Enabling the Next Frontiers in Astrobiology —Ocean and Ice Worlds Explorations with a Radioisotope Power System Inside a Pressure Vessel

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Introduction

A new exploration paradigm requires novel technological solutions. Exploring Ocean and Ice Worlds [1] below the surface could help us to understand the origin and evolution of life in the universe, and how these bodies form and evolve [2]. In our solar system, NASA has identified [1] six Ocean Worlds. These are: Earth, Europa, Ganymede, Calisto, Enceladus, and Titan. Other potential targets include Dione, Triton, and Pluto. Beside Earth, their oceans exist below ice-shells several to tens of kilometers thick. These planetary destinations contain known constituents of life, which are: water, chemical building blocks, a source of energy, and time. Extreme radiation at Europa's surface, and space weathering on the surface at all target destinations necessitate subsurface access to resolve questions about their astrobiology potential. For this, a subsurface mission needs enabling technologies and a robust instrument payload to melt through the ice, reach and swim in the ocean, and analyze samples for scientific discovery [3]. Ocean Worlds exploration also aligns with the proposed OPAG strategy [4]. To perform a subsurface access mission, key technological challenges revolve around the power source, and mitigation of extreme pressures and the cold. Far away from the sun, and melted into the ice, we can only rely on long-lived internal power generation. Radioisotope Power Systems (RPS)—utilizing the heat of decaying Plutonium-238 (Pu-238)—could be good candidates to address thermal and electric power needs. The RPS could power the science payload and the subsystems, as well as provide a heat source for melting/sublimating the ice, while keeping the components at operating temperatures. Mitigating the external pressure while inside the ice-shell, and in the ocean below it, requires an RPS that operates inside a Pressure Vessel (PV).

In this paper, we take an enabling-technology focused approach to address interconnected aspects of a notional concept through all mission phases (e.g., assembly, testing and launch operations (ATLO), launch, cruise, descent/landing, surface operations, subsurface operations in the ice-shell, swimming in the ocean, and the end of mission), and planetary protection. We address how the concept of operations would influence mission design considerations, such as mission architectures, and RPS accommodation requirements. These design considerations would respond to environmental constraints, g-load tolerance, as well as the sizing of the power and thermal systems for science measurements. We focus on Europa and Enceladus as baseline cases for ice-shell and ocean explorations. Once developed, the RPS inside a PV configuration could be used at subsequent Ocean Worlds destinations. (Titan is not addressed, as the presence of an atmosphere would require a different approach.) Our findings inform the science community on instrument accommodation possibilities, and the use of RPS inside a PV when developing these type of mission concepts.

Ocean Worlds characteristics and extreme environments

NASA's Ocean Worlds Roadmap [1] identified Europa and Enceladus as the top two targets with solid scientific foundational knowledge to build upon and address key science objectives. Given these priorities and the extreme environments that these targets represent, in our study we baselined them for our RPS inside a PV enabled concept.

Mission relevant extreme environment conditions at Europa and Enceladus are shown in Figure 1. Their *in-situ* surface and subsurface exploration is driven by extreme environmental conditions and largely unknown topography (based on limited coverage by Galileo and Cassini). It is expected to improve significantly at Europa after the

Figure 1: Extreme environment conditions at Europa and Enceladus

Europa Clipper mission. **Surface** conditions impact landing and surface operations. The salts in the ice could become chemically active due to melting from landing thrusters or a probe traversing below the surface. The sublimated ice at these airless bodies is expected to deposit on the surface. The probe's mass, geometry, and heat output, as well as the moderate gravity environment impact mobility. **Under the surface**, the moons have two regimes of ice. (i) Near the surface, it is cold and highly thermally conductive (~3x more than the interior). (ii) The potentially convecting ductile interior ice is more insulated and warmer at near-melting-temperature. Faults may penetrate deep into the cold layer, and may experience shear during low-recurrence interval seismic events. The porous ice might connect the deep interior to vacuum down to multiple kilometers. Salt concentration may increase along the melt-traverse path, while large exogenic material (e.g., rocks, dust) are unlikely. Trapped gases in the ice-shell could explode if drilled into. The **ice-ocean interface** region, with unknown topography and structure, is a key target to search for life. The transition thickness and conditions at the interface are unknown, although entrained particles are unlikely. Due to the unknown environment, in-ice mobility could be impacted by shallow diurnally active cracks, deep faulting, potential voids from fracture porosity, melt-water in warm ice that obscures sharp interface detection, topography at the ice-ocean interface, brinicles, clathrates (trapped gases), and ocean currents. The melt-probe must be designed for the low-gravity environment to avoid buoyancy. The pressure at the ice-ocean interface is an important design driver for the PV. **Sub-ice ocean** current could vary with the interface topography, impacting the probe's glide speed and maneuverability. Currents might be extreme in the south pole of Enceladus, where jets at the surface might connect to the ocean.

