# PROMETHEUS: Progress Toward an Integrated Cryobot for Ocean World Access

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## Abstract

Ocean Worlds in our Solar System are attractive candidates in the search for extra-terrestrial life. The best chances for detecting biosignatures and biology on these bodies lie in in situ investigations of sub-ice oceans in contact with rocky interiors. The actual conditions that will confront an ice-penetrating vehicle ("cryobot") performing such investigations are largely unknown. However, any Ocean World cryobot must be able to, at a minimum, successfully negotiate five different operating regimes to have a chance of reaching a subsurface ocean: starting at the surface in vacuum at cryogenic temperatures; brittle/cold ice transit; ductile/warm ice transit; negotiating or penetrating salt or sediment layers, and other obstacles; and detecting and transiting ice-water transitions such as voids and the final ocean entry. PROMETHEUS (nuclear-Powered RObotic MEchanism Technology for Hot-water Exploration of Under-ice Space) represents a full cryobot concept and set of key technology demonstrations that advance the capability to perform such investigations. The PROMETHEUS concept is targeted for deployment on Europa, and consists of a fully-instrumented science vehicle able to actively control descent through the ice shell and into the subsurface ocean. The concept employs closed-cycle hot water drilling (CCHWD) technology as the primary means of penetrating ice, and making forward and turning progress. A "passive" (purely conductive) heat transfer system enables penetration starting on the surface where liquid water cannot exist until hole closure is achieved and the system proceeds inside a melt water "bubble". PROMETHEUS is compatible with a small fission reactor (the NASA Kilopower design) and employs a vertical motion control system using a trailing tether frozen into the ice to guard against falling through voids and enabling controlled entry into the sub-ice ocean. The design is capable of achieving a 20 km descent through a Europan ice profile in under a year and under 500 kg vehicle mass, including reactor mass.

# Progress Toward an Integrated Cryobot for Ocean World Access

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## 1. Cryobots for Ocean Worlds

The PROMETHEUS project, funded by the NASA SESAME program, aims to develop a full vehicle (**cryobot**) concept for the **penetration of the Europan ice crust** into the global ocean. This concept will enable the *in situ* investigation of this unique environment of interest in the **search for extraterrestrial life**. PROMETHEUS seeks to identify, develop, and experimentally validate remaining critical component technologies to support a cryobot concept able to penetrate 15 km of ice in less than 300 days, carrying a payload of 30 kg.

## 2. Background

Since early work on "hotpenny" (purely conductive) melt probes for terrestrial glaciology [1],[2],[3] several groups have investigated the idea of an ice penetrator for Ocean Worlds [4],[5]. A purely conductive melt probe will be stopped by areas of sediment or salt accumulation, so that several types of mechanical augments have been proposed [6],[7]. PROMETHEUS focuses on **closed-cycle hot water drilling (CCHWD)** as the most promising melt-penetration method for a cryobot. CCHWD is an extension of state-of-the-art surface hot water drills proven most effective for deep ice drilling on terrestrial ice sheets [8],[9]. In CCHWD, the heat source is placed inside a vehicle, and meltwater from boring is drawn in to be heated and jetted out the nose. This allows the melt cavity to refreeze behind the vehicle reducing total energy required. In addition, CCHWD efficiently transfers heat to the ice, breaks up sediments, and enables steering via directional jetting. CCHWD was used early on in the JPL Cryobot [10], and the technology has been more fully developed since then in several Stone Aerospace vehicles [11].

