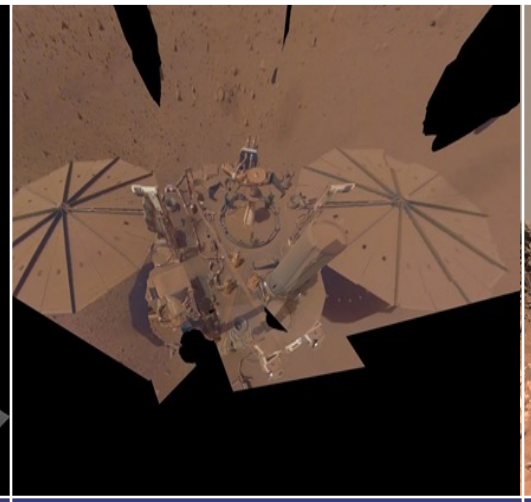
Spirit

Power: Solar
Heat: Radioisotope
Lifetime: 6.2 years (power lost)
Latitude: 14.6N



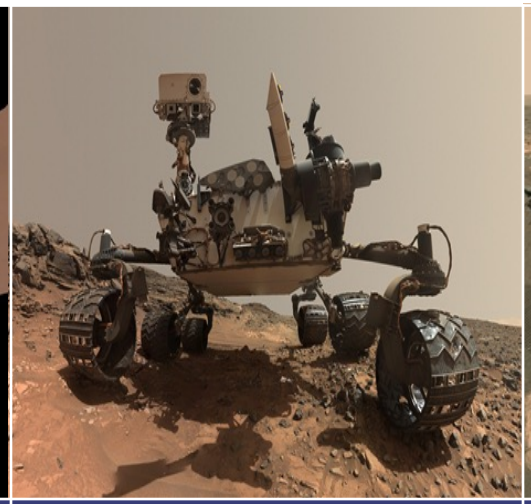
Opportunity

Power: Solar
Heat: Radioisotope
Lifetime: 14.4 years (power lost)
Latitude: 1.9S



Insight

Power: Solar
Heat: None
Lifetime: 4.0 years (power lost)
Latitude: 4.5N



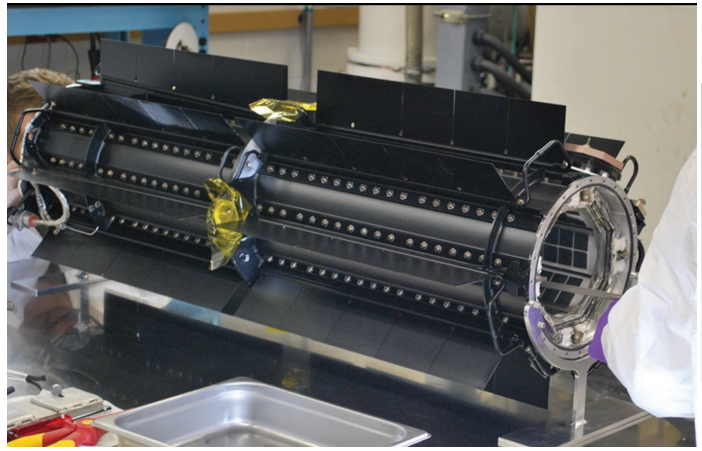
Curiosity

Power: Radioisotope
Heat: Radioisotope
Lifetime: 10+ years (still alive)
Latitude: 5.4S

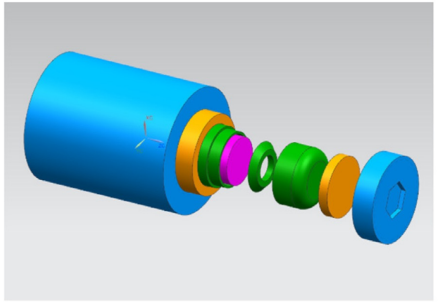
Perseverance

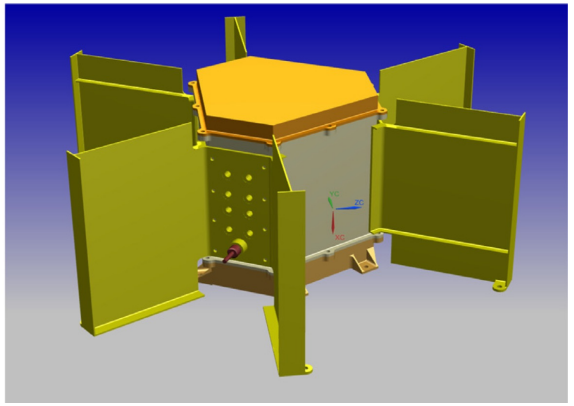
Power: Radioisotope
Heat: Radioisotope
Lifetime: 2+ years (still alive)
Latitude: 18.4N

Expanding RPS Technologies

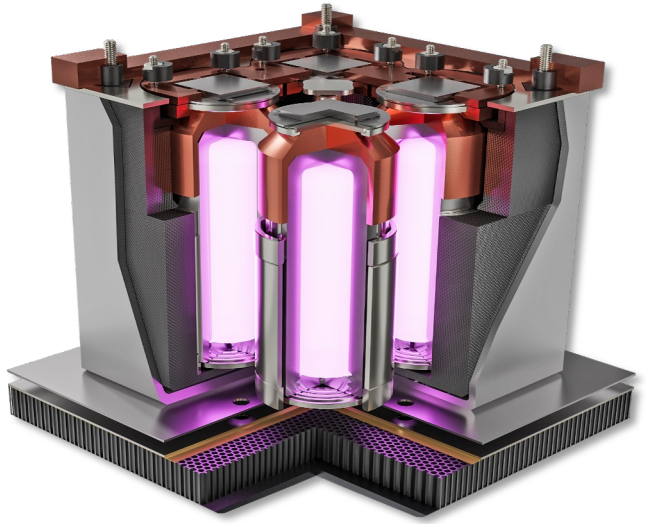


Next Gen RTG Mod-0
(Pu-238)