These extreme environmental conditions make ocean worlds exploration challenging. (While not discussed here, it is expected that design considerations at other potential ocean worlds targets can be derived from Europa and Enceladus.)

Ocean Worlds Science and Notional Instruments

The science goals for Ocean Worlds exploration are detailed in [1] and [2]. An RPS inside a PV could make *in-situ* subsurface exploration feasible at these targets. On such science missions, while searching for signs of extinct or extant life, we would address—among others—questions related to habitability, chemical composition, salinity, local

hydrology, D/H ratio, morphology, water properties, structure of the ice-shell, porosity, elemental abundances, tidal functions of the ocean, and contextual imaging. In general, we would characterize the ice-shell and the ocean, assess habitability, and advance the search for life in the solar system.

The RPS could provide power to the payload and probe subsystems, while providing heat for keeping them warm, as well as to assist with melting the ice during traversing or swimming in the ocean. Probe design considerations should be given to assure that the collected samples are not altered nor destroyed by the heat or radiation from the RPS, and how this heat is dissipated to the environment. While responding to these objectives, we have identified a number of potential instruments. Our main focus was not related to the performance of these instruments, but how the measurement methods influence the PV design. That is, if they require remote sensing, contact with the ice or liquid, samples brought inside the PV through an opening, visual observations through a window, or contact measurements outside the PV. The power, mass, and volume requirements of these instruments would also influence the RPS and PV sizing. To bound the mass and power allocation for our notional payload suite, we used the Curiosity mass and power budget as an analogy with a 25% upper margin. This resulted in a mass and power range of 75-100 kg and 60-80 W_e. The list of instruments and their accommodation needs are shown in Table 1.

RPS Inside a PV Considerations

In this White Paper, we provide considerations for a generic subsurface and ocean exploration platform, with a focus on how the RPS inside the PV, as an enabling technology, is being impacted by the Ocean Worlds environments and representative concept of operations (ConOps). For specific point designs, there have been a number of other past concept studies by NASA, JPL, academia and industry. Examples include: the Europa Tunnelbot (by NASA COMPASS); PRIME (by JPL); Cryobot (by JPL); THUR (by Stone Aerospace); SLUSH (by Honeybee Robotics); and VERNE (by Georgia Tech). Our approach is not to compete with them, but to inform mission designers and technologists about considerations for this specific power source by focusing on concept of operations for the end-to-end mission phases.

Pressure Vessel Considerations: Specific to this configuration is that the RPS is housed inside a PV, which in turn protects the power source, payload, and subsystems from the extreme environments. **This configuration does not currently exist, and will require a dedicated technology development effort to mature the technology, if decadal science goals warrant this type of subsurface Ocean Worlds exploration.** There are a number of emerging capabilities and approaches which could make this development feasible. For example, additive manufacturing overcomes the limitations of traditional methods, and allow for the creation of complex, optimized, generative structures. It can be used to manufacture hybrid structures that integrate heat pipes, fluid channels, and wiring paths into the structural shell, and can be used to construct high/low-conductivity regions. This would lead to unique thermal designs for RPS waste heat management and utilization, from directing heat for survival, to heating the PV walls for ice-melting and rejecting the excess heat to the environment. The Ocean Worlds environments may contain sulfuric acid (<40% mol) near the surface, and high concentration of salts (<~25% in ice-shell, <~2% in ocean), causing corrosion. To protect the payload and anything that touches the liquid, Ni-based highly-corrosion resistant 3D printable super-alloys (e.g.,

