Thermal Modeling of Ice Penetrators for Ocean Worlds

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Abstract

Starting in 2010 with the VALKYRIE cryobot project (NASA ASTEP), Stone Aerospace has been investigating methods to penetrate thick layers of ice. The focus of these methods is to develop cryobot vehicles capable of transporting payloads representative of an Ocean Worlds sub-ice mission (including on-board sensing and deployable swimming rovers). Critical to these types of carrier vehicles—and in fact any efficient ice-penetrating probe—is a detailed understanding of the thermal and physical dynamics of ice penetrators under the wide variety of conditions that may be encountered in the five operating regimes of such a mission: starting (under cryogenic temperatures and vacuum), brittle ice transit, ductile ice transit, dirty ice, and breakthrough. Early work on terrestrial ice-penetrating probes generated initial closed-form models which remain powerful for first-cut analyses. Further work on refining these models for more exotic environments (cryogenic or/and impure ices as will be encountered on Europa and other Ocean Worlds) has resulted in varying levels of success. Above all, the field suffers from very sparse, limited experimental validation. We review the current understanding of the thermodynamics of ice-penetrating vehicles in a variety of ice environments, both terrestrial and those of other Ocean Worlds, and present new models for ice regimes expected in both terrestrial and extraterrestrial applications. In addition, to begin to address the limited empirical understanding of these penetration dynamics—particularly in very cold environments—we present initial results and planned further work on validation tests in the Stone Aerospace Europa Tower cryogenic vacuum chamber. Validated thermodynamic models for cryobots operating in multiple regimes will allow for the assessment of feasibility of designs, prediction of full mission times, and enable optimal design of critical top-level parameters such as required power, vehicle shape, and internal heat distribution mechanisms.

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1. Understanding the Dynamics of Ice Penetrators

The PROMETHEUS project, funded by the NASA SESAME program, aims to develop a full vehicle concept for the **penetration of the Europan ice crust** into the global ocean. One of the most important system-level considerations for such a vehicle is the dynamics of its penetration through the ice. Stone Aerospace has a long history in the development and deployment of ice-penetrating vehicles in terrestrial ices, and has developed and tested thermal models for these applications. However, in the cold ice environment in the first few kilometers below the surface of Europa, the **thermal properties of ice are poorly understood**—both the effect of cryogenic temperatures, as well as the type and amount of impurities and their effects on thermal conductivity and heat capacity. Thus, the dynamics of **thermal probes** melting in these regimes are highly uncertain. Initial thermal modeling of the probe behavior in the ice requires experimental validation for the top-level design of the PROMETHEUS mission.

2. Previous Work

Aamot [1] developed a thermal model of the "envelope" of an ice-penetrating probe, i.e. how the heat exiting the surfaces of a probe interacts with the surrounding ice. This model evaluates two heating requirements for:

1. Heat at the **probe tip** to melt the ice below
2. Heat along the **probe side walls** to prevent the probe from freezing in place

Maximum **efficiency** is achieved when these heating requirements **balance the probe's generated power.** There is a technical gap of **experimental results** to validate the thermal models for ice-penetrating probes in cryogenic ices.

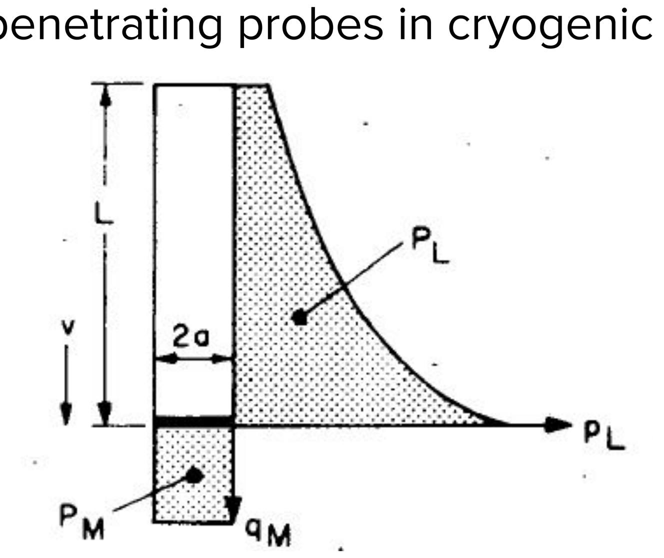

Figure 1 - Dissipation of heat into the ice along the length of the moving probe. [1]

