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MISSION CONCEPT CONSIDERATIONS FOR OCEAN WORLD EXPLORATION USING RPS INSIDE A PRESSURE VESSEL

Young H. Lee, Tibor Balint, Brian Bairstow, Benjamin Donitz

Jet Propulsion Laboratory, California Institute of Technology

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RPS-enabled Mission Themes

❖ RPS might make deep space exploration more feasible for orbital and flyby missions. These missions can be applicable to any of the following themes:

- Identifying Ocean Worlds
  - Finding and characterizing ocean worlds for further exploration
- Characterize oceans
  - To reach the ocean in situ, RPS is likely required
  - Heat source would be required and is available from the RPS directly
- Assess habitability
  - To reach inside the ice or ocean, RPS is likely required
  - Heat source would be provided by RPS
  - Better understanding of how to ensure samples are not destroyed by the heat or radiation is required
  - Better understanding of heat dissipation of the RPS in an alien ocean is required
- Search for life
  - To reach inside the ice or ocean, RPS is likely required
  - Heat source would be provided by RPS
  - Better understanding of how to ensure samples are not destroyed by the heat or radiation
  - Better understanding of heat dissipation of the RPS in an alien ocean

Exploration with RPS inside a Pressure Vessel

- Ocean Worlds Science
- Ocean Worlds Characteristics and Extreme Environments
- Notional Instruments
- Pressure Vessel Considerations
- Considerations for an RPS (Inside a Pressure Vessel)
- RPS-Specific Planetary Protection Considerations
- Concept of Operations Through Mission Phases
- Key Planetary Protection ConOps Steps and Points
- General Key Findings
- RPS-enabled Mission Themes
- Acknowledgements

If developed, an RPS Inside a Pressure Vessel would enable future Ocean and Ice Worlds exploration missions

Ocean Worlds Science

❖Considered five science objectives

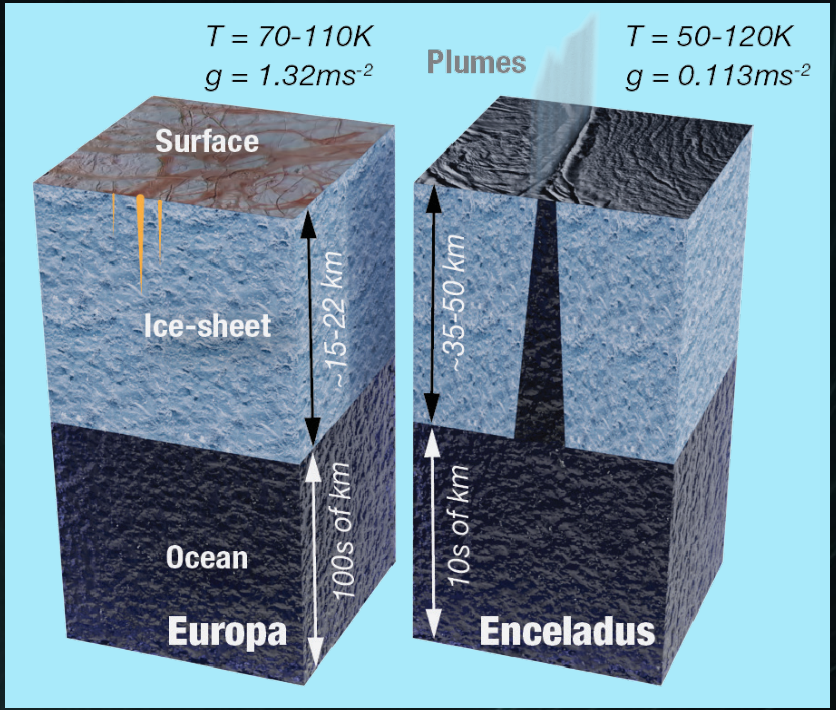
1. Search for and characterization of life within the ice shell and ocean
2. Investigate the habitability of the ice shell and ocean
3. Characterize the physical properties within the ice shell and ocean
4. Characterize the chemical state and processes within the ice shell and ocean
5. Investigate the ice-ocean interface, including chemical and physical processes and material exchange

❖Considered Ocean Worlds destinations

- Europa and Enceladus as baseline cases for ice-shell and ocean explorations with an RPS inside a pressure vessel
- Considerations for and sensitivities to other destinations were also examined

