Experimental Results and Model Validation of Melt Probes in Cryogenic Ice for the Exploration of Ocean Worlds

Paula do Vale Pereira[1], Kristof Richmond[2], Bartholomew Hogan[2], Alberto Lopez[2], Kerri Cahoy[1], and William Stone[2]

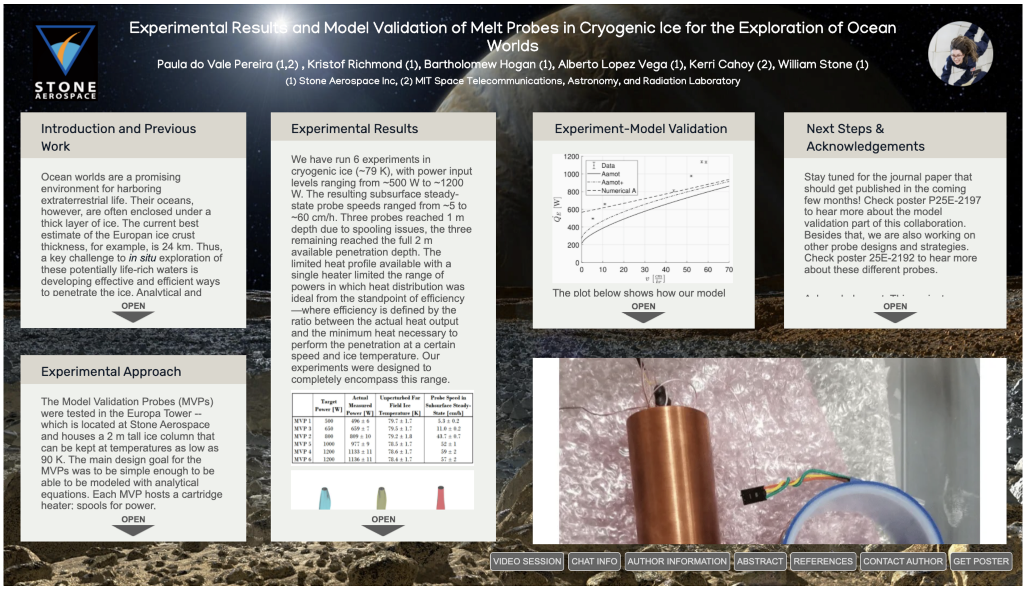
[1]Massachusetts Institute of Technology
[2]Stone Aerospace

November 24, 2022

Abstract

Ocean worlds are a promising environment for harboring extraterrestrial life. Their oceans, however, are often enclosed under a thick layer of ice. The current best estimate of the Europan ice crust thickness, for example, is 24 km. Thus, a key challenge to *in situ* exploration of these potentially life-rich waters is developing effective and efficient ways to penetrate the ice. Analytical and numerical thermal models of ice penetrators in cryogenic ice are available in the literature, but experimental validation of these models has been limited. To help close this gap, we have built scaled Model Validation Probes (MVPs) and evaluated their performance in the Europa Tower—a cryogenic vacuum chamber hosting an ice column of 0.75 m diameter and 2 m height, capable of maintaining ice at 90 K and surface pressure at near-vacuum (10^{-3} torr), similar to the conditions found on Europan surface. The tests monitored the fundamental probe performance variables of power and penetration speed, and additional variables such as ice and meltwater temperatures, and rough measurement of melt-hole shape. Seven tests were performed, ranging from 500 W to 1,200 W of input power. Four probes reached ~1 m of cryogenic ice penetration, and three probes reached the bottom of the 2 m ice column. All probes had confirmation of hole closure and the presence of liquid water inside the closed hole. This is the first realistic Europa-environment testing (cryogenic and vacuum) with subsurface penetration, hole closure, and liquid water. Comparison of our experimental results to the seminal Aamot model modified to handle temperature dependence of ice thermal properties shows that probe efficiency was below expectations, especially for high power probes. A detailed comparison of the experimental results to full finite volume numerical models results in better agreement and reveals the parameter range over which the Aamot model is valid. These results validate the core of the Aamot model while giving insight into its regime of applicability and the important factors governing deviations from its assumptions. The result of these endeavors is a deeper understanding of the dynamics of cryogenic ice penetration, directing future technological development and mission planning to enable direct exploration of environments that may harbor extraterrestrial life.