3. Probe Descent Velocity Model

- Scaled Probe
- 1.5" Diameter
- 7.5" Length
- Length / Dia. = 5
- Ice Temp. 80 K

- Aamot [1] based model, modified for variable ice temp. properties
- Model corroborated by novel independent FEM techniques
- 100% "Envelope" Efficiency shown

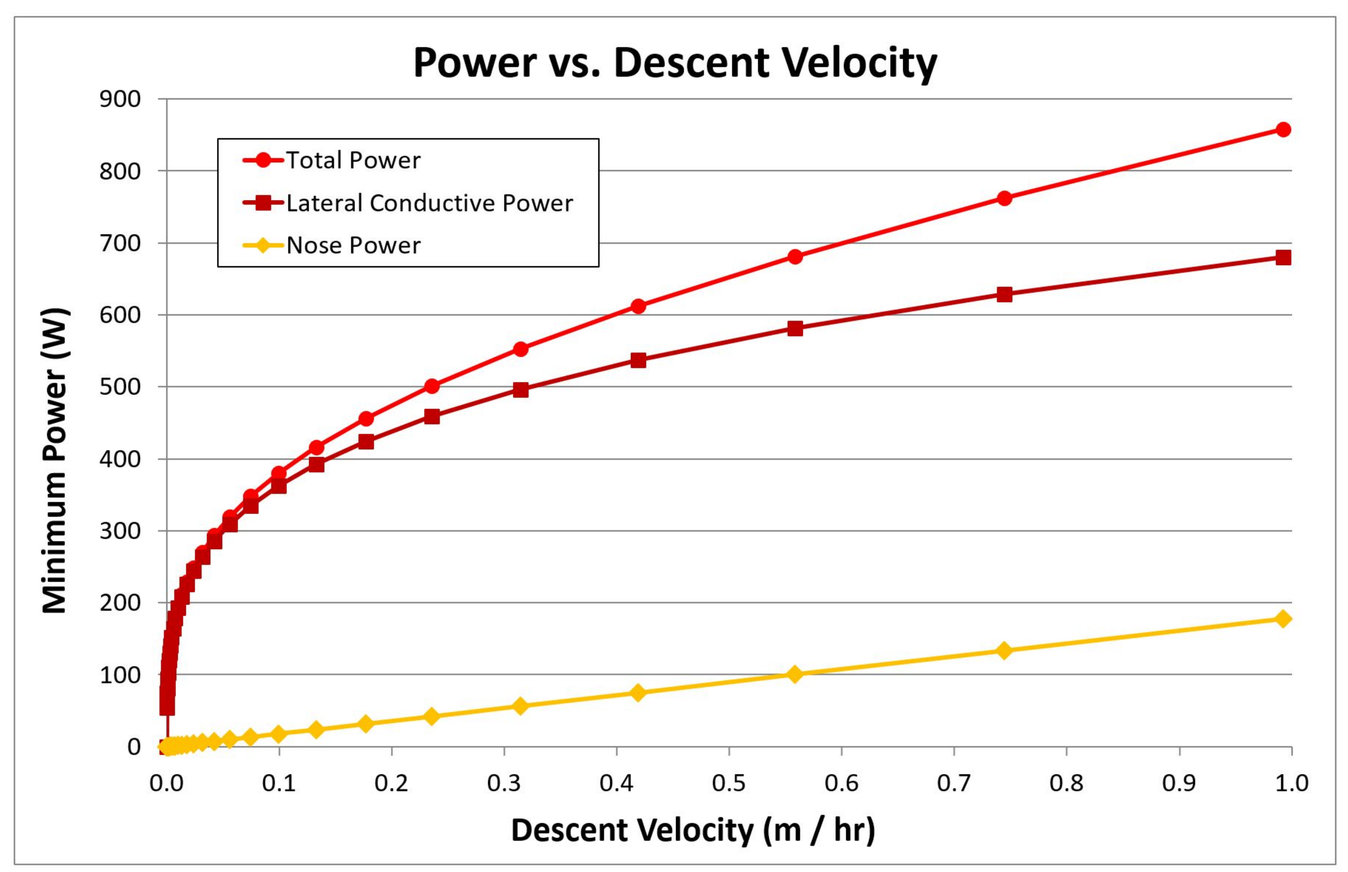

Figure 2 - Descent velocity change as a function of applied power.