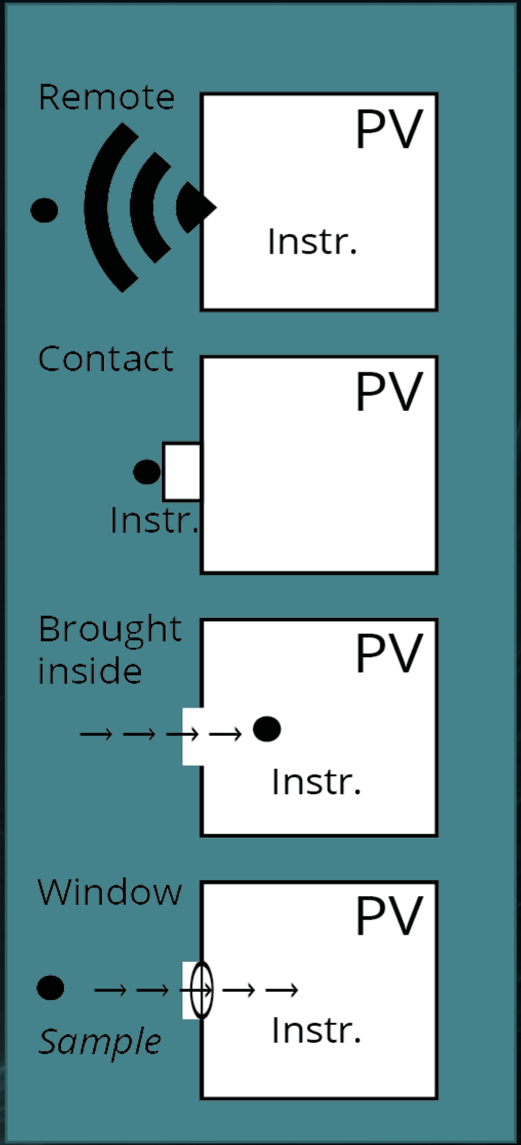
Ocean World Characteristics and Extreme Environments

- Salts in the ice
  - Sublimated ice deposits on probe
  - Salt concentration may vary along path
- Porous ice
  - Connection to the surface
  - Trapped gases could explode
- Ice regimes
  - Near surface: cold, thermally conductive
  - Interior ice: more insulated, warmer Faults may penetrate deep, seismic events.
- Ice-ocean interface
  - Unknown topography, structure, Transition thickness, and conditions
- Other factors
  - Low gravity, buoyancy
- Ocean currents
  - Surface jets connecting to the ocean Impact glide speed, maneuverability



Notional Instruments

- An RPS would be used to
  - Power the payload and subsystems and provide heat for survival, ice melting, and mobility in the ice and the ocean
- Science measurements could be done through
  a) Remote sensing (e.g., sonar ranging)
  b) Contact with the ice or liquid outside the PV (e.g., thermophysical property suite, pitot tube)
  c) Samples brought inside the PV through an opening (e.g., GCMS, holographic Microscope, In situ sampling)
  d) Measurements through a window (e.g., Raman Spectrometer, Cameras, LIBS)
- Must ensure that the heat and radiation from the RPS wouldn't be altering the samples
- For a notional payload suite, ~75-100 kg and ~60-80 W_e considered
- Power, mass, and volume of these instruments would influence the RPS and pressure vessel sizing



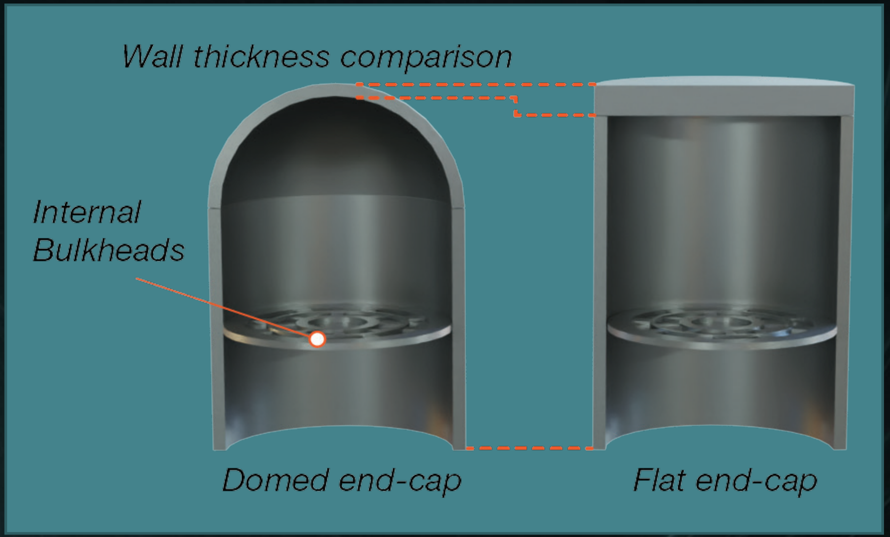
Pressure Vessel Considerations (1)