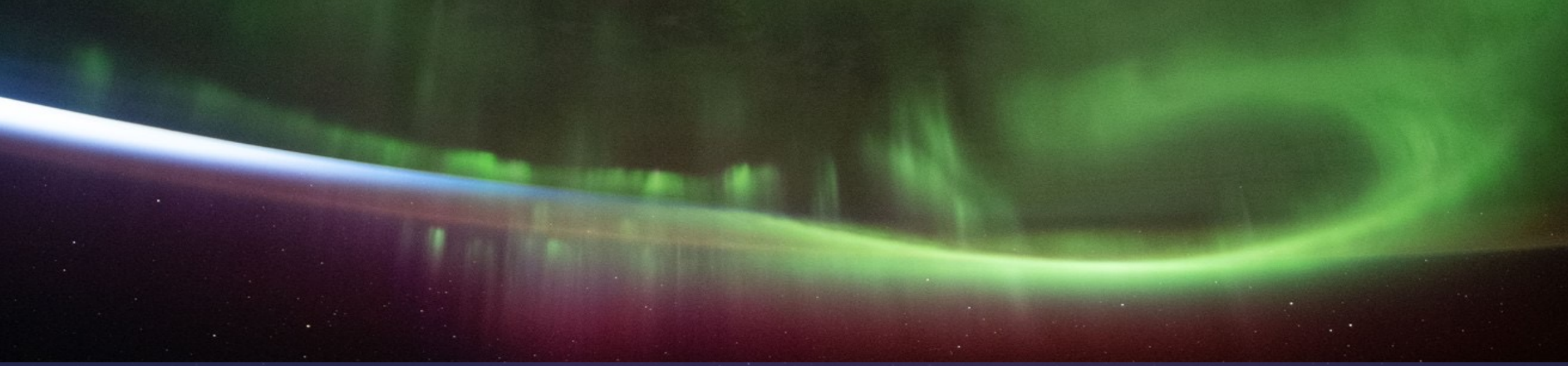


European RHU and RTG
(Am-241)



Zeno Power RPS
(Am-241, Sr-90)

