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Thermal Modeling of Ice Penetrators for Ocean Worlds

B. P. Hogan[1], K. Richmond[1], W. C. Stone[1], P. do Vale Pereira[1,2], A. López Vega[1], K. Cahoy[2]
[bart.hogan, kristof.richmond, billstone, paula.do.vale.pereira, alberto.lopez]@stoneaerospace.com, kcahoy@mit.edu
[1]Stone Aerospace, Inc. [2]MIT Space Telecommunications, Astronomy and Radiation Laboratory

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.

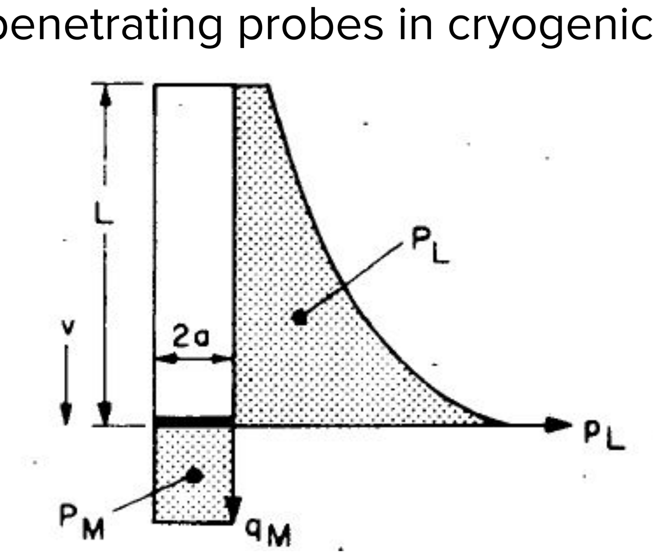

Figure 1 - Dissipation of heat into the ice along the length of the moving probe. [1]