- ❖ Pressure vessel protects and houses the RPS, payload, and subsystems

- ❖ Using additive manufacturing could:
  - Create complex, optimized, generative structures
  - Manufacture hybrid structures that integrate heat pipes, fluid channels, and wiring paths into the structural shell
  - Construct high/low-conductivity regions
  - 3D print corrosion resistant PV walls from Inconel-718 to protect the payload

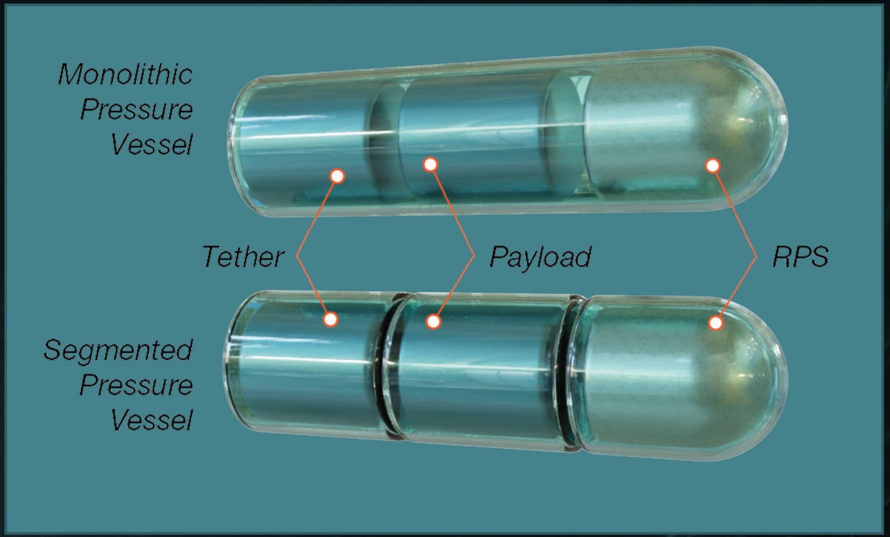
- ❖ A unique thermal design could
  - Direct heat for survival
  - Heat to pressure vessel walls for ice melting, and
  - Reject excess heat to the environment

- ❖ Buckling under high pressure is a typical failure mode
  - Thicker walls
  - Domed caps
  - Flat end caps have advantages and disadvantages.



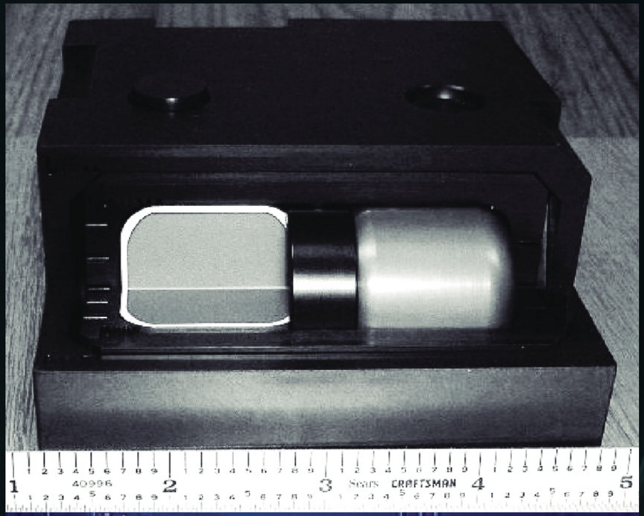
Pressure Vessel Considerations (2)