Experimental Results and Model Validation of Melt Probes in Cryogenic Ice for the Exploration of Ocean Worlds



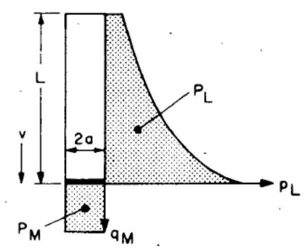
Paula do Vale Pereira (1,2) , Kristof Richmond (1), Bartholomew Hogan (1), Alberto Lopez Vega (1), Kerri Cahoy (2), William Stone (1)

(1) Stone Aerospace Inc, (2) MIT Space Telecommunications, Astronomy, and Radiation Laboratory

PRESENTED AT:

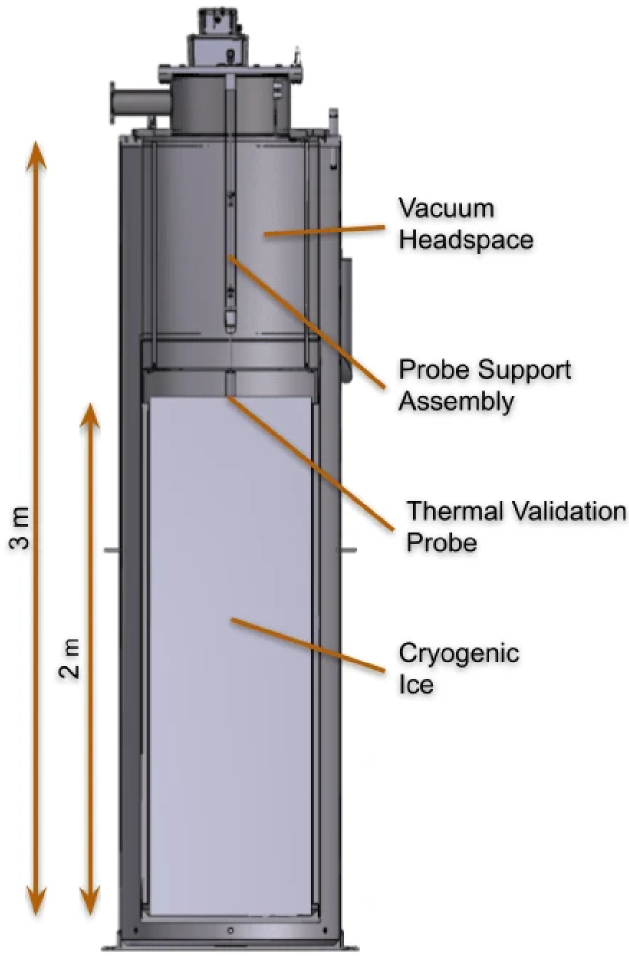
INTRODUCTION AND PREVIOUS WORK

Ocean worlds are a promising environment for harboring extraterrestrial life. Their oceans, however, are often enclosed under a thick layer of ice. The current best estimate of the Europan ice crust thickness, for example, is 24 km. Thus, a key challenge to *in situ* exploration of these potentially life-rich waters is developing effective and efficient ways to penetrate the ice. Analytical and numerical thermal models of ice penetrators in cryogenic ice are available in the literature, but experimental validation of these models has been limited. Basic models propose potential optimized heat distributions, but some of their assumptions are not realistic [1]. Our experiments will help close that gap and culminate with a way of actually describing the optimum heat distribution on a probe body.