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

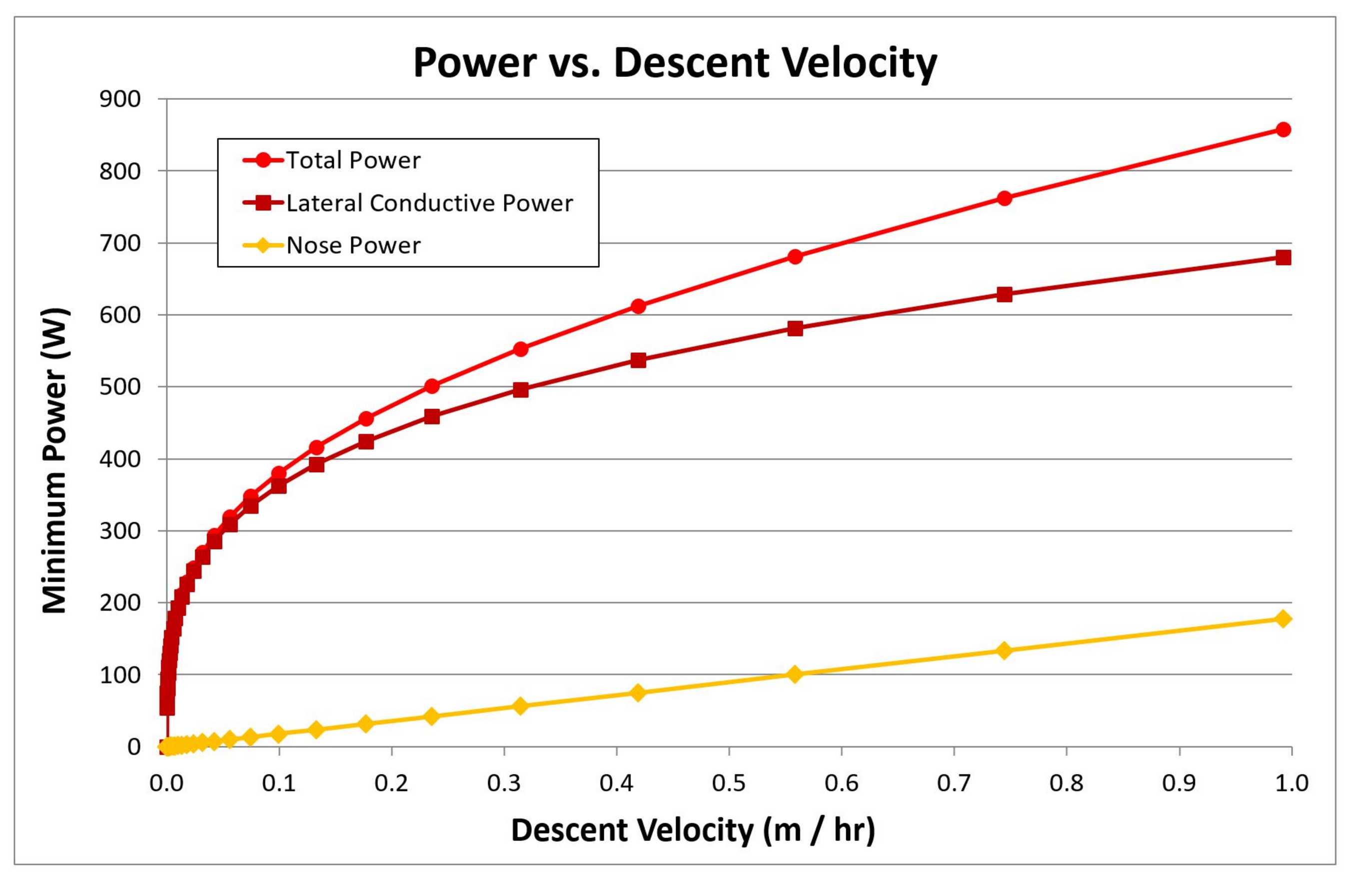

Figure 2 - Descent velocity change as a function of applied power.

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.