4. Experiments

The ambient conditions for the validation experiments are set to replicate conditions near the surface of Europa (Fig. 3):

- Temperature: approximately 80 K
- Pressure: 10^{-3} Torr (below the triple point of water)

Electric heaters provide controllable power to a scale-model "hotpenny" penetration probe to melt through the ice.

Due to low ambient temperature, the hole re-freezes behind the probe (verified in previous experiments in the Europa Tower [6]).

Thus, to continue progressing, the wires providing power from the surface must be spooled from the probe.

The Europa Tower allows for up to 2 m penetration, enough to achieve steady state velocities.

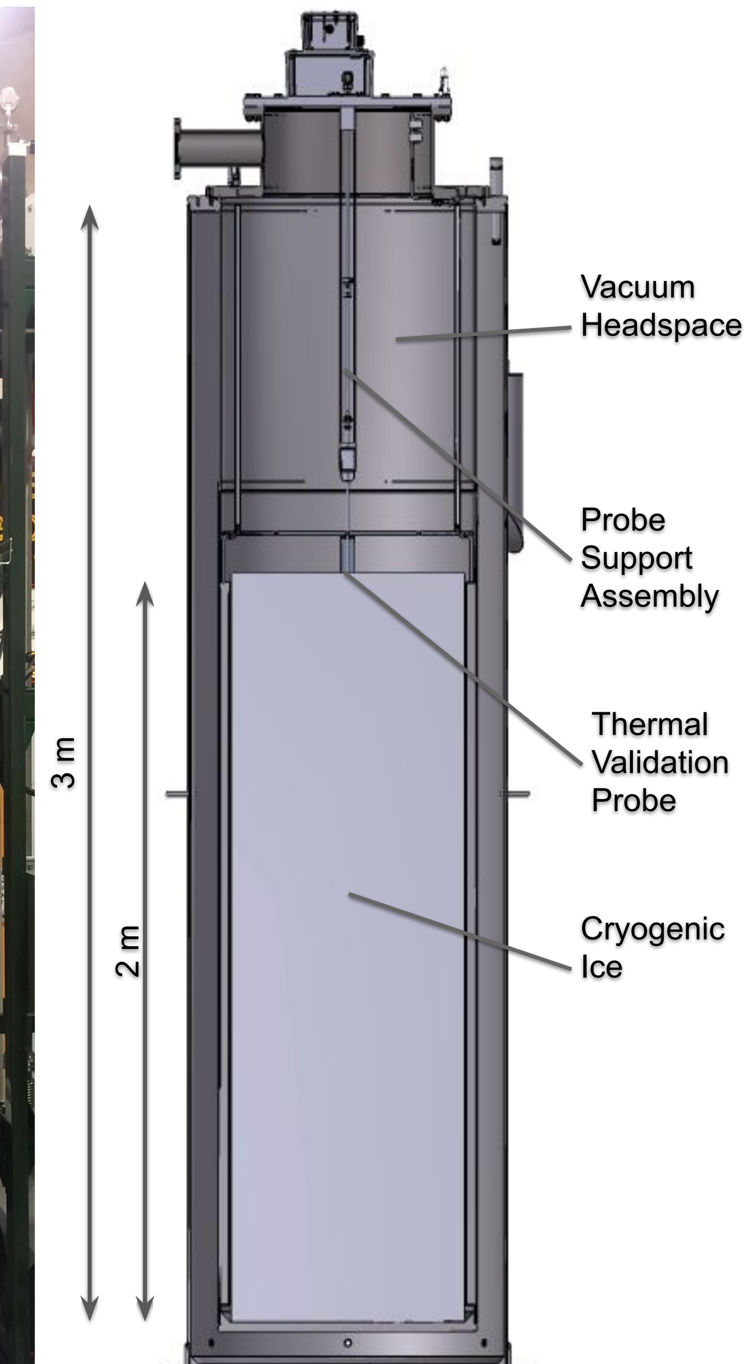

Figure 3 - The Europa Tower cryogenic vacuum facility at Stone Aerospace will be used for validation of thermal models.