EXPERIMENTAL APPROACH

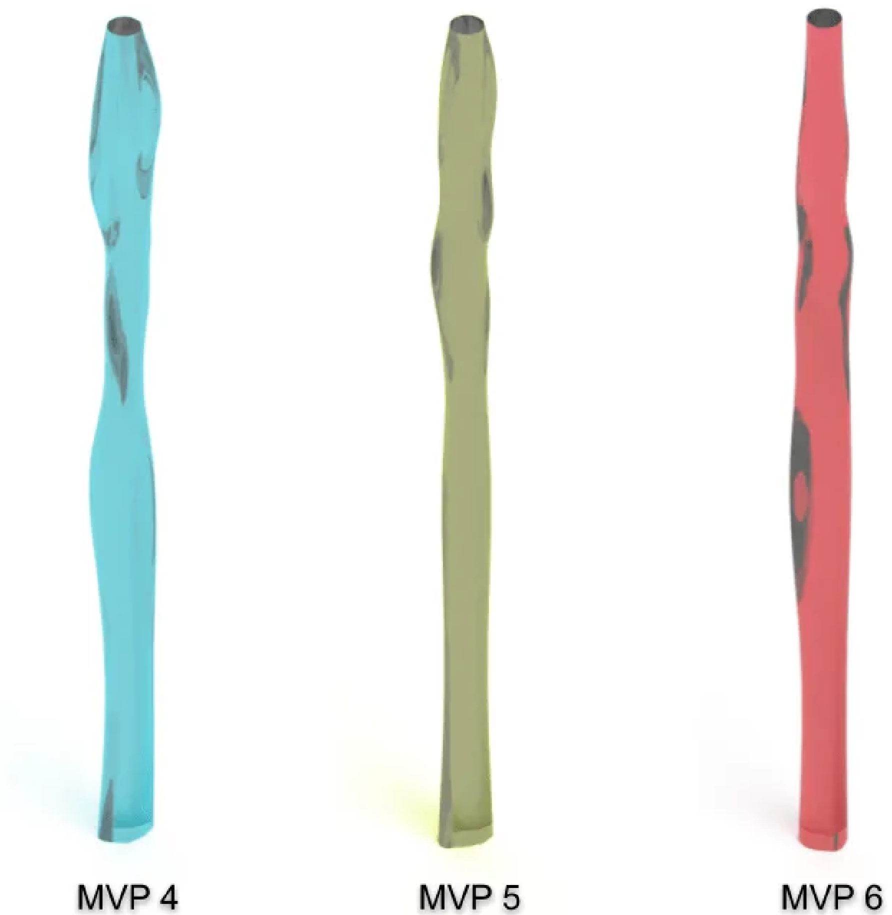
The Model Validation Probes (MVPs) were tested in the Europa Tower -- which is located at Stone Aerospace and houses a 2 m tall ice column that can be kept at temperatures as low as 90 K. The main design goal for the MVPs was to be simple enough to be able to be modeled with analytical equations. Each MVP hosts a cartridge heater; spools for power, thermocouple, and position encoder wires; and a dye source for the meltwater. The probe body is made out of copper to promote heat distribution, the spools are necessary to allow for subsurface penetration when the melt hole refreezes behind the probe.



EXPERIMENTAL RESULTS

We have run 6 experiments in cryogenic ice (~79 K), with power input levels ranging from ~500 W to ~1200 W. The resulting subsurface steady-state probe speeds ranged from ~5 to ~60 cm/h. Three probes reached 1 m depth due to spooling issues, the three remaining reached the full 2 m available penetration depth. The limited heat profile available with a single heater limited the range of powers in which heat distribution was ideal from the standpoint of efficiency—where efficiency is defined by the ratio between the actual heat output and the minimum heat necessary to perform the penetration at a certain speed and ice temperature. Our experiments were designed to completely encompass this range.

