PRIME: "Probe using Radioisotopes for Icy Moons Exploration"
A Comprehensive Cryobot Architecture for Accessing Europa's Ocean

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Introduction: Thermal ice-melting probes, or "cryobots" have emerged as the leading technology concept for accessing Europa's ocean and studying the potential life within. This study derived a holistic system-level cryobot architecture design—the latest in a decades-long series of formulation efforts at JPL and the most comprehensive to date. The design is based on the best-available environmental models [1], and is, wherever possible, based on technology demonstrated in terrestrial field or laboratory prototypes, or high-fidelity models.

System: The conceptual cryobot and RTG were systematically sized to (1) accommodate a (30 L) payload derived from a science traceability matrix (STM), (2) core engineering subsystems, and (3) to yield an acceptable descent time based on high-fidelity physics modelling [2] and a probabilistic ice shell model [1]. The result is a 23 cm-diameter, 3.9 m long (fully margined) probe with a total volume of 150 L, mass of 350 kg. The 10.5 kWt RTG consists of 12 compact heat source modules (CPHS), each containing 7 Pu238 graphite impact shell (GIS) modules [3]. The cryobot would descent at ~25 cm/hr in the coldest ice (100 K) and ~180 cm/hr in the warmer (250 K) ice, reaching the ocean in about 2-6 years, depending on the ice shell thickness.

Power / Thermal: The heart of the cryobot is the RTG and surrounding thermal management system, which consists of a pumped two-phase loop pulling heat from the cold side of the thermoelectric modules down to the front end, where a finned condenser exchanges heat to a vapor chamber in the nose. This vapor chamber heats the nose for ice melting and also communicates with an array of (passive) variable-conductance heat pipes which run along the length of the probe for side-wall heating (as needed). An auxiliary (external) fluid loop circulates water with the melt pore (through an array of nozzles in the nose and rear intake/filter), and also serves as the heat exchange with the lander radiator during cruise.

Mobility: In addition to the nominal mode of vertical melting, various hazard mitigation strategies are included to handle possible encounters with ice "impurities." A closed-cycle water-jet system motivates dust/particulate through an array of nose nozzles, which may be differentially controlled for enhanced steering. A rotary drill mode allows for mechanical removal of thicker dust/salt layers. Finally, a (linear) phased array sonar and radar are included on the nose, which, when rotated, scan, detect, and localize (rock/void) hazards beneath the probe. Rear electrically-heated fins "cut" through the ice like a hot knife, providing (1) drag stabilization, (2) counter-torque for the drill, and (3) differential drag for steering.

Communication: The design of the communication system was driven by (1) a science-derived data rate requirement of ~100 bps, (2) a dual-channel redundancy requirement (1 kbps / 100 bps, primary/secondary), and (3) the spectrum of probable ice shell profiles [1]. The resulting architecture uses: (1) a partially-reinforced optical fiber from surface to ocean (only primary in warm ice), (2) radio patch antenna (~100 MHz) deployed at the base of the cold ice layer for the primary comm. channel to the surface, and (3) acoustic transducers (~1 kHz) for secondary comm. through warm convective ice layer (with 1 relay). The two deployed relays are accompanied by mini RTGs with a 1-GIS heat source, producing ~10 We, and the final acoustic relay acts as terminal ice anchor.

Conclusion: While significant technology maturation efforts remain, this cryobot architecture demonstrates concept feasibility within a reasonable mass (similar to Europa Lander), and without requiring major (long lead) technology development (e.g. compact reactors).

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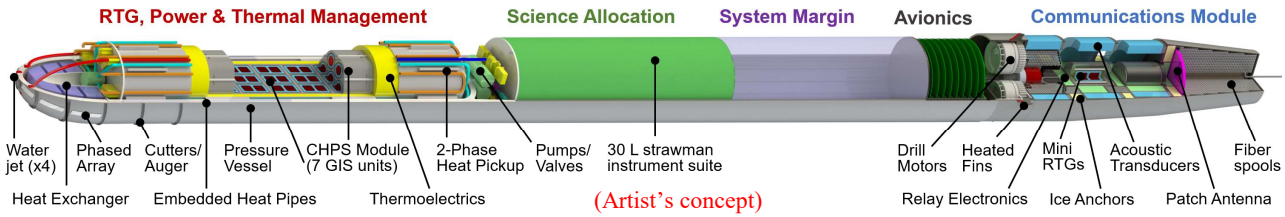
References:

[1] Howell, S. (2021) *Planetary Science Journal* 2(4), 129.
[2] Durka, M. J., ea. (2022) *Acta Astronautica.*
[3] Durka, M. J., ea. (2022) *IEEE Aerospace* (in press).



System (Margined)	
Mass	**350 kg**
Volume	150 L
Length	3.1 m (cylinder) 3.9 m (total)
Diameter	23 cm

Mobility System	
Speed (cold layer)	4.4 km/yr
Speed (warm layer)	17.2 km/yr
Detectable hazard	1 cm (estimated)
Steering radius	10 m (estimated)
Debris Removal	Waterjet / drill

Power/Thermal System	
Total Heat	10.5 kWt
Peak Power	1 kWe
Skin temperature	25 C
WJ flow rate	3 L/min
Survival pressure	53 MPa

Communication System	
Data (primary)	1 kbps
Data (secondary)	100 bps
# Relays	3
Relay power	10 W
Fiber Length	70 km