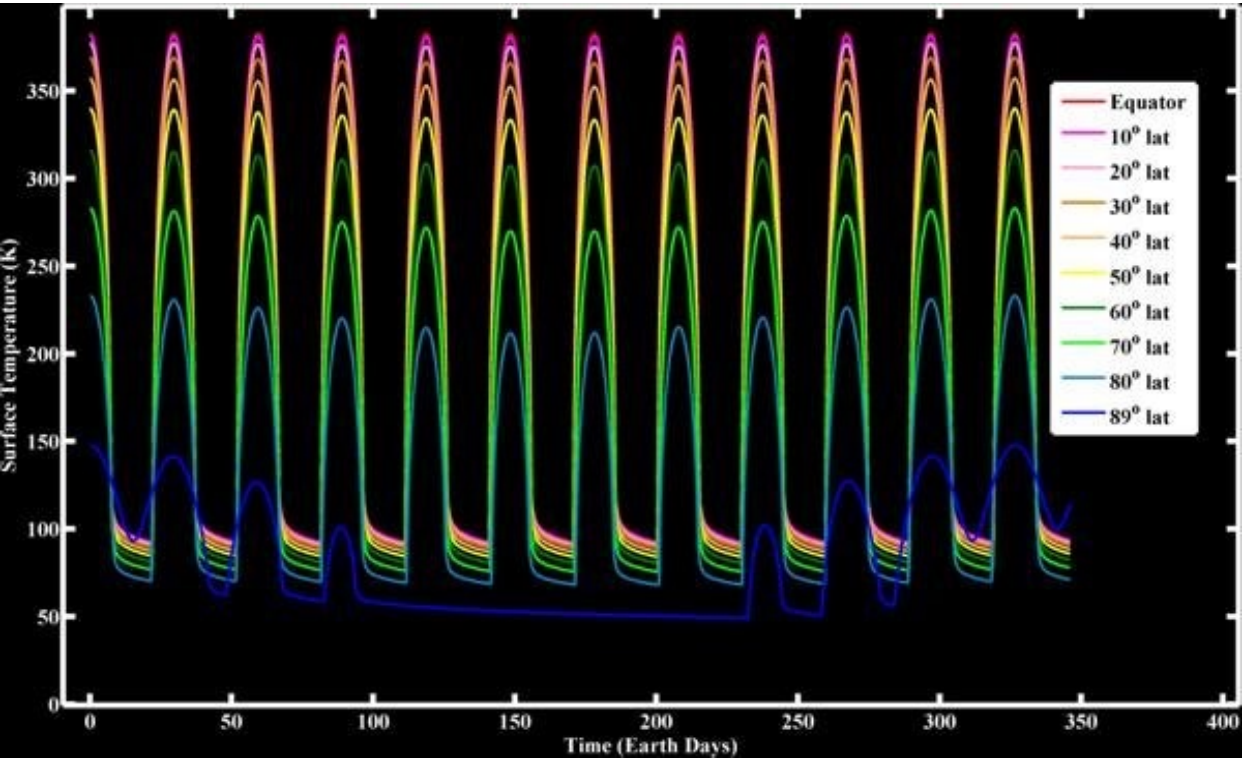
Sources: DOE, Barco et. al., Zeno Power

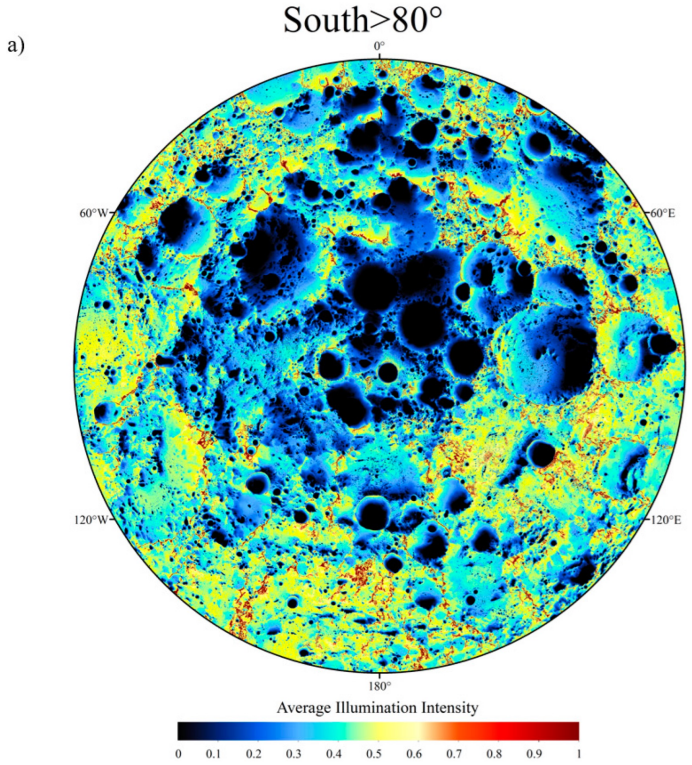


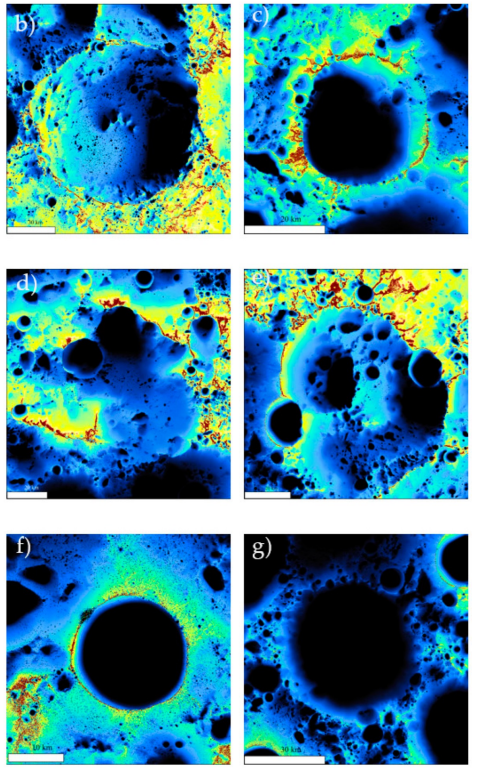
RPS for Space Resources

Survive the Lunar Night and Permanently Shadowed Regions

RPS enable spacecraft to survive the lunar night, lengthening spacecraft lifetimes (and therefore potential use-cases) by a significant amount