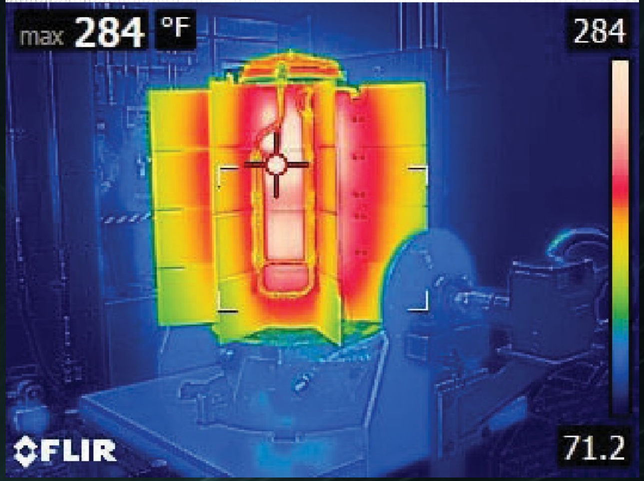
- Feedthroughs for electrical wiring, sample acquisition, and windows
  - Could weaken the pressure vessel structure
  - May introduce thermal issues
  - Need to be safe against differential pressure across the wall, and sealed to prevent fluid ingress
- The pressure vessel could be
  - evacuated or pressurized
  - segmented or subdivided to multiple sections
- Need to address purging of the RPS-generated helium (a byproduct of Pu-238 radioisotope decay)
- Pressure vessel designs must be customized and optimized through all mission phases, and for target environments



Considerations for an RPS (Inside a pressure vessel)

- Study approach was agnostic to the RPS inside the pressure vessel design. We assumed:
  - 75kg for the RPS with ~50–300 W_e and ~1500–4000 W_t
  - Static or dynamic conversion
  - Step-2 (GPHS) modules (~250 W_t at BOL)
- Assumed RPS dimensions inside the pressure vessel:
  - 20–35 cm (finless diameter) and 90–110 cm (length)
- Excess heat would be used for
  - Component heating, or rejected through the pressure vessel for ice melting
- Challenges to fit an RPS inside the
  - Proximity of radiation source to instruments
  - Mitigation: distance, shielding, rad hard components
- RPS design lifetime is 17 years from BOL (fueling) to EOL (decommissioning)
  - This may need to be revisited for Ocean Worlds missions