Table 1: Notional Payload Suite for an Ocean Worlds subsurface ice and ocean explorer mission concept

<i>Instruments (with mass/power estimates)</i>	<i>Measurement Objectives / Descriptions</i>
External Instruments (mounted outside of the Pressure Vessel)	
Thermophysical Property Suite (5-10 W, ~0.25 kg)	Ice / environment thermal properties
Pitot Tube (~1 W, Mass: 0.01 kg)	Measure flow rates and currents in ocean
Sonar Ranging/Mapping Package: (~12 W, ~8 kg)	Ice-ocean interface topography, backscatter (density and porosity)
Elastic Wave Analyzer (~5 W, ~5 kg)	Characterize porosity, voids, inclusions, melt content, ice properties
Observations through a window	
Raman Spectrometer (~45 W, ~4.5 kg)	Identification of salts and simple organic molecules
Multispectral Camera (~20 W, ~1.5 kg)	Ice texture, layering, composition, context
Camera Illumination (e.g., with LEDs)	Supports science imaging
LIBS (~0.2 W, ~6 kg)	Elemental analysis of salts and minerals
Sample brought inside the Pressure Vessel	
In Situ Sampling System (~25 W, ~10 kg)	Allow direct sampling of pristine ices
Holographic Microscope (~15 W, ~10 kg)	Cell motility, cell counts/density
Mass Spectrometer (~100 W, ~40 kg)	Identification and quantitation of organics and volatile species
Gas Chromatograph Mass Spectrometer (GCMS) (~82 W, ~11.5 kg)	Identification and quantitation of organic molecules (including chirality of amino acids if chiral GC column is included)
X-Ray Diffraction (~40 W, ~10 kg)	Identification and abundance of salts and minerals
Inside the Pressure Vessel with no direct contact to the outside environment	
Seismometer: (5–10 W, ~0.2 kg)	Investigating ice-shell/interior structure, ocean and ice-shell thickness

Inconel-718) could be employed. The pressure environment at ice-ocean interface could be as high as ~50 MPa at Europa, and up to ~1 MPa at Enceladus. Under these conditions, an ill-designed PV could fail due to buckling. As shown in Table 1, some of the instruments would require feedthroughs for electrical wiring, sample acquisition, and windows. These could weaken the structure, could introduce thermal issues, would need to be safe against differential pressure across the wall, and would need to be sealed to prevent fluid ingress. A longer PV would need thicker walls to avoid buckling, which could dramatically increasing the overall mass. End-caps (domes) are pressure resistant, but not mass and volume efficient. Flat end-caps could save on volume, but the added thickness would increase the mass. The use of an internal bulkhead or stiffening rings could decrease the effective length of a PV. The mass is strongly dependent on the material selection as well. Furthermore, the PV must accommodate the RPS, the payload, and the subsystems. A smaller RPS would be advantageous as it would reduce both volume and mass. It would also generate less power, pointing to the need for continued development of low-powered systems and instruments. A PV at Europa, with its high-pressure environment, would require a more robust and heavier design than a PV at Enceladus. At this stage it is not yet known if the PV would be evacuated or pressurized, or segmented to multiple sections, separating the RPS from the instruments and subsystems. These configurations need to address the purging of the slowly generated helium gas, a byproduct of the Pu-238 radioisotope decay. The PV design, optimized for mass and performance, would need to address environmental and operational constraints through all mission phases.

Radioisotope Power System Considerations: Our study approach was agnostic to the RPS inside the PV design. For planning purposes, we assumed an average system mass of 75 kg (~60–90 kg), an electric power output of ~50–300 W_e, and a thermal output range from 1500 W_t to 4000 W_t, (based on the number of GPHS modules and the power conversion method, static or dynamic). The considered dimensions for the RPS were assumed at 20–35 cm (finless diameter) and 90–110 cm (length), which need to be accommodated inside the PV. Today’s Radioisotope Power Systems are designed with a 17 years lifetime from the Beginning of Life (BOL)—which corresponds to the time of fueling—to the End of Life (EOL) at decommissioning. Launch is expected at 1 to 3 years after BOL. With long cruise times to the outer planets and the multi-year *in-situ* operation below the surface, **this lifetime capability may need to be extended for the RPS inside the PV configuration.** (Note: the pre-Decadal study Groundrules extended the assumed RPS lifetime to 20 years, if required.) The heat source would likely be based on Step-2 General Purpose Heat Source (GPHS) modules, each producing 250 W_t at BOL. The excess heat produced by the GPHS modules would need to be rejected through the PV by conduction, convection, and/or radiation. This waste heat could be routed to other parts of the spacecraft to keep the components warm, and ice melting. Fitting the RPS inside the specific geometry constraints of the PV poses a design challenge, combined with mitigating radiation from the RPS, that could have noise effects on instrument measurements, and cause long-term instrument damage if not addressed.