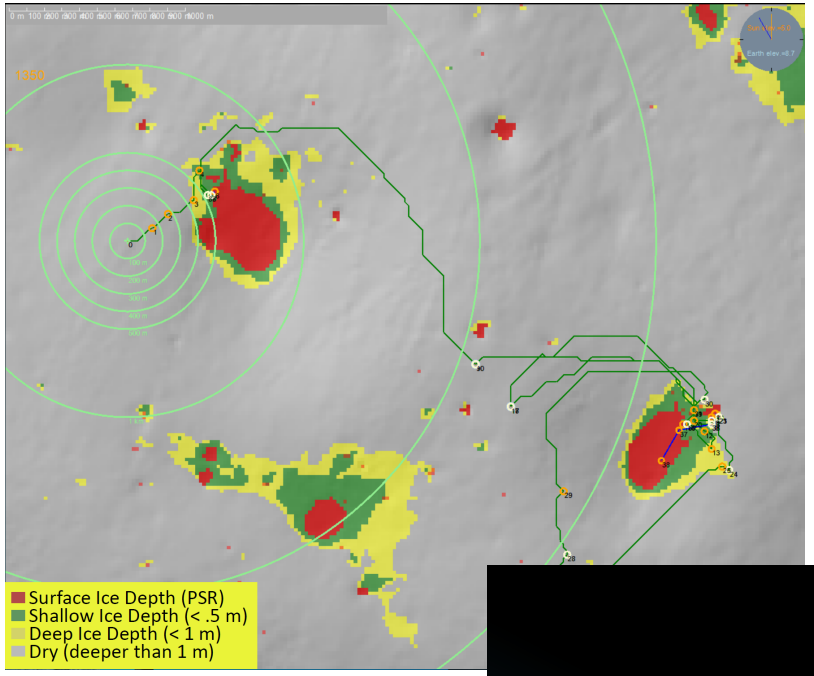


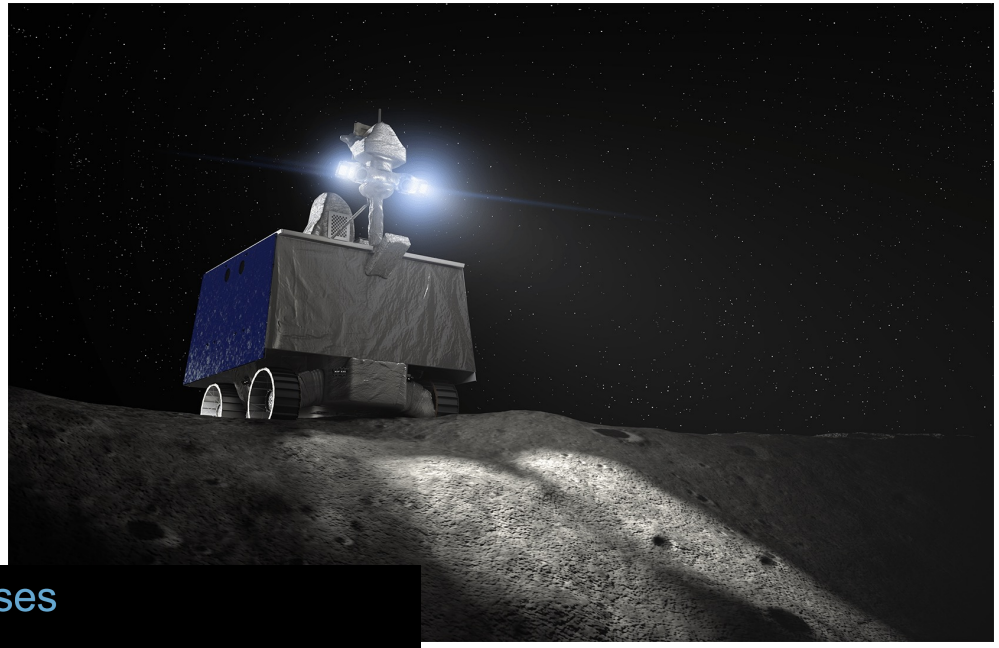


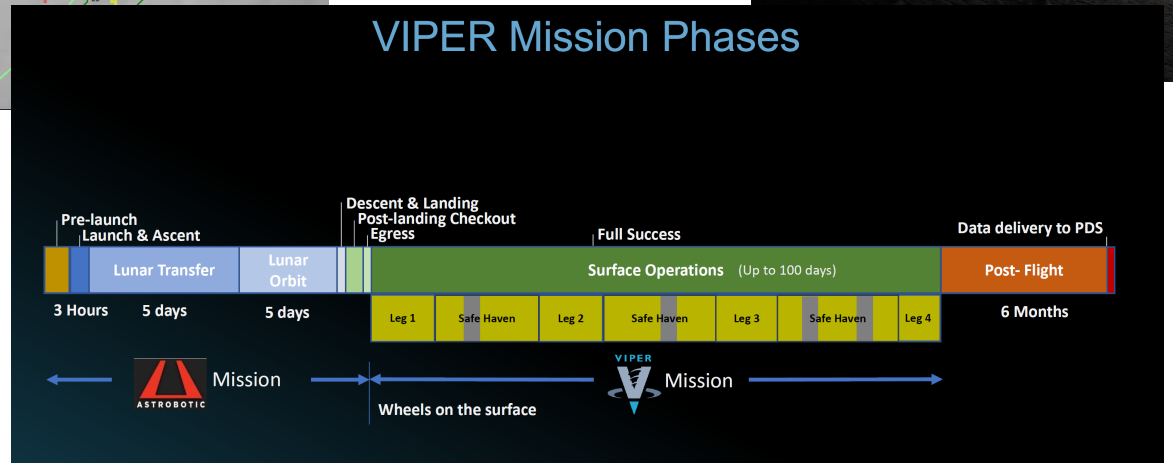


Images: NASA, Jia et. al.

Lunar surface without RPS







Images: NASA and Smith

Lunar surface with RPS

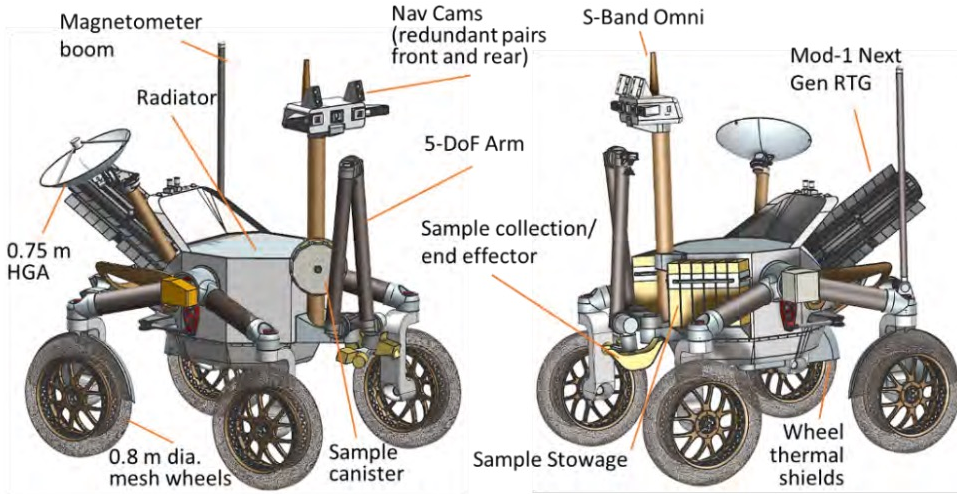
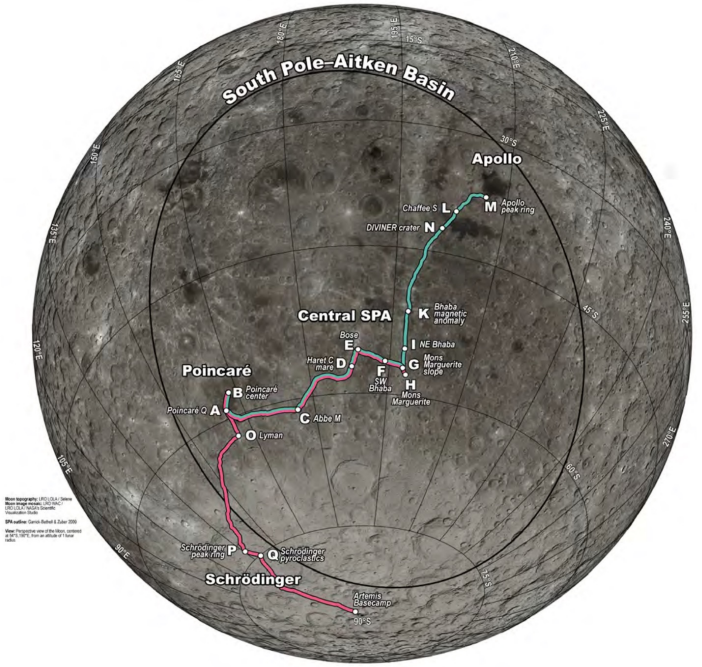
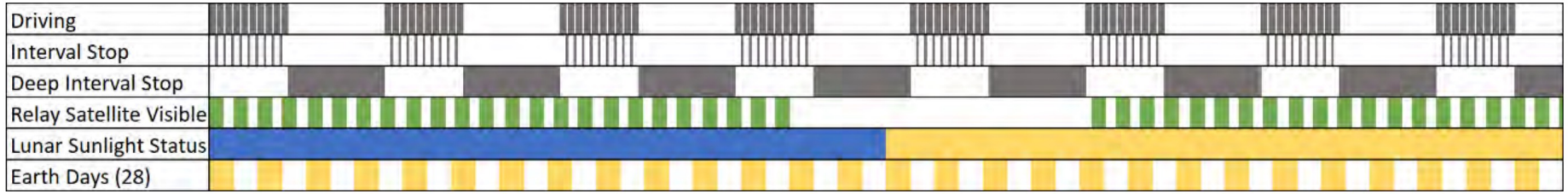