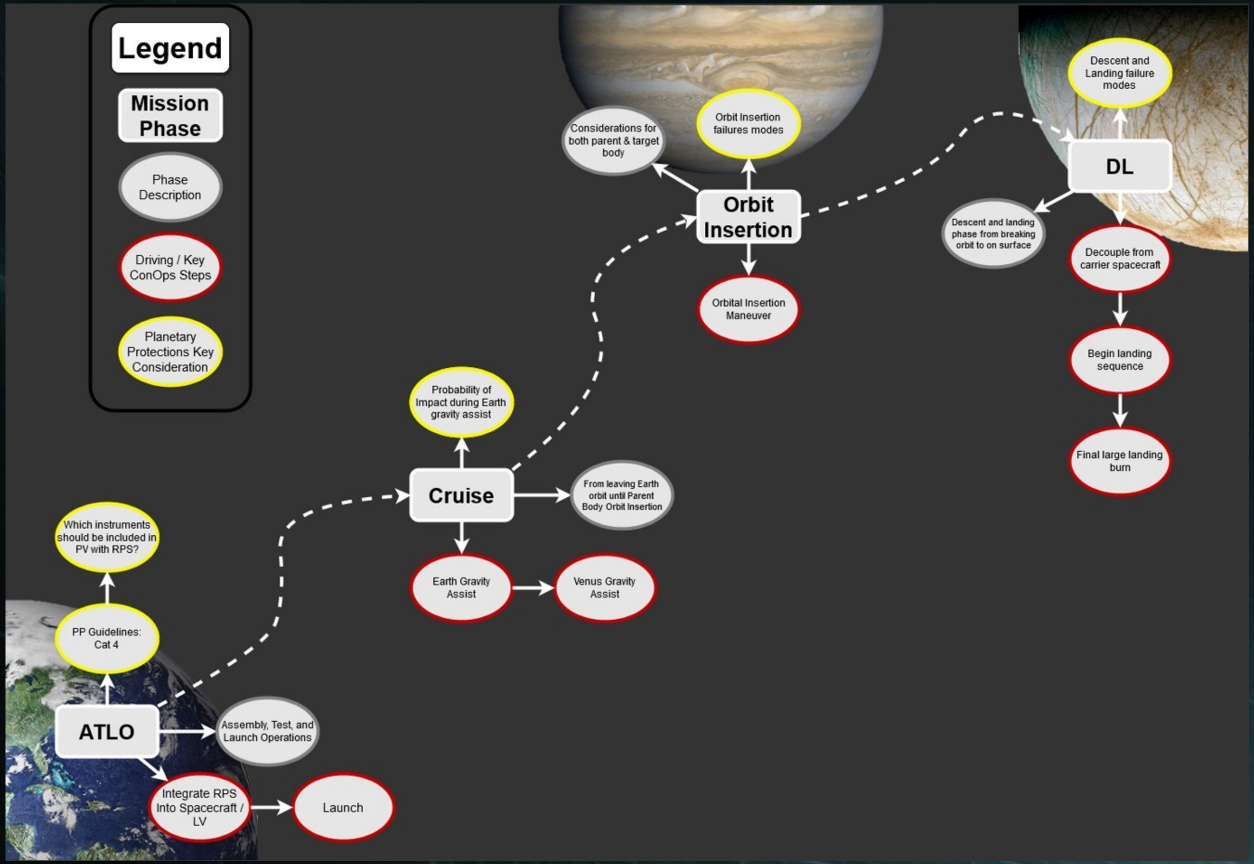


RPS-Specific Planetary Protection Considerations

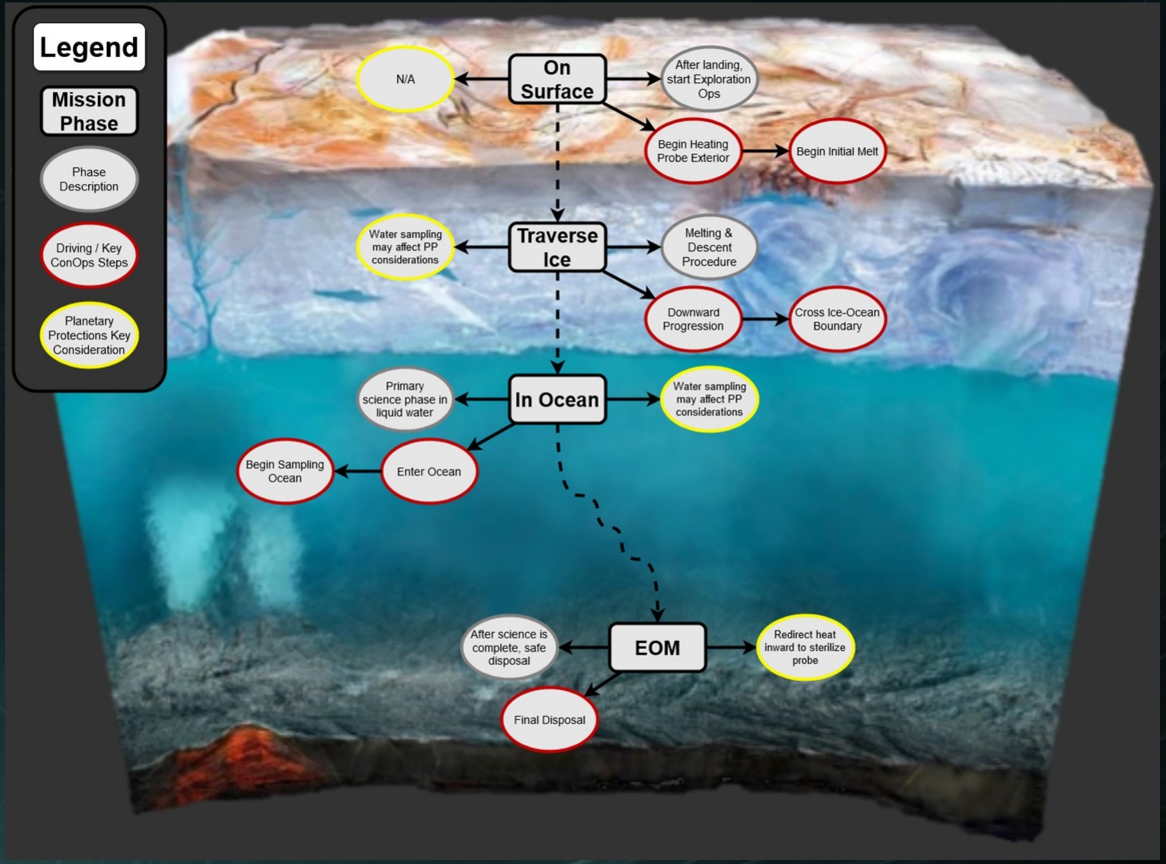
- ❖Physical placement of the RPS system needs to be far enough away from the instrument testbed/work volume/sample ingest such that heat and radiation do not impact the scientific integrity of the mission objectives
- ❖Instrument operation needs to be tested in the same proximity as an active RPS system to build confidence that datasets are not being modified by an active radiation source
  - Cameras for image quality
  - Organic detection analyses (Raman, GC) with regard to yield and sample ingest
  - Analysis (XRD, GCMS) with regard to organic magnitudes
  - Non-Brownian motion (DHM, SoS) with regard to cell mobility