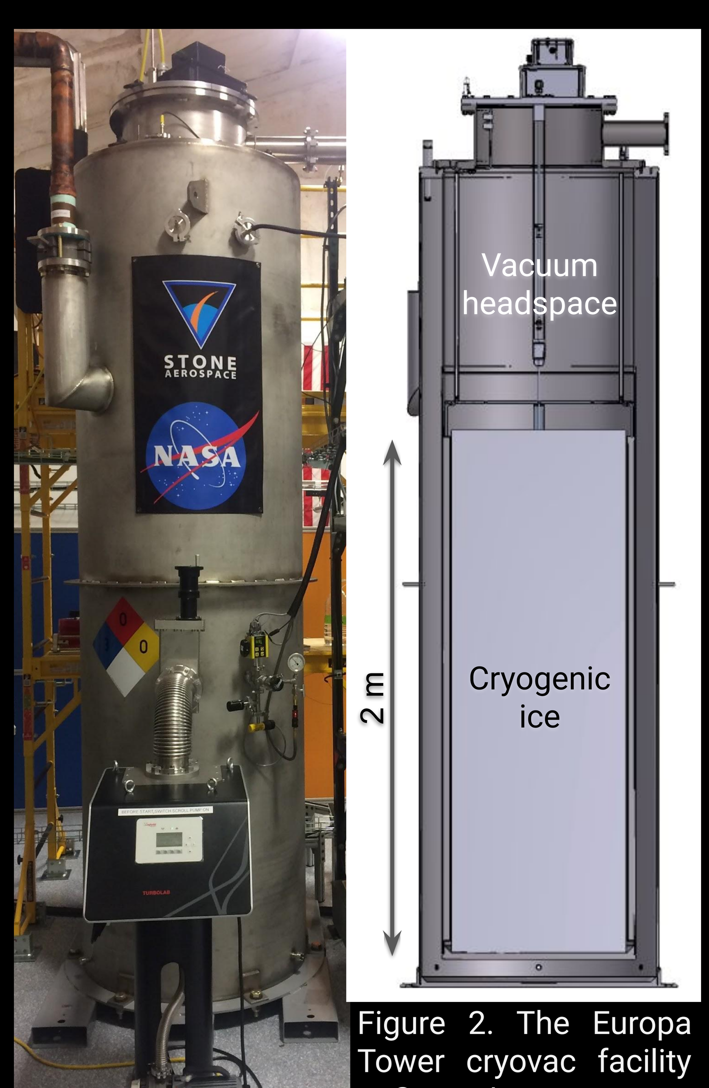



Figure 2. The Europa Tower cryovac facility at Stone Aerospace.

## 3. System Concept

Fig. 1 shows the PROMETHEUS vehicle concept. It is powered by the NASA Kilopower reactor [12] for melting heat and electrical power, and uses CCHWD for propulsion and steering. When external melt water is unavailable (at the surface or during drainage events), a "passive mode" circulates reserve fluid inside the nose to transfer heat, albeit at a slower rate, enabled by the controllable reactor. An array of antenna elements in the skin forms a forward-looking, ice-penetrating radar. A vertical motion control system spools out a fine tether which freezes in behind the vehicle and is able to support it to provide safety and enable critical maneuverability (see Sec. 7). A stack of RF communications pucks deployed periodically during ice transit forms the primary comms link.

- Total mass (including reactor): 610 kg
- Science payload: 30 kg
- Thermal Power: 43 kW
- Electrical Power: 380 W

Predicted performance

- Speed in 100 K ice: 1.3 m/hr
- Speed in 270 K ice: 4.9 m/hr
- Penetration time (15 km Europan profile): 294 days

## 4. CCHWD in Cryogenic Ice

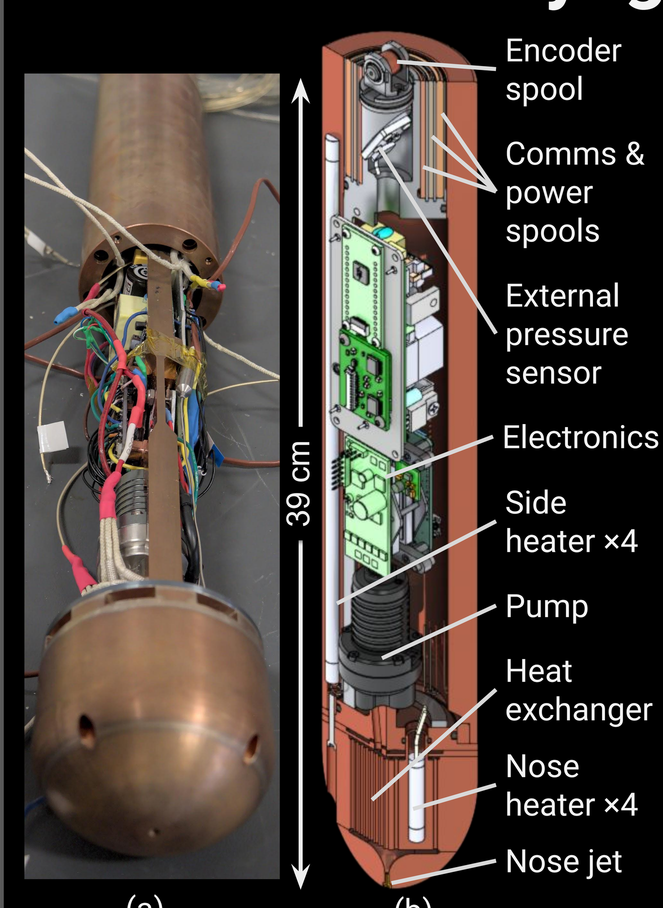



Figure 3. The SubScale CCHWD cryobot demonstrator. (a) The test article in preparation for initial tests. (b) Schematic showing primary elements. Not shown are 7 thermocouples reading temperatures.