Considerations for Concept of Operations Through Mission Phases

Assembly, Testing, and Launch Operations (ATLO): ATLO for the RPS system would initiate at the Idaho National Laboratory (INL)—a Department of Energy (DOE) facility—for fueling, testing, transportation, and storage. The process would start well before RPS fueling (scheduled at Launch-18 months). Fueling would involve loading the Pu-238 into the housing unit, performing acceptance testing for the thermoelectrics, shock and vibration, and environmental testing. The fueled RPS would then be inserted into the PV and sealed (L-12 mo). The PV could be either pressurized or evacuated. If pressurized, the fill gas would need to be non-corrosive to the equipment. If other spacecraft components share the PV, those components would need to be integrated at the INL facility. A fueled system would likely require active cooling from storage through launch. The cooling method would depend on the size of RPS (e.g., using liquid cooling). The system would go through acceptance testing, and must meet PV integrity standards. The system could be stored at INL for up to 3 years from BOL. After delivery to the launch site inside a special container (L-6 mo), the system may be integrated with other flight hardware to allow performing integrated functional checks. A modular PV design would allow for easier access to the RPS. Just before launch, the spacecraft (with the RPS) would be integrated into the launch vehicle (LV) fairing, and may require continuing cooling. RPS are designed for launch shock and vibration loads (up to ~20 g), and also to mitigate launch failure risk.

Cruise Phase: If the trajectory involves a Venus flyby, the thermal design would need to account for a higher heat input from the Sun on spacecraft surfaces. It would reduce radiator efficiency to reject the excess heat from the RPS to space, compared to rejecting it to the 4 K deep space temperature during nominal cruise to the outer planets. The deep space cruise phase could take up to 10 years. Earth flyby is considered a critical event for an RPS-powered spacecraft. It is related to safety and should be assessed for the probability of impacting the Earth.

Orbit Insertion and Arrival to Target: The radiation environment around the targeted planetary system may determine the chosen orbit and target arrival. The orbit insertion vibration and shock loads would be expected to be below launch loads.

Descent and Landing: After decoupling from the carrier, the RPS may need to provide its own thermal control during the short 1-hour descent and landing sequence. Autonomous hazard avoidance and soft landing would be implemented to minimize g-loads below the launch levels. Contamination by the descent thrusters on the target surface should be avoided, as it could bias sample analysis.

Surface Operations and Initial Melting: The amount of time allowed on the surface would be driven by the radiation environment (highest at Europa). Salt and ammonia deposits might create an acidic layer on the surface, requiring corrosion resistant materials. During initial melting, most of the RPS heat would be focused to the nose, while the PV-probe would need to be oriented vertically. It would be designed to withstand tectonic-, pressure-, and tidal-forces. The melt-probe would likely have to be anchored; surface hardness would drive the anchoring method. Melting techniques could include drilling, melting, and/or water jets. Due to the low gravity environment, if the melted water does not sublime and develops a liquid pocket, the probe may become buoyant, preventing further descent. This becomes an increasing challenge on Enceladus or other smaller moons, and traversing may require mechanical methods.