Figure 3-1. Rover overview (Endurance-R on left, Endurance-A on right). The rover designs are identical other than sample collection and caching systems.





Images: Keane et. al.

Figure 3-7. A typical lunar day during the Traverse phase. Note the 6-day relay satellite gap that occurs monthly.

Impact of RPS on Prospecting Missions

Rover	VIPER	ENDURANCE
Location	Only most favorable polar sites	Across lunar southern hemisphere
Duration	100 days	>5 years
Distance Travelled	~12 miles	~1,000 miles
Survive the Night Strategy	Safe Havens	Radioisotope
Operate in Night Strategy	Hibernation	Full operation
Extended mission?	Unlikely	Many options

Lunar Applications: Survive, Operate, Thrive

Artemis needs nuclear

Survive

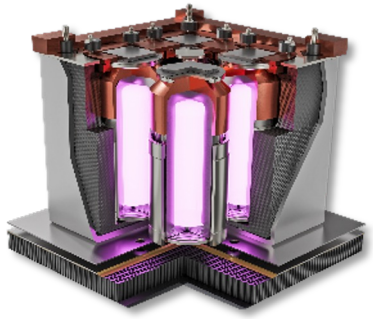
Problem: Reliable, redundant heat to enable survival of lunar infrastructure without sensitivity to landing location

Capability: Modular, distributable Radioisotope Heater Units (RHU) ranging from 1-15 W_t

Operate

Problem: Simple, distributed power network to enable continuous lunar operations anywhere on the moon

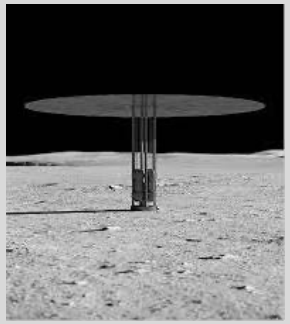
Capability: Modular, distributable RTGs and dynamic RPS ranging from 10-100 W_e



Thrive

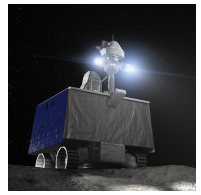
Problem: ISRU and human habitation will require 100s of kW capable of emplacement anywhere on the moon

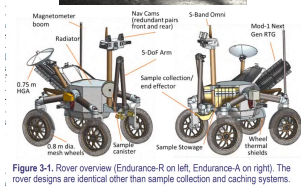
Capability: distributed RPS-powered nodes, >10kW nuclear reactors



Paired Technology Development Pathway

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





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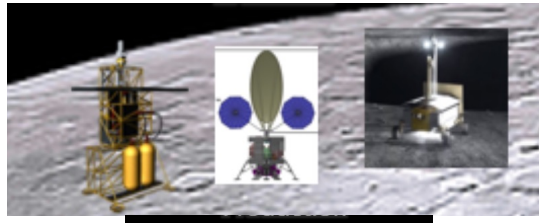
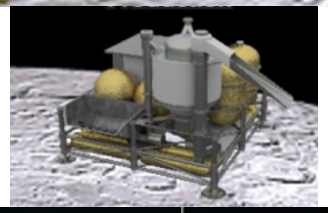