To validate the concept of CCHWD starting in cryogenic vacuum conditions, we have constructed the SubScale CCHWD demonstrator (Fig. 3). This cryobot incorporates all of the primary components required for CCHWD in a package that can operate inside the Europa Tower (Fig. 2). The SubScale CCHWD ice-penetration tests will include ice with impurities (salts) representative of Europa and will take place in the Europa tower in February of 2022.

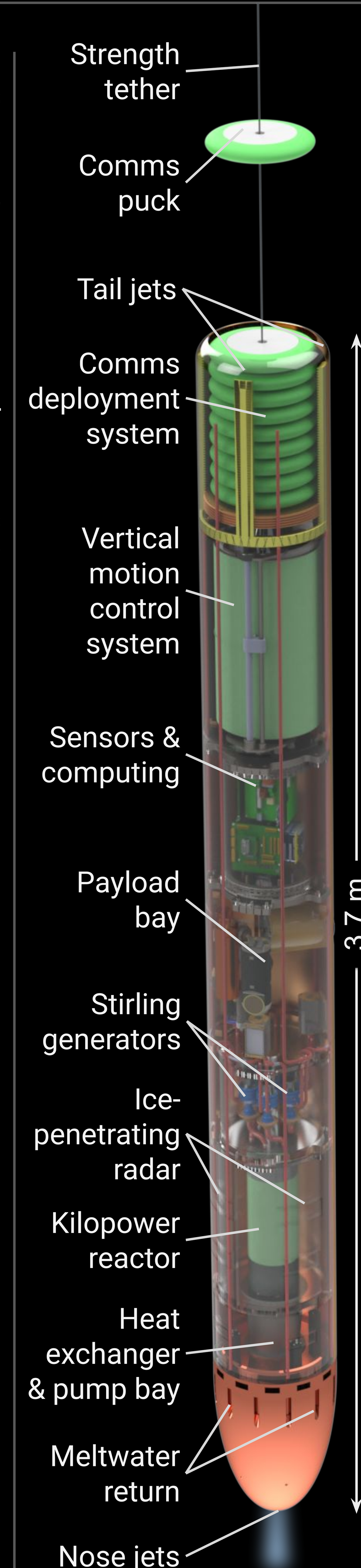



Figure 1. PROMETHEUS Cryobot Concept

## 5. Thermal Model Validation

Initial tests in the Europa Tower showed that closure of the melt hole is rapid for small probes [11]. Testing with larger-diameter probes will attempt to extend this finding. The initial tests also provided data to validate predictive models of cryobot performance in ice. Additional, more detailed validation data, including full coverage temperature readings and control of heat distribution in the probe and real-time readings of melt-hole diameter, will be gathered using the Highly Instrumented Probe (HIPPY, see Fig. 4) in the Europa Tower in late spring 2022.

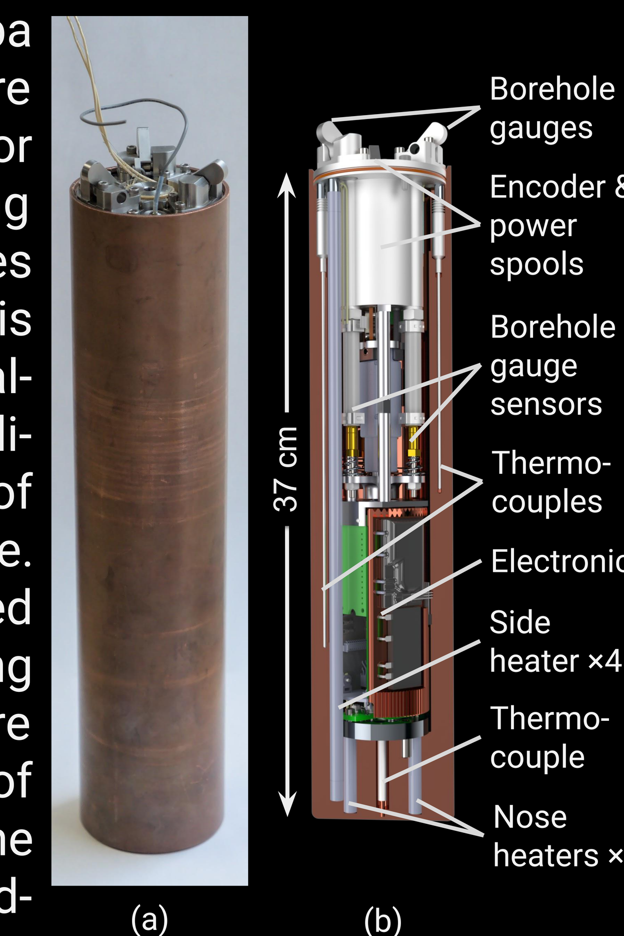
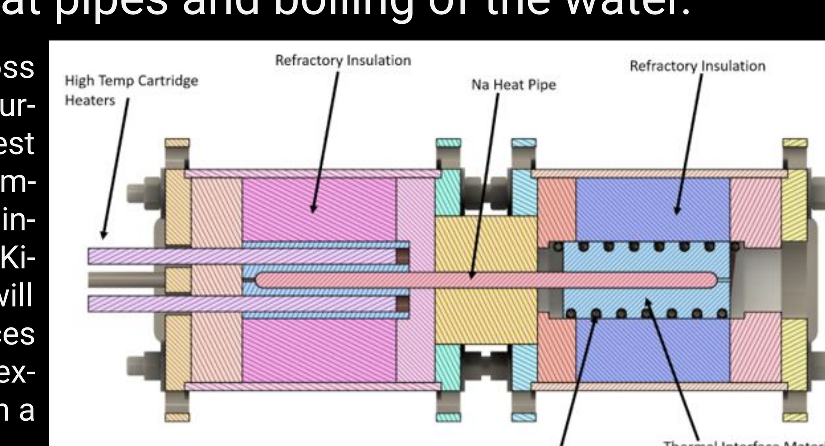