Subsurface Traversing in the Ice-shell: The probe's geometry—including front- and side-wall thermal designs—would be closely coupled with the environmental conditions, and would impact its traversing speed and ultimately the duration to reach the ocean. For example, warmer pure ice would be softer than contaminated cold ice. A compact probe would be more desirable. A 20 cm-diameter RPS inside the PV and a few meters length could traverse the ice efficiently. Miniaturization of the payload and subsystems could reduce the energy requirements as well as allow for a compact PV design. Doubling the length of the probe would provide more volume, but more than double the power requirements, increase mass, impact landing configuration, and influence thermal design for heat distribution. The probe may need a dedicated heat rejection system, instead of being directly tied to the PV wall. For a segmented PV design, the segment housing the RPS would need to provide both electric and thermal power to other segments. Thermal control and power-source safety would be important considerations for all types of RPS technologies. Variable thermal power to the walls would control the melt speed and sample acquisition, and allow for freezing into the ice while performing science investigations at the ice-water interface. Alternatively, a suitable anchoring system could be used that is designed not to interfere with mobility, and could mitigate positive buoyancy in a melted ice pocket.

In-Ocean Operations: The probe could either move freely in the ocean or could be tethered to the point of entry; the chosen option would have implications to the disposal at the end of mission. A tethered non-buoyant design lowered from the entry point would differ from a swimmer configuration, which would need to be buoyant, with a dedicated propulsion system, and telecom for data return. Unknown ocean currents would further complicate the design. The higher pressure at Europa would lead to a heavier design than at Enceladus, with the mass impact rippling through all design phases. The mission duration, combined with the ocean composition would impact corrosion mitigation efforts, material selections, probe mass, and overall design.

End of Mission (EOM) / Decommissioning: This requires further analysis, as it could occur either in the ice or the ocean. In the ice over time, the RPS may melt a liquid pocket. While the decaying Pu-238 with an 87.7 years half-life would naturally reduce its heat output to safe levels over a timeline of decades, corrosion of the PV may expose it to the ocean. Further analysis is needed to determine the appropriate time-frame for disposal in line with Planetary Protection guidelines.

Planetary Protection Considerations: An Ocean Worlds sub-surface and ocean explorer mission at Europa or Enceladus would be considered Category 4 under Planetary Protection (PP). This would impact the design and placement of the instruments, driving whether they would be outside the PV and directly in contact with the environment or inside with the RPS. During launch operations, Contamination Control (from launch vehicle materials) would need to be analyzed. Further PP and safety considerations would be required to assess the probability of any Gravity Assist maneuvers en route to the destination, or impacting a potential astrobiology target during orbit insertion, descent and landing. PP considerations would likely be similar to that of the Europa Lander during descent and landing, and on the surface. While traversing in the ice and the subsurface ocean, PP would be impacted by how water is sampled and moved inside the PV. At the end of the mission, if instruments were not sterilized prior to flight (due to sensitive equipment), sterilization would need to be performed prior to disposal, e.g., by baking out the components *in-situ*.

Summary and Recommendation

In this White Paper, we provided considerations for a novel power system—a Radio-isotope Power System inside a Pressure Vessel—that could enable Ocean Worlds exploration of ice-shells and oceans. It should be noted that the information presented about future mission concepts and their notional power systems is pre-decisional and is provided for planning and discussion purposes only. We highlighted the complex challenges and considerations that technology developers face and need to address while developing an RPS inside the PV. During subsequent development steps these considerations could lead to guidelines, then to accommodation requirements for this power system. Such development is expected to take years, and a focused effort. We hope that the material presented here may inform the science, technology and mission development communities about mission design and operation considerations for these types of *in-situ* exploration mission concepts. This technology could be also cross cutting to Earth Science, specifically to study Antarctic ice shelves.

We recommend that when discussing science goals and related enabling technologies for long-term Ocean Worlds exploration over subsequent decades, **the Decadal Committee should consider including a statement about the need for this RPS inside the PV technology.** Such endorsement would help to prioritize and allocate appropriate resources to mature the technology over the following years.

References

[1] Hendrix, A.R., et al. (2019). *Astrobiology*, Vol.19, No.1, Mary Ann Liebert, Inc., DOI: 10.1089/ast.2018.1955 [2] Squyres, S.W., et al. (2011). *National Academies Press, Washington, D.C.*, p 410. [3] Howell, S., et al. (2020). “Ocean Worlds Exploration and the Search for Life,” PSDS White Paper. [4] Moore, J., et al. (2020). “Exploration Strategy for the Outer Planets 2023–2032: Goals and Priorities, OPAG,” PSDS White Paper.