5. Tradeoffs in Probe Design

Material	Aluminum	Copper
	Easier to acquire and machine	Higher thermal conductivity
Type of heater	Cartridge	Patch
	Easier to install, higher power	Allows different heat distribution patterns
Number of heaters	One	Multiple
	Only one pair of wires	Smaller gauge wire each
Heater size	½" diameter, 8" length	¾" diameter, 4" length
	Smaller cross section	Smaller axial distribution
Heater power	1000 W, 240 V AC	500 W, 120 V AC
	Higher melting power	Smaller gauge wire
Probe size	0.25" wall	0.5" wall
	Smaller wall thermal resistance	Higher axial heat transfer
Velocity sensor	Ultrasound Onboard	Ultrasound External
	Better measurement	Smaller thermal influence

6. Probe and Spool Designs

- The outermost diameter of the spool is 22.2 mm and the innermost diameter is 9.7 mm
- Two power wires and two thermocouple wires are spooled
- The probe's diameter is 46 mm and length is 183.6 mm

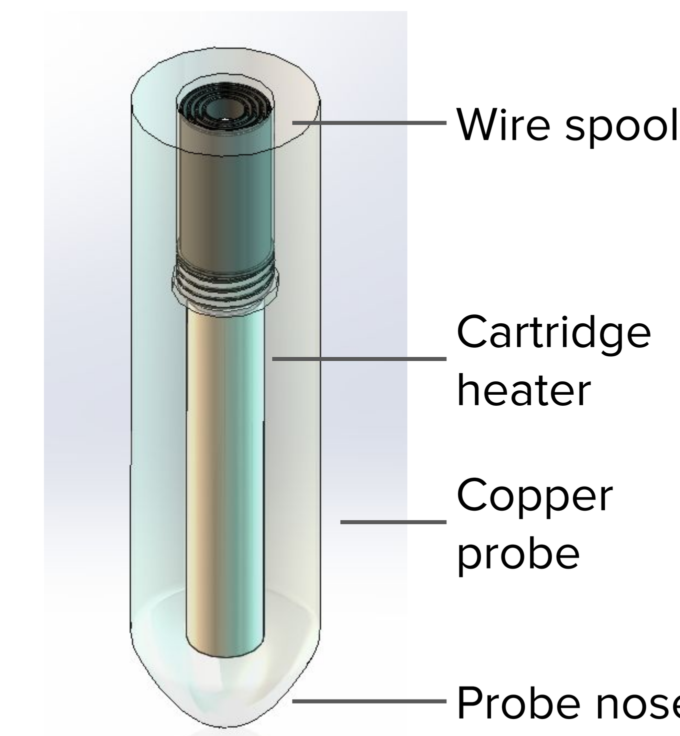

Figure 4 - Probe and spool current designs.

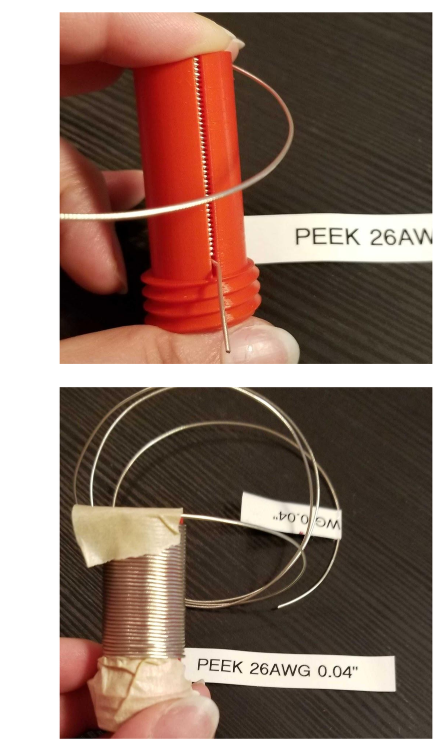

Figure 5 - Prototype of current spool design.

7. Next Steps

- Finalize the probe and spool designs and prototyping
- Perform the hotpenny probe experiments
- Use the experimental results to improve the thermal model
- Start the design of a new, more complex probe
- Make the thermal model of the new probe
- Perform new experiments

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