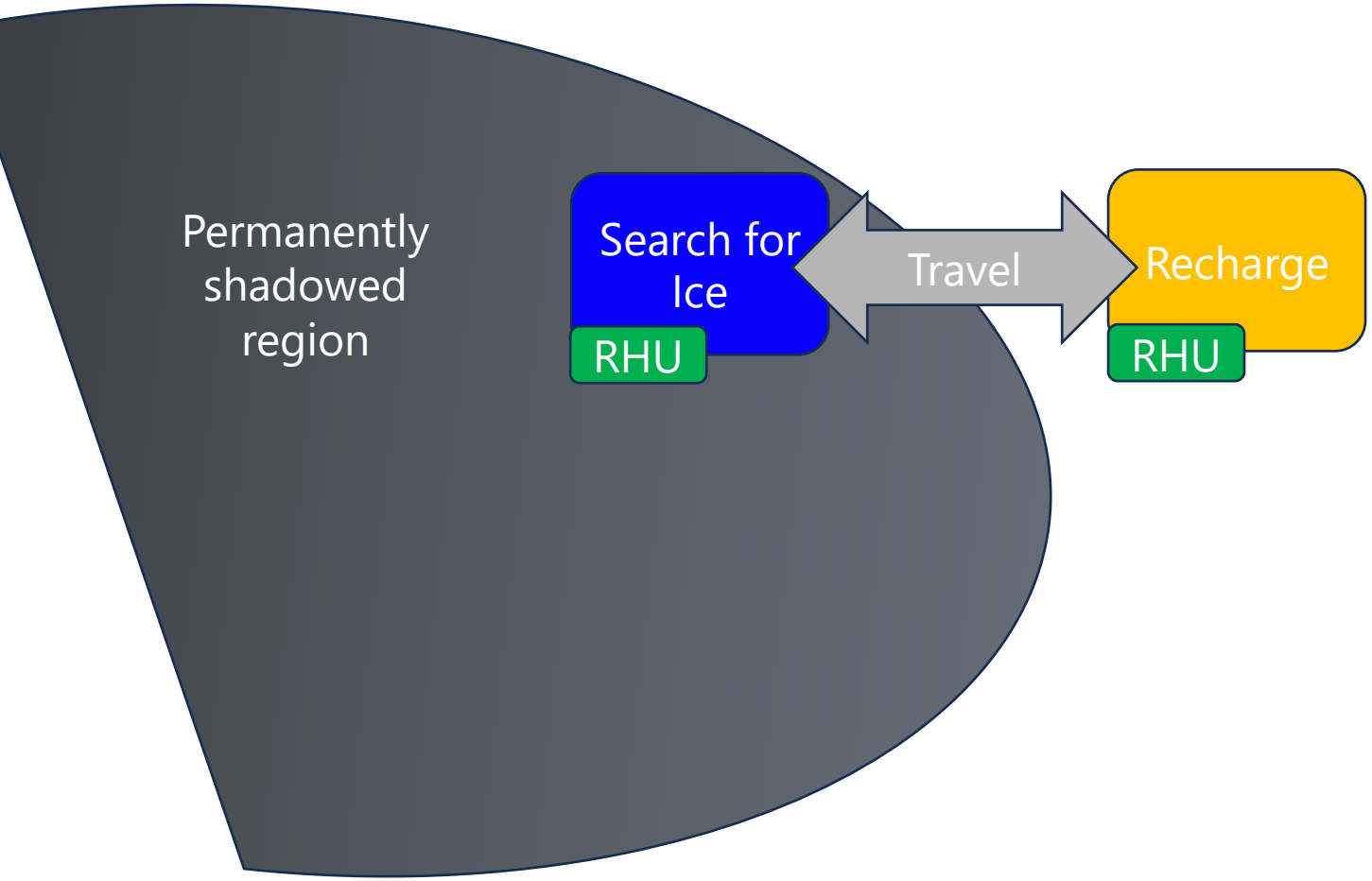


- RPS - Survive
- Low Power RPS
- Higher Power RPS (100s We)
- Early Fission, widespread RPS
- Industrial Fission, ubiquitous RPS

Images: Smith, Keane, NASA, ICON

Science

Image: Smith



Prospecting

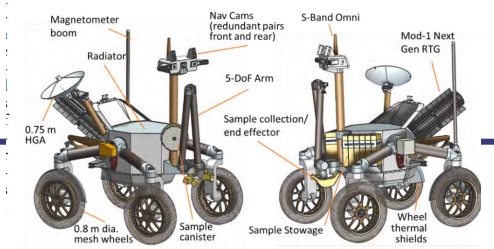


Figure 3-1. Rover overview (Endurance-R on left, Endurance-A on right). The rover designs are identical other than sample collection and caching systems.

Image: Keane

Permanently shadowed region

Search for Ice

RHU RPS

Travel

Search for Ice

RHU RPS

Demonstration

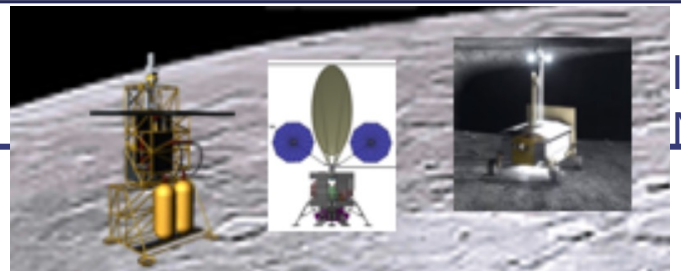
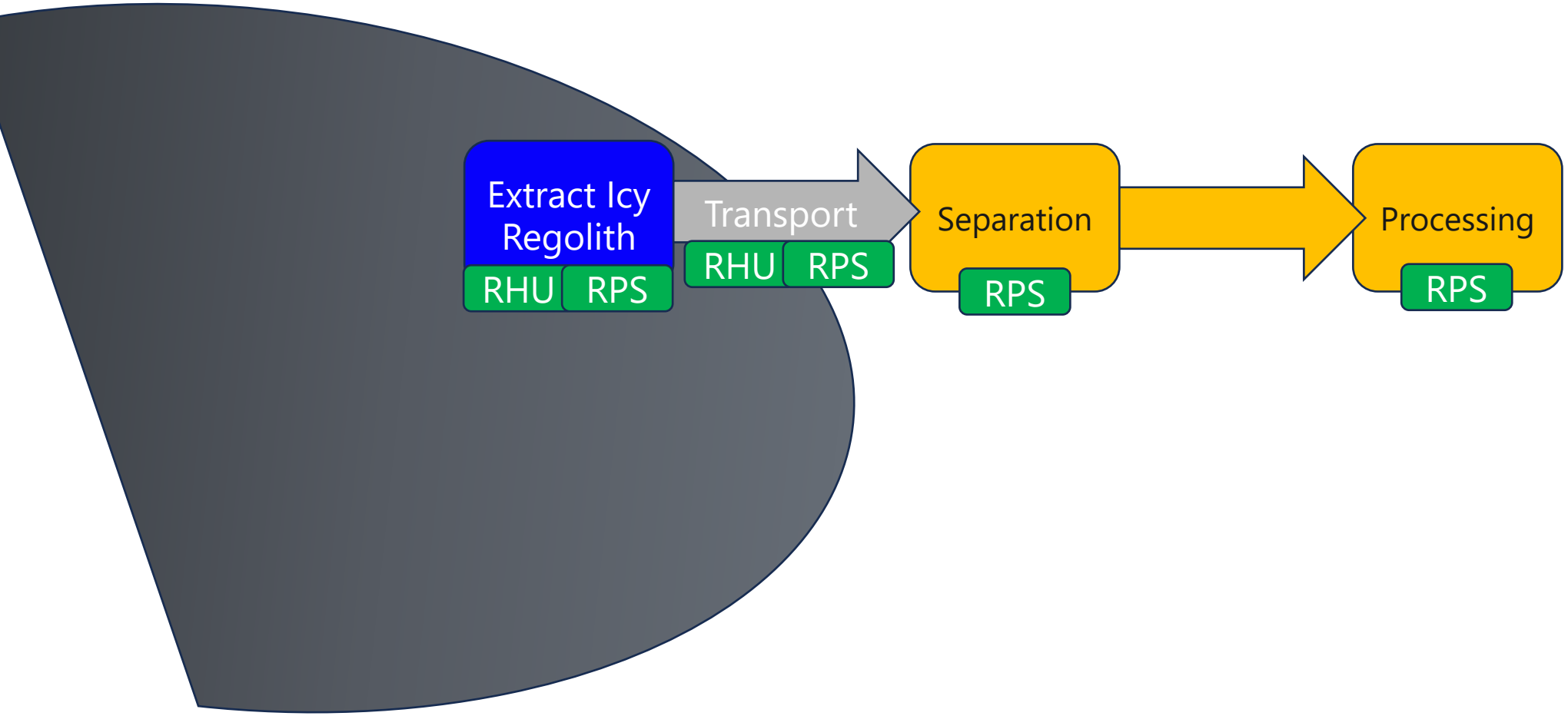


