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RPS-POWERED PRESSURE VESSEL MISSION CONCEPTS FOR IN-SITU OCEAN WORLD AND VENUS EXPLORATION

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The NASA Radioisotope Power Systems (RPS) Program Mission Analysis Team requested a Jet Propulsion Laboratory (JPL) Innovation Foundry Architecture Team (A-Team) study to assess mission pull for RPS-powered pressure vessel mission concepts on Ocean Worlds, such as Europa and Enceladus, and Venus. The A-Team is JPL's concurrent engineering design team for science definition and early mission concept development. The RPS-in-a-pressure-vessel study goals and objectives were to: (1) examine the science case for exploration concepts targeting Ocean Worlds and Venus destinations that require pressure vessels, (2) develop the architecture space of potential pressure vessel mission concepts on targeted bodies, and (3) determine the possible mission requirements impacting RPS across the architecture space. This mission pull study was performed to address the future work that was documented by the Next-Generation Radioisotope Thermoelectric Generator (RTG) Study (Ref. 1). The Next-Generation RTG study was performed in order to determine the characteristics of options for a new RTG that would best fulfill NASA Planetary Science Division (PSD)'s upcoming mission power needs.

The RPS-in-a-pressure-vessel study was conducted over three days at JPL with a wide range of scientists and engineers. Day-one was focused on identifying the notional science goals, measurements required, and instruments necessary for in-situ pressure vessel missions on Ocean Worlds and Venus. On day-two, engineers and mission architects developed potential requirements both on the mission concepts and on the power system to accommodate RPS in a pressure vessel. Day-three brought scientists and engineers together to develop preliminary mission concept architectures for high priority science target bodies. Subsequent to the A-Team study, the Mission Analysis Team continued work to determine preliminary payload power needs that were identified during the A-Team study for ice, ocean, and Venus in-situ explorers. This paper describes the collaborative engineering processes that the A-Team and Mission Analysis Team used to reach results quickly and the findings to inform the RPS Program about mission concept power requirements on RPS in a pressure vessel.

I. INTRODUCTION

A number of missions and studies have led to the conclusion that there are a number of bodies in the solar system which could have or are known to have a liquid water ocean. These "Ocean Worlds" are prime science targets for the search for life beyond Earth (Ref. 2). In addition, a long-life in-situ explorer for Venus has been a goal of the science community.

These destinations are unique to others in the solar system because they would require a pressure vessel to contain instruments and other components. To respond to this need, the RPS program conducted a JPL A-Team study to better understand the science goals for Ocean Worlds and Venus and to identify potential mission concept architectures. This information was used to inform what the potential requirements for using RPS in a pressure vessel are in order to identify new capabilities that may drive RPS design decisions. The study included the following objectives:

- What would be the science justification for in-situ, long-life explorers on Ocean Worlds and Venus?
- What measurements and types of instruments would be needed to realize the science goals?
- What would be the mission requirements needed to utilize a Next-Generation RTG in a pressure vessel?
- Create draft mission architectures to achieve the notional science goals with the use of an RPS power source in a pressure vessel.

II. STUDY FINDINGS

II.A. Overview of Environments

An Ocean World can be defined as all bodies in the solar system which could plausibly have or are known to have a liquid water ocean. These destinations include outer planet moons, such as Europa and Enceladus, asteroid such as Ceres, or planets such as Pluto.

The study science team first characterized the atmospheres and environments of the potential Ocean World and Venus mission destinations in order to produce guidelines for mission architecture generation. From these environmental overviews, the team was able to determine which mission types and destinations were feasible with current and expected technology development for missions in the next twenty years. Barriers to certain missions included expected pressures of over 1000 bars at some destinations that would require a pressure vessel with a mass that is difficult to launch. Figure 1 presents environmental overviews for Europa and Enceladus, two of the potential Ocean World destinations that the study team considered.

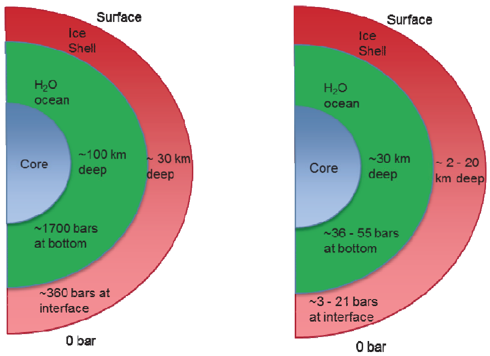

Fig. 1. Example environmental findings, showing estimated surface and subsurface pressures for Europa (*left*) and Enceladus (*right*).

II.B Notional Science Goals, Measurements, and Instruments

The study team developed notional science goals for each identified destination with RPS-enabled missions in mind, considering that the RPS enables in-situ, long-duration science at these destinations where other power sources (e.g solar, primary batteries) are not feasible.