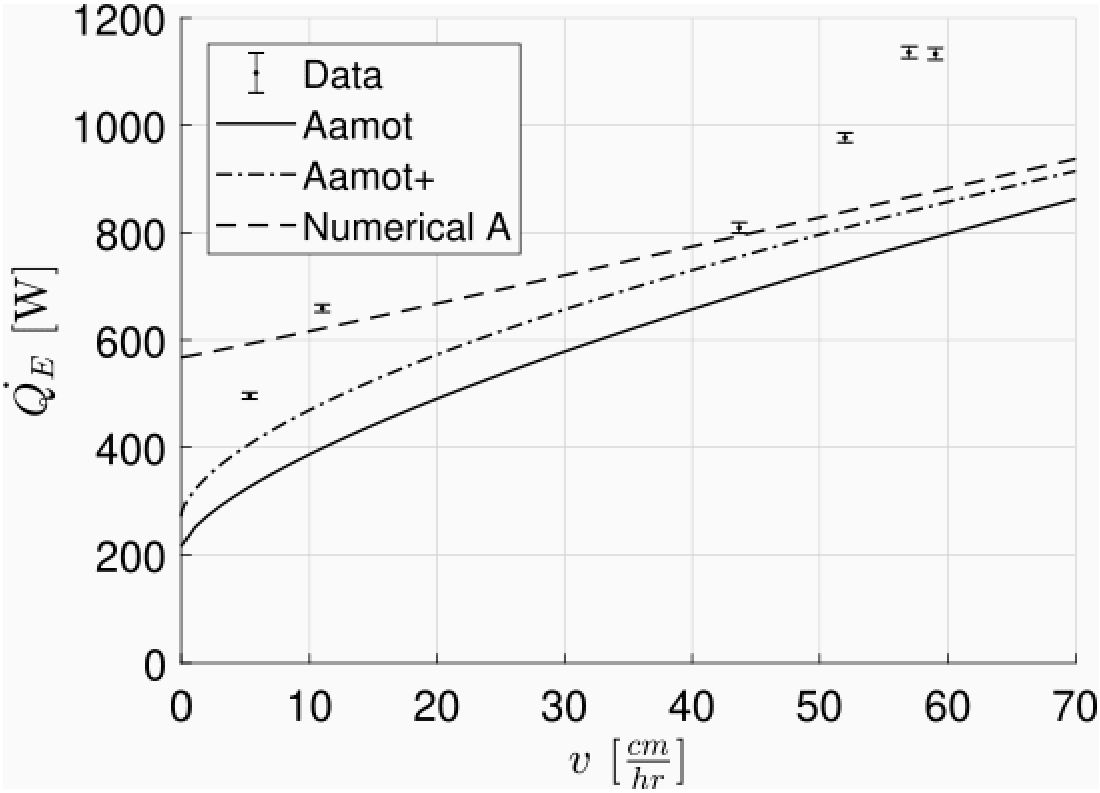
	Target Power [W]	Actual Measured Power [W]	Unperturbed Far Field Ice Temperature [K]	Probe Speed in Subsurface Steady-State [cm/h]
MVP 1	500	496 ± 6	79.7 ± 1.7	5.3 ± 0.2
MVP 3	650	659 ± 7	79.5 ± 1.7	11.0 ± 0.2
MVP 2	800	809 ± 10	79.2 ± 1.8	43.7 ± 0.7
MVP 5	1000	977 ± 9	78.5 ± 1.7	52 ± 1
MVP 4	1200	1133 ± 11	78.6 ± 1.7	59 ± 2
MVP 6	1200	1136 ± 11	78.4 ± 1.7	57 ± 2



[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639590627/agu-fm2021/F9-F6-2B-A4-2C-64-4B-71-58-74-AA-6E-EA-94-0B-F6/Video/AroundTheChamber_ok7bgk.mp4

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639590638/agu-fm2021/F9-F6-2B-A4-2C-64-4B-71-58-74-AA-6E-EA-94-0B-F6/Video/EnteringMVP5_lxn03n.mp4

EXPERIMENT-MODEL VALIDATION

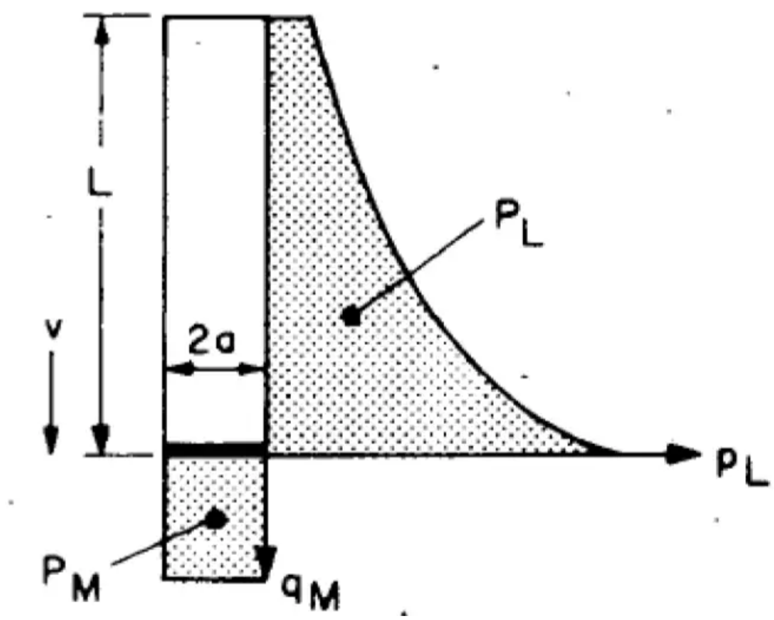


The plot below shows how our model compares to the seminal Aamot model. Note that there are discrepancies both on the low power and on the high power end. We are currently analyzing these discrepancies in the context of the general validation of models of thermal melt probes in a working paper [2] to be submitted shortly. In summary, in the low-power experiments, the is a lack of sidewall heating causing sticking to the ice during descent. In contrast, in the high-power experiments, there is too much sidewall heating leading to unnecessary melting and an excessively large melt pocket. However, overall, our experiments show that the Aamot model can be used to predict the performance of high aspect-ratio, efficient probes in cryogenic ice with high precision.