Concept of Operations Through Mission Phases
Key ConOps Steps Discussed

Transport and Transit Operations



Exploration Operations



ConOps Steps and Points, Key Planetary Protection (1)

- Assembly, Test, Launch and Operations
  - Initiate mission launch support preparation
    - Planetary protection guidelines determined: Cat IV
  - Acceptance testing of RPS in a pressure vessel system
    - Which instruments should be included inside the pressure vessel with the RPS? This will affect ConOps of sampling and planetary protection considerations
- Launch
  - Safety and reliability in failure modes
- Cruise
  - Earth-gravity assist
    - Probability of impact
- Orbit insertion
  - Begin orbit insertion phase
    - Failure modes need to be carefully explored, including in the context of planetary protection
- Descent and landing
  - Begin descent and landing phase
    - Failure modes need to be carefully explored, including in the context of planetary protection

ConOps Steps and Points, Key Planetary Protection (2)

- On surface
  - None identified
- Traversing ice
  - Science (liquid sampling)
    - How is water ingested and how are samples captured? This will affect instruments and potentially planetary protection as well
  - Cross ice–ocean boundary
    - Need to make sure that samples don't get destroyed at ice–ocean interface with the RPS. Need to be able to obtain untainted sample
- In ocean
  - Begin sampling ocean
    - The sample strategy for each instrument will likely be a driving consideration and vary from one instrument to another. Sampling technique might also drive PP considerations. If samples are coming inside the probe, they will need to be kept away from any non-sterilized instruments/surfaces
- End of Mission
  - Redirect heat inward to sterilize probe
    - Redirect all heat inward to reach a maximum internal temperature and bake out any Earth-origin contaminants

General Key Findings (1)

- Lifetime
  - RPS technologies will need careful consideration of their total lifetime to ensure not getting stuck in the ice due to degradation over the multiyear mission
- Vibration
  - Different RPS technologies might have different vibration tolerance and interact with the payload in different ways. This vibration concern needs further exploration
- Planetary protection
  - Planetary protection would inform considerations and requirements for near bodies (Earth, flybys, and target), in-ice and in-ocean operations, sampling, and decommissioning
- Payload
  - Payload would likely not be a driving factor for RPS size/power - heat required to get through ice would
- Corrosion
  - Corrosive elements in the environment might drive the design and composition of the pressure vessel or whatever surface is exposed
- Surface anchoring
  - For low-gravity bodies especially, anchoring to the surface might be a major challenge. Since surface hardness and porosity will be difficult or impossible to determine prior, anchoring stability and method will need careful consideration

General Key Findings (2)

- Heat-distribution method
  - During ice traversal, most heat will need to be directed to the front of the probe. This amount might need to vary to slow the probe down for sampling, making a variable distribution system ideal. Needs further exploration
- Heat management during decoupling
  - If the heat rejection system is physically part of the cruise phase, the lander must be able to survive the heat buildup during the landing sequence while radiators will likely be inaccessible. Upon landing, the lander would be able to deploy new radiators or begin bleeding heat into surface (trade required)
- RPS physical size
  - Physical size of the RPS is driven by the probe diameter, general-purpose heat source (GPHS) configuration, and Department of Energy's shipping container size
- Thermal power
  - RPS needs to consistently produce 6–8 kW_t to enable probe descent through ice
- Control in Ice
  - It will be necessary to be able to control speed and, to some extent, trajectory of descent to collect samples and avoid obstructions within the ice

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