The study team recognized that there was significant commonality between the notional science goals for the various Ocean World destinations. The considered Ocean Worlds science goals included, among others:

- Ocean and ice composition
- Ice shell thickness and thermal conductivity
- Assessment of potential active seismology
- Assessment of how the body has changed over time
- Past and present potential habitability assessment
- Presence and sources of hydrothermal vents

The considered Venus goals for in-situ science in the low altitude (zero to ten km) Venus environment included, among others:

- What is the interior structure of the planet?
- What is the history of the planet?
- Measure seismic activity and weather over a long duration
- Measure momentum exchange
- Characterize and understand super-rotation in the deep atmosphere (<10 km)
- Characterize and understand the boundary layer

Based on the notional science goals, desired measurements and potential instruments were identified for each of the considered destinations. Figure 2 shows an example set of notional measurements and instruments for Venus.

Measurements (Instruments)

- **Surface**
  - Imaging (visible camera, contact camera)
  - Meteorology (XRD/XRF I/d GRS, APX 1/6 h, mossbauer 1/6, laser ablation 1/15 μm, IR spectrometer 1-15 μm, NIR camera)
  - Seismology (seismometer 20 Hz – 0.001 Hz)
  - Planetary System (Infrasound instrument: 0.001 - 1 Hz)
  - Deep atmosphere composition (GC/MS)
  - Energy balance (heat flux radiometer)
- **Atmosphere**
  - Meteorology package
  - Wind measurements (Doppler)
  - Boundary layer measurements (thermometer, barometer)
  - Clouds/particulate (Nephelometer)
  - Composition of rare gas species (Mass Spectrometer)
  - Cloud and surface structure (IR camera)
  - Energy balance (Net flux radiometer)
  - Life detection (microscope)
  - (Raman/lidar)
  - (UV Spectrometer)

Fig. 2. Example potential measurements (*in black*) and instruments (*in blue*) to meet the notional Venus science goals for an in-situ, long-duration mission.

II.C Conceptual Mission Architectures

The study team developed preliminary RPS-powered mission architecture concepts to explore the identified mission destinations and meet the identified notional science goals. The primary destinations considered were Europa, Enceladus, Titan, and Venus, as these destinations were deemed to be the most probable locations for a pressure vessel mission in the next twenty years. Many notional science goals and preliminary architectures identified for Europa, Enceladus, and Titan would be applicable to other potential Ocean Worlds, such as Ceres, Ganymede, and Pluto (Ref. 2).

The team brainstormed mission concepts in the following regions:

- Europa ice shell (2 concepts)
- Europa ocean (4 concepts)
- Enceladus ocean (2 concepts)
- Titan methane/ethane sea (3 concepts)
- Titan ice shell (3 concepts)
- Titan ice/ocean interface (3 concepts)

- Venus surface (4 concepts)
- Venus aerial (4 concepts)

The dozens of concepts created during the brainstorming exercise covered a wide range of architectures and included things such as an ice penetrator on Enceladus, a submarine or buoyant rover in the ocean of Europa, and a long-life balloon or rover on Venus.

The team then narrowed the concept focus to produce more detailed concept architectures for the following high-priority areas:

- Ice only (applicable to all Ocean Worlds)
- Ocean only (applicable to all Ocean Worlds)
- Venus surface

II.C.1 Ice Explorer

This concept would be a multi-year, kilometer-scale ocean world ice shell explorer that would use a Next-Generation RTG power source to slowly descend through the icy surface that is thought to encase bodies such as Europa. The science goals could be ice shell composition (as a function of depth), deuterium to hydrogen (D/H) ratio, compositional stratification, salinity, porosity, thermal profile, life detection, and history deposition. The possible payloads to address these goals include a laser sounder, a UV-VIS-IR imager, a magnetometer, a mass spectrometer, a biomolecule detector, and a radar or imager for hazard avoidance.

The ice explorer would need a long, skinny aspect ratio (< 2 m × < 30 cm) (Ref. 3) and could use RPS heat to melt through the ice, or an RPS-powered saw or water jets to cut through the ice. The explorer would need the ability to navigate past obstacles such as rocks (cut through or steer around them). As the ice explorer descends, the thick ice is expected to make direct-to-Earth communication difficult, so a tether to a lander at the surface could serve as a communications relay. Stops could be made during the descent to take ice samples with a drill, or melted ice from the RPS heat source could be drawn into the pressure vessel for analysis with instruments.

The potential primary requirements on RPS that were identified are as follows:

- May need an RPS qualified for longer life (20 year +) to melt through very thick ice (Ref. 3)
- Strict dimensional requirements (30 cm diameter, 2 m length) may be necessary (Ref. 3)
- Melt penetration rates would be highly dependent on Next-Generation RTG power (need > 4kW thermal, prefer ~ 7 kW thermal) (Ref. 3)
- Average power requirements for notional payload would be less than 1 W_e – mission power needs driven by electrical/thermal power needed for ice transit.

II.C.2 Ocean Explorer

This concept would be a liquid ocean in-situ explorer using Next-Generation RTG power on bodies such as Europa and Enceladus. The science goals could be habitability assessment, life detection, ocean composition, D/H ratio, energy balance measurements, source of plumes, topography of ocean floor, and dissolved gases. The possible payloads include a mass spectrometer, cameras, sonar, microfluidics, microscope, temperature/pressure sensors, and a selective ion probe.