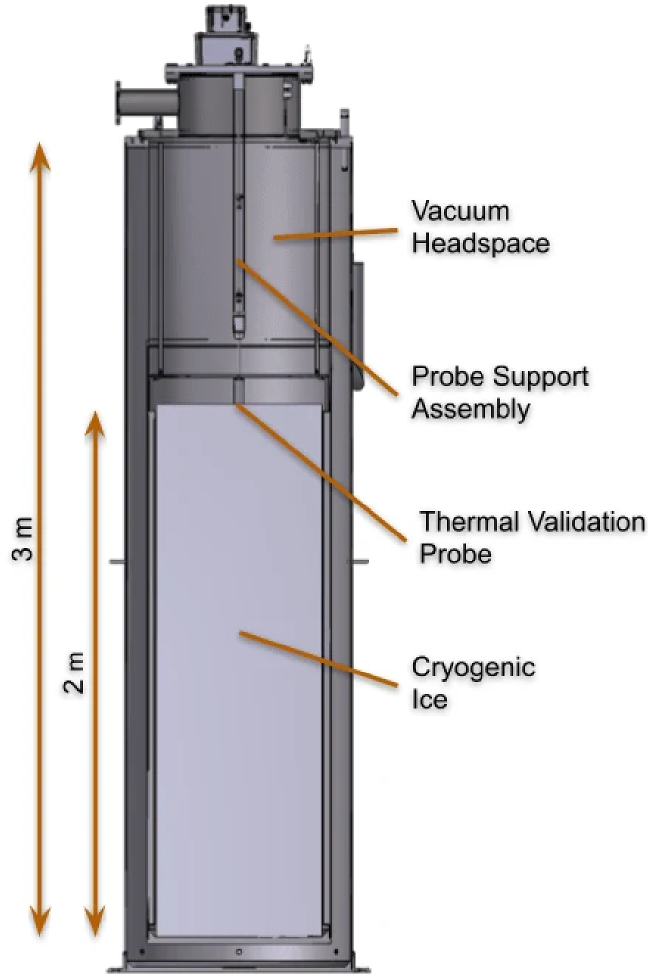
NEXT STEPS & ACKNOWLEDGEMENTS

Stay tuned for the journal paper that should get published in the coming few months! Check poster P25E-2197 to hear more about the model validation part of this collaboration. Besides that, we are also working on other probe designs and strategies. Check poster 25E-2192 to hear more about these different probes.