Image: NASA



Artisanal

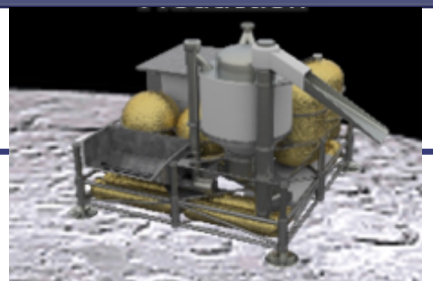


Image: NASA

Permanently shadowed region

Extract Icy Regolith

RHU RPS

Transport

RHU RPS

Separation

FSP

Processing

Storage

RHU

Use or shipment off Moon?

Emerging support architecture (PNT, comms, etc.)

RHU RPS

Industrial

Image: ICON

Permanently shadowed region

Extract Icy Regolith

RHU RPS

Transport

RHU RPS

Separation

Transport

Processing

MW FSP

Storage

RHU

Use or shipment off Moon

NEP/NTP

Distributed support architecture (PNT, comms, rover recharging and heat stations, etc.)

RHU RPS

RPS Expands Lunar Ice Resource Base

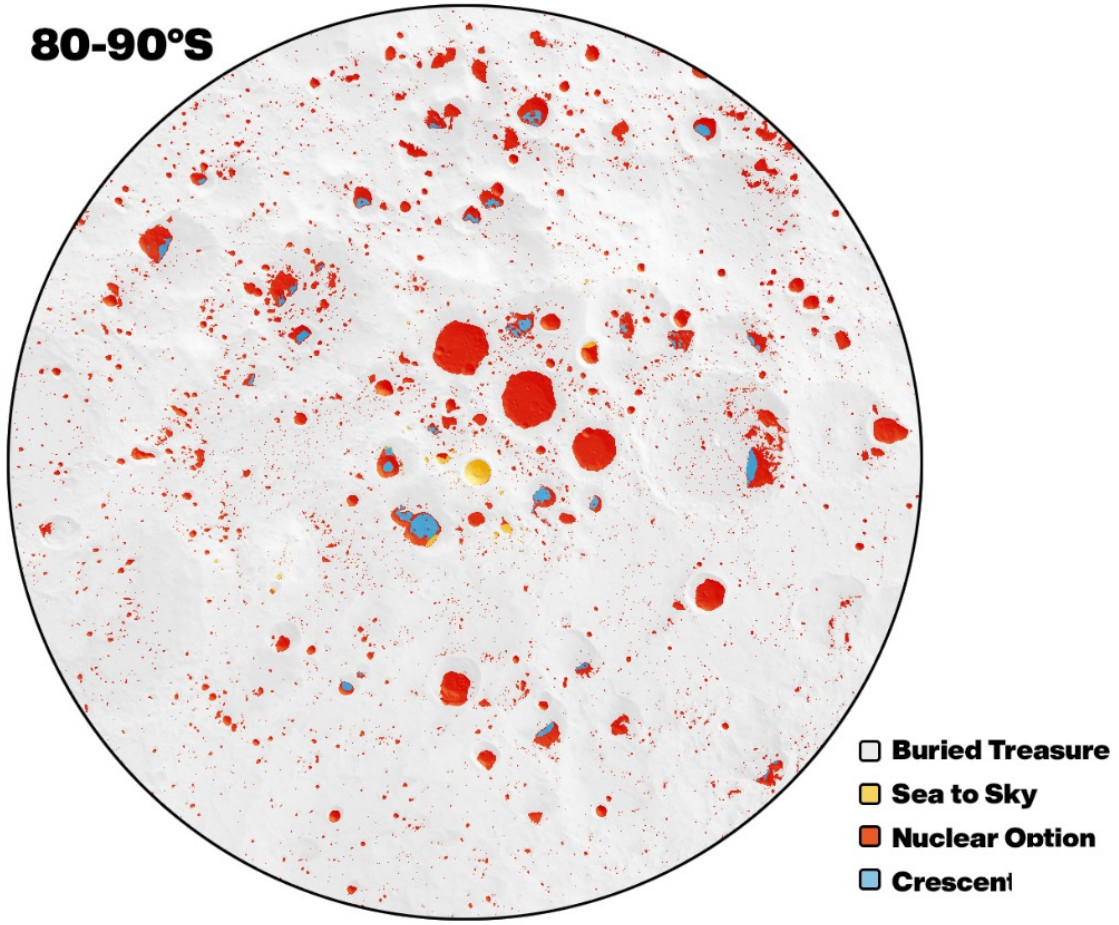
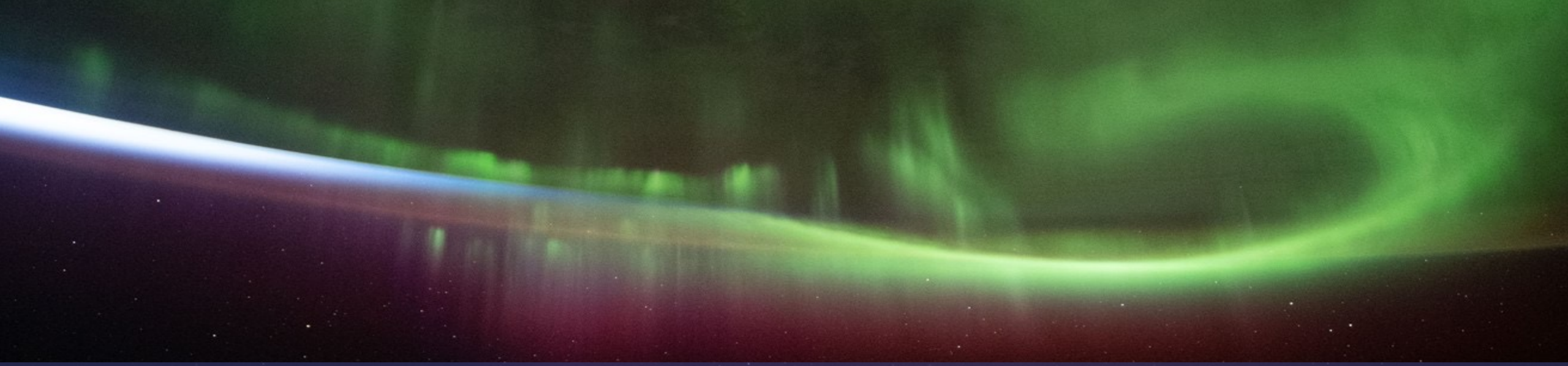