Different types of architectures would be possible (stationary system, buoyant rover, submarine), but from a science perspective, mobility would be preferred (~ 1km vertical and horizontal in the liquid ocean). In order to understand temporal changes, it is beneficial for the mission to operate for an extended period of time (850 hours, or 10 orbits around Jupiter, as an example for Europa). The ocean explorer could carry additional "deep ocean probes" to be dropped and take measurements at greater depths. It is expected that the thick ice shell will make direct-to-Earth communication from the explorer impossible, but signals could be relayed through the ice using a tether to the surface or isolated "pucks" that would require a separate power source.

The potential primary requirements on RPS that were identified that go beyond the ice explorer requirements are as follows:

- Capability to withstand extreme pressures (up to ~400 bar at Europa ice/ocean interface)
- Capability to withstand environment temperature fluctuations (40 – 273 K)
- Average power requirements for notional payload would be ~2 W_e – mission power needs driven by electrical/thermal power needed for mobility, telecom, and thermal.

II.C.3 Venus Surface

This concept would be a long-lived (greater than one year) Venus surface lander using Next-Generation RTG power. The science goals could be small-scale stratigraphy, seismology, atmosphere and surface composition, long-term weather monitoring, heat flow measurements, energy balance, and the study of super-rotation. The possible payloads include a meteorology package, a mass spectrometer, a sampling system, a seismometer, an imager, and a heat flux relay.

The lander could use a direct atmospheric entry with a drag plate to slow down, and perform atmospheric science on descent. The lander would likely require an orbiting data relay asset for > ~100 bps telecom. Some components would require active cooling, while other, more robust, components would remain exposed to reduce cooling power, pressure vessel size, and complexity.

The potential primary requirements on RPS that were identified are as follows:

- Capability to handle a cold side temp of at least 550°C (550°C for sufficient ΔT for heat rejection) – heat loops that support sufficient heat exchange
- Capability to withstand entry loads of 50 – 80 g
- High temperature (500°C - 1000°C) materials must be integrated into Next-Generation RTG configuration
- Thermal control through all phases of the mission (launch, cruise, entry, operations) would need to be provided
- Capability to withstand atmospheric chemistry environment, super critical CO_2
- Next-Generation RTG could potentially be outside of the main pressure vessel if the casing was designed to be a pressure vessel itself
- If all components could be made robust to the Venus environment, then a mission could be possible with <100 W_e. However, due to inefficiency in cooling, if any components require cooling the mission would require 100-1000+ W_e.
- Average power requirements for notional payload would be ~2 W_e. If this heat would need to be rejected from a cooled pressure vessel at 1% efficiency, then the impact on the average power requirement would be ~200 W_e.

III. TOP IDENTIFIED REQUIREMENTS ON RPS FOR MISSIONS USING PRESSURE VESSELS

Analysis of the study results resulted in several identified requirements for new capabilities that may drive Next-Generation RTG design decisions.

1) **RPS must allow for removal of fins.** The aspect ratio with fins would make melt probes infeasible.
2) **RPS may need 20+ year design lifetime.** Depending on ice thickness and melt rate, ocean Worlds missions may take 20 or more years to reach their targets.
3) **RPS may need additional attachment points for cooling loops.** Larger heat pipes may be necessary to support sufficient heat exchange to reject to Venus environment.
4) **RPS may need to be qualified to higher g-loads for entry, decent and landing.** G-loads to land on Venus are difficult to reduce below 50-80 g. This would be a trade between mission requirements and qualifying the RPS to 50+ g.
5) **RPS may need special ATLO considerations for integration into pressure vessel.** RPS may need to be installed into a pressure vessel on a flight system within an aeroshell. Easily accessible attachment points or rails might reduce the complexity. Additional engineering analysis would be needed to refine this requirement.

IV. CONCLUSIONS

The study findings support that the science community has important questions to answer on Ocean Worlds and Venus that could be enabled or enhanced by the ability to integrate RPS in a pressure vessel. Other findings include potential requirements on RPS to be accommodated in a pressure vessel, such as the removal of fins and 20 years or longer design life. The study also resulted in preliminary mission concept architectures that could be excellent candidates for further design studies.

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REFERENCES

1. D. F. WOERNER et al, “Next-Generation Radioisotope Thermoelectric Generator Study Final Report,” National Aeronautics and Space Administration (2017).
2. T. HURFORD and A. HENDRIX, “Roadmap to Oceans Worlds - Goals, Objectives and Investigations for Ocean Worlds” (2017).
3. D. F. WOERNER and J. P. FLEURIAL and T. HENDRICKS and H. D. NAYAR and K. I. OXENVAD, “Ocean Worlds, Icy Bodies, and RTG Concepts for Exploration,” 68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017, International Astronautical Federation (IAF) (2017).