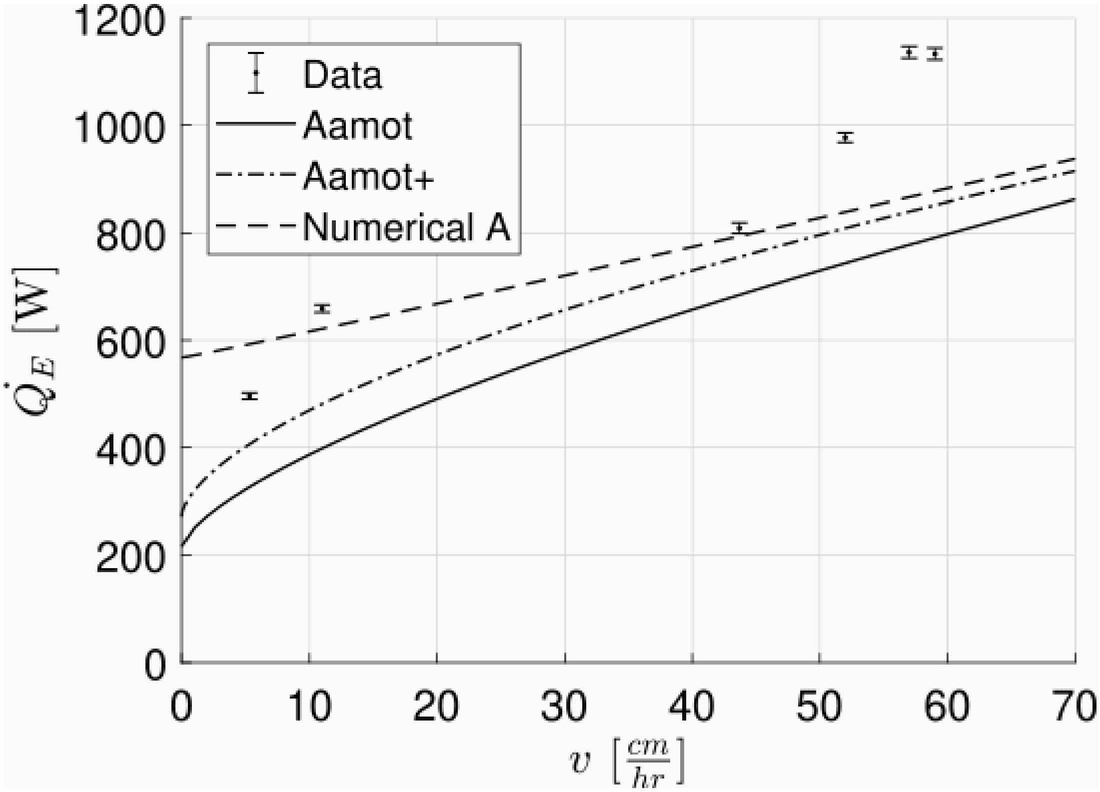
Acknowledgment: This project was funded under the NASA SESAME program, NASA Grant 80NSSC19K0612.