Figure 4. The HIPPY cryobot probe designed to measure primary parameters affecting thermal models of melt probe performance. (a) The test probe fully assembled. (b) Cross-section schematic showing primary elements of the probe and instrumentation. Not shown is the wireless through-ice comms system.

## 6. Nuclear Reactor Surrogate

We are designing and testing a surrogate thermal source (Fig. 5) with identical geometry, thermal signature and electrical output as Kilopower for use in terrestrial testbeds where nuclear power would entail extreme logistical challenges. The design relies on electrical heaters delivering power to heat-pipe systems equivalent to the Kilopower reactor. Initial proof-of-concept tests in January 2022 will operate at 1250 W with an 1157 K max core temperature. These tests will evaluate heat pipe routing options for incorporation into the PROMETHEUS system in a low-g environment and options for the thermal interfaces between heat pipes and liquid water to avoid both stalling of the heat pipes and boiling of the water.

Figure 5. Schematic cross section of the nuclear surrogate system. This test article will be used to simulate the heat flow in a single heat pipe of the full Kilopower reactor, and will be used to test interfaces for and control of heat exchange with meltwater in a CCHWD system.




## 7. Vertical Motion Control

During the months-long transit across the Europan ice shell, it is likely that a cryobot will encounter obstacles or voids. In order to be able to back up and deviate around obstacles, and to traverse voids or safely conduct final breakthrough at the under-ice ocean, the PROMETHEUS concept includes an actively spooled strength tether system to help control vertical motion. We are developing a test bed (see Fig. 6) to simulate expected events and evaluate tether spooling systems along with methods to control vehicle motion when the nose is unsupported, and to detect possible off-nominal vertical motions.

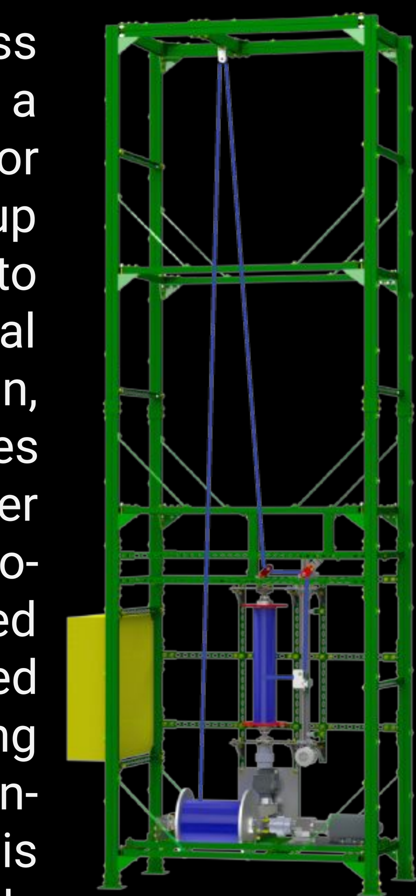



Figure 6. Vertical motion control testbed.

## 8. Conclusions

Technology enabling penetration of the Europan ice crust is rapidly moving from concept to hardware and testing.

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