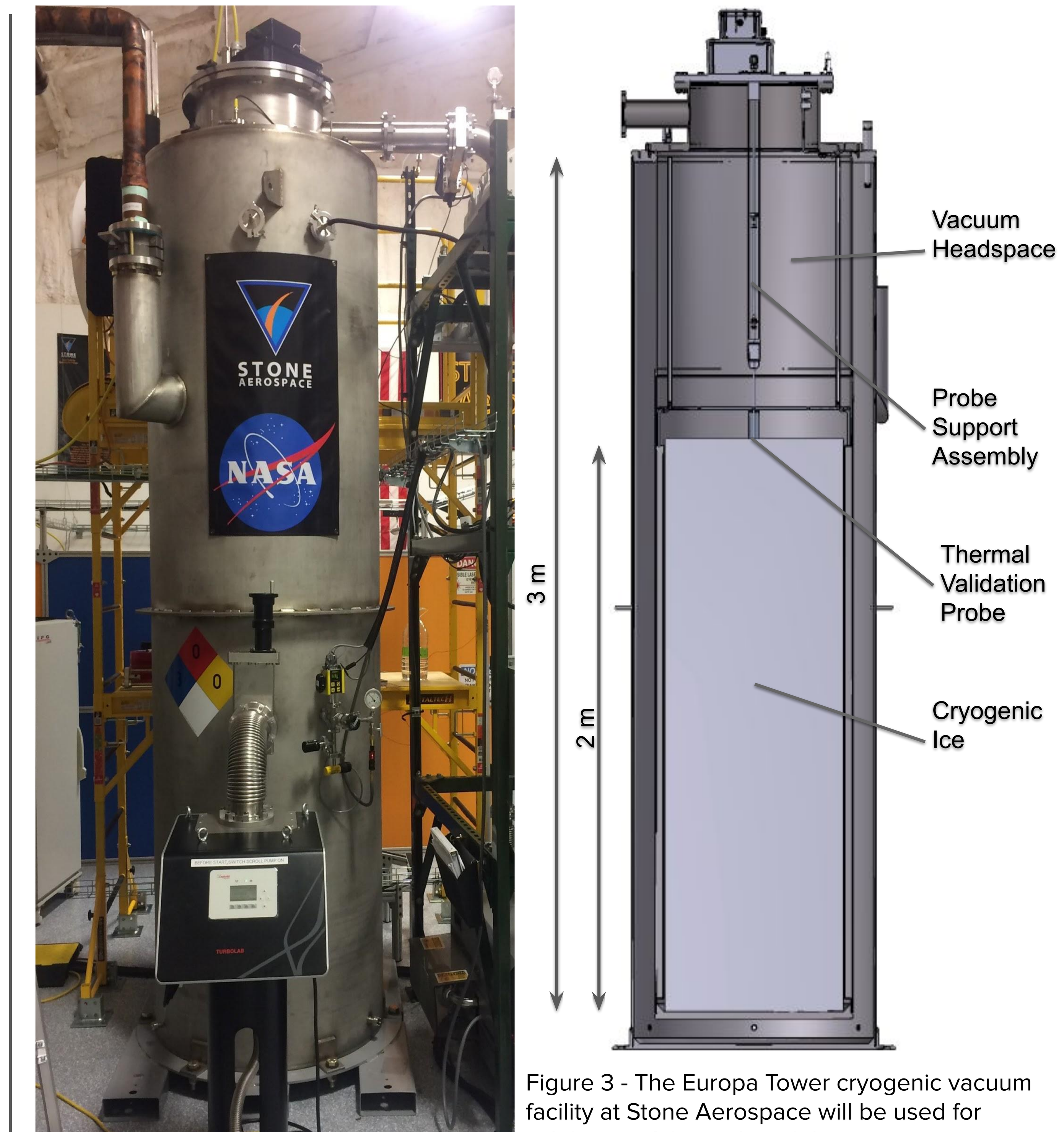

Figure 3 - The Europa Tower cryogenic vacuum facility at Stone Aerospace will be used for validation of thermal models.

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

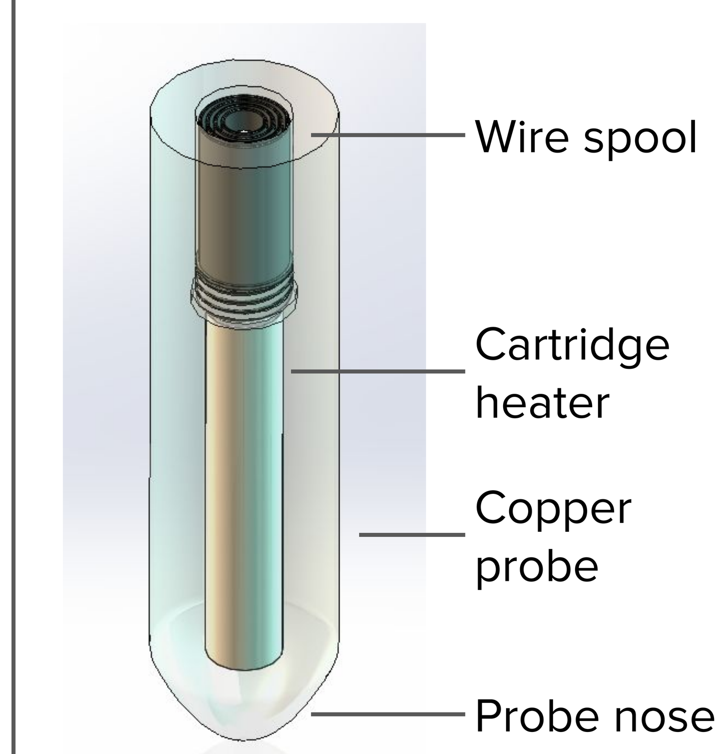

Figure 4 - Probe and spool current designs.

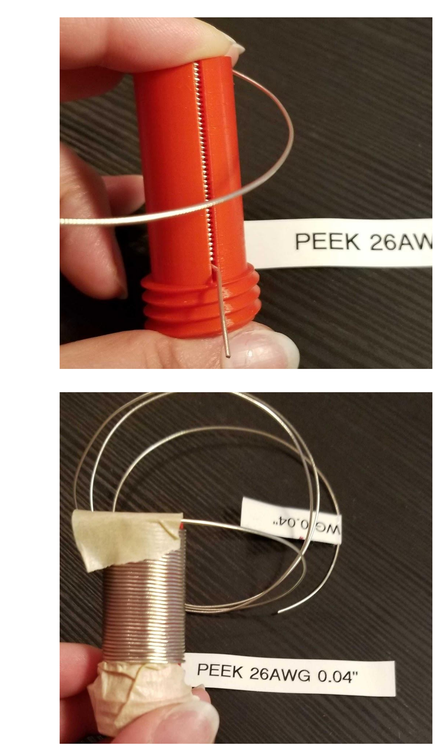

Figure 5 - Prototype of current spool design.

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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