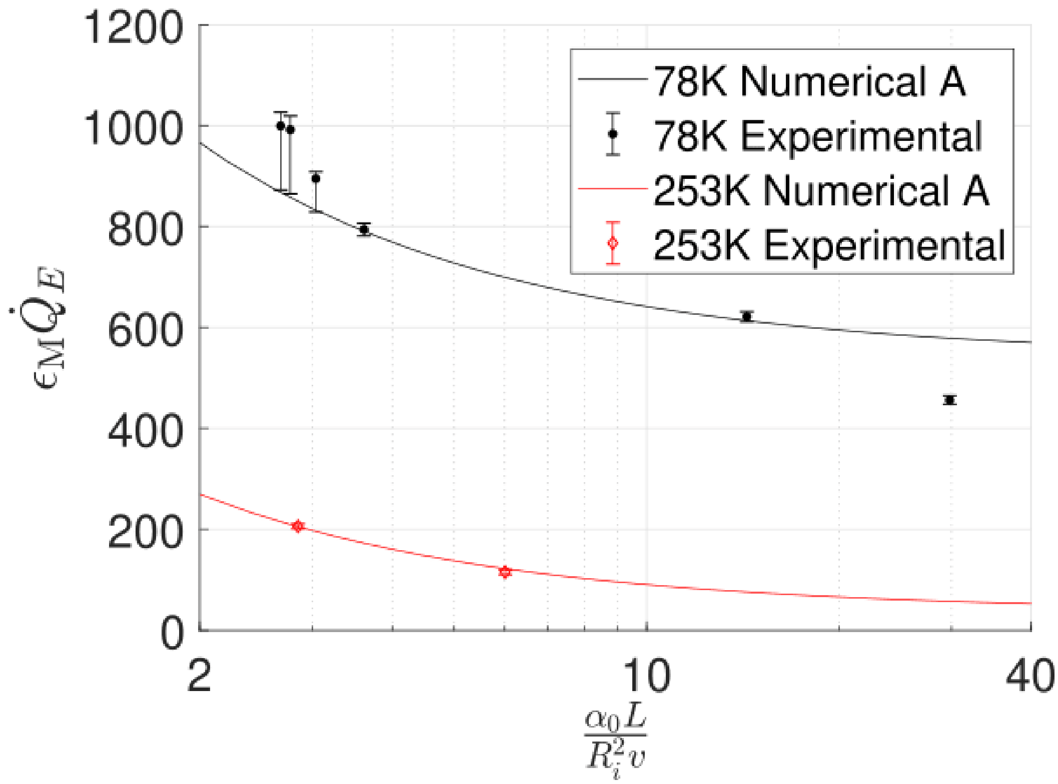


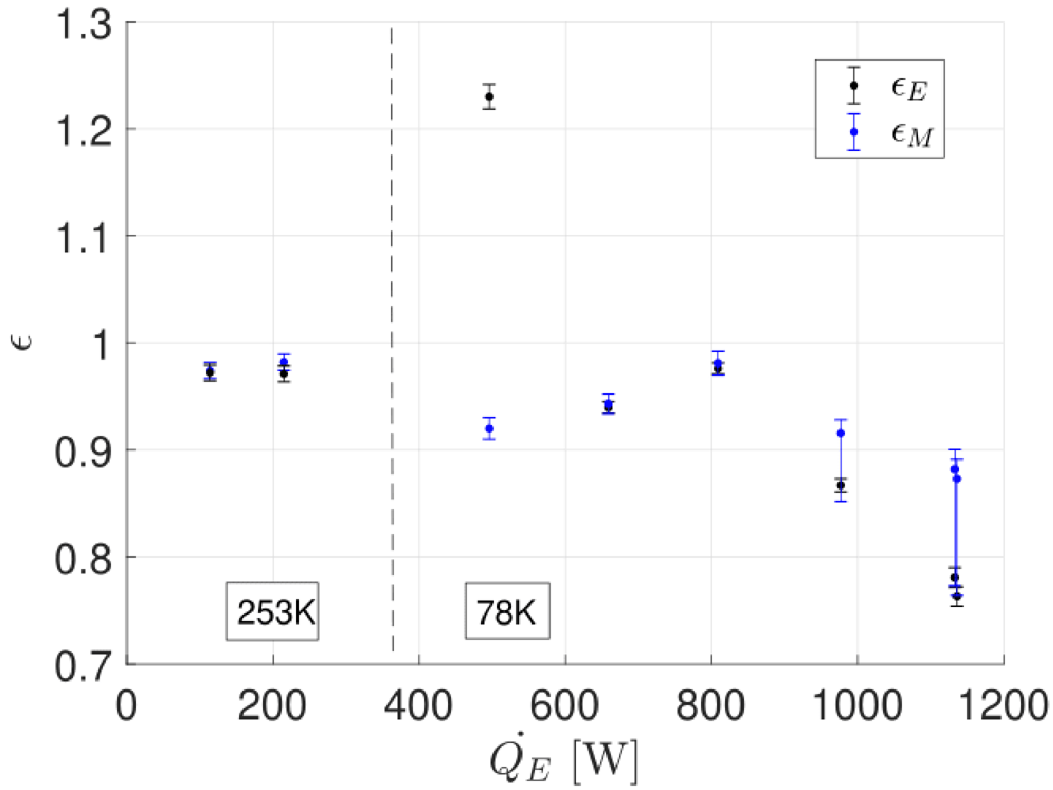

STONE
AEROSPACE
NASA

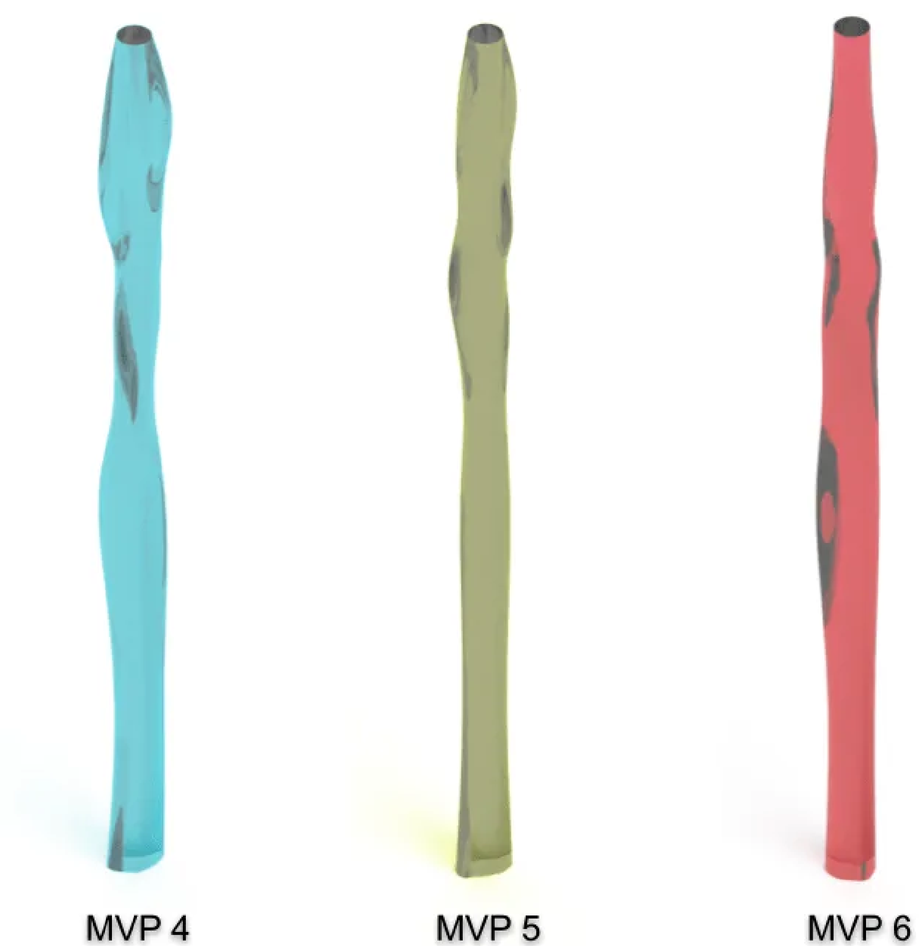

3 m
2 m
Vacuum Headspace
Probe Support Assembly
Thermal Validation Probe
Cryogenic Ice

	Target Power [W]	Actual Measured Power [W]	Unperturbed Far Field Ice Temperature [K]	Probe Speed in Subsurface Steady-State [cm/h]
MVP 1	500	496 ± 6	79.7 ± 1.7	5.3 ± 0.2
MVP 3	650	659 ± 7	79.5 ± 1.7	11.0 ± 0.2
MVP 2	800	809 ± 10	79.2 ± 1.8	43.7 ± 0.7
MVP 5	1000	977 ± 9	78.5 ± 1.7	52 ± 1
MVP 4	1200	1133 ± 11	78.6 ± 1.7	59 ± 2
MVP 6	1200	1136 ± 11	78.4 ± 1.7	57 ± 2


Data
Aamot
Aamot+
Numerical A
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70
$\dot{Q}_E$ [W]
v $\left[\frac{cm}{hr}\right]$


78K Numerical A
78K Experimental
253K Numerical A
253K Experimental
0
200
400
600
800
1000
1200
2
10
40
$\epsilon_M \dot{Q}_E$
$\frac{\alpha_0 L}{R_i^2 v}$


1.3
1.2
1.1
1
0.9
0.8
0.7
ϵ
ϵ_E
ϵ_M
253K
78K
0
200
400
600
800
1000
1200
$\dot{Q}_E$ [W]


MVP 4
MVP 5
MVP 6

AUTHOR INFORMATION

Paula do Vale Pereira:

paulavp@mit.edu or paula.do.vale.pereira@stoneaerospace.com

Kristof Richmond:

kristof.richmond@stoneaerospace.com

ABSTRACT