Image: Cannon



Zeno RPS Technologies

Z1: the First Sr-90 Heat Source in 40 years

Design Parameters

- Radioisotope: Sr-90
- Power: 2.5 W_t
- Dimensions: 76.15mm (ø) x 83.75mm (H)

Goals accomplished!

1. build nuclear hardware
2. transfer benchtop non-rad fabrication flowsheet into a hot cell environment at a National Lab
3. validation of bremsstrahlung radiation with our novel fuel matrix and shielding
4. validation of Zeno's computational modeling tools with data.

PNNL Hot Cell for Fabrication

Z1 Heat Source Demonstration

Z1 Heat Source and Shielding Capsule

We've secured our initial nuclear fuel supply and facilities

FUEL

- Zeno has acquired a legacy source of Sr-90 from the Department of Energy – providing fuel for 10+ RPSs
- Zeno is engaged with commercial partners to extract large-scale quantities of Am-241

FACILITIES

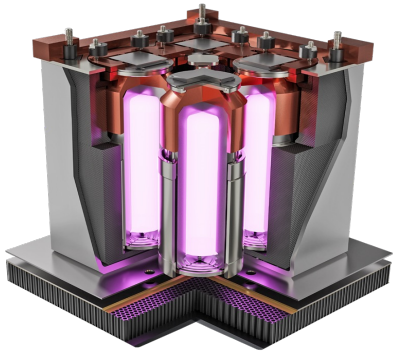
- Zeno is under contract with Westinghouse to utilize their radiological facility to build and assemble the initial RPSs

Developing full suite of RPSs

RHUs

Size: 1s W_t – 10s W_t
Efficiency: N/A
Status: Pre-Conceptual

RTGs



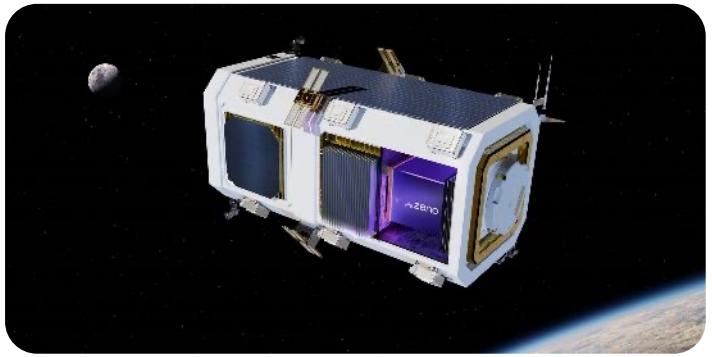
Size: 10s W_e – 100s W_e
Efficiency: ~5%
Status: Final Design Review
Demonstration: 2026

RSGs

Size: 10s W_e – 100s W_e
Efficiency: ~25%
Status: Preliminary Design Review
Demonstration: 2026

First missions

Space



LENS

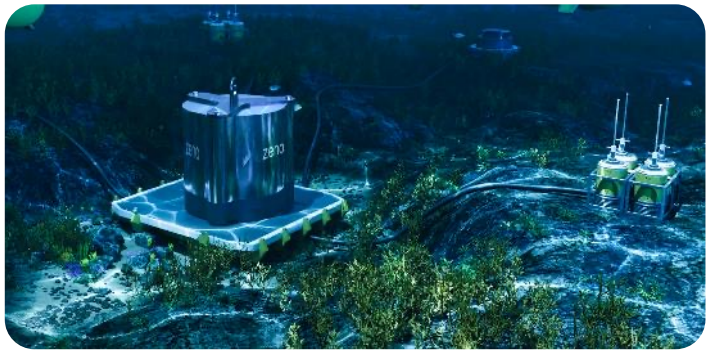
Customer: US Space Force
Description: Sr-90 RTG to enable dynamic space operations

Moon

Harmonia

Customer: NASA
Description: Am-241 ESG for lunar surface

Maritime



Maritime

Customer: US Navy
Description: Sr-90 RSG for power on the seabed

RHU

- Currently developing a RHU for lunar surface applications
- Seeking input from end users
- General parameters of 1-10 watts-thermal
- Approximately 24 months lead time from order to launch
  - Missions as soon as 2026

RHU RFI survey