Ocean worlds are a promising environment for harboring extraterrestrial life. Their oceans, however, are often enclosed under a thick layer of ice. The current best estimate of the Europan ice crust thickness, for example, is 24 km. Thus, a key challenge to *in situ* exploration of these potentially life-rich waters is developing effective and efficient ways to penetrate the ice. Analytical and numerical thermal models of ice penetrators in cryogenic ice are available in the literature, but experimental validation of these models has been limited. To help close this gap, we have built scaled Model Validation Probes (MVPs) and evaluated their performance in the Europa Tower—a cryogenic vacuum chamber hosting an ice column of 0.75 m diameter and 2 m height, capable of maintaining ice at 90 K and surface pressure at near-vacuum (10^{-3} torr), similar to the conditions found on Europan surface. The tests monitored the fundamental probe performance variables of power and penetration speed, and additional variables such as ice and meltwater temperatures, and rough measurement of melt-hole shape. Seven tests were performed, ranging from 500 W to 1,200 W of input power. Four probes reached ~1 m of cryogenic ice penetration, and three probes reached the bottom of the 2 m ice column. All probes had confirmation of hole closure and the presence of liquid water inside the closed hole. This is the first realistic Europa-environment testing (cryogenic and vacuum) with subsurface penetration, hole closure, and liquid water. Comparison of our experimental results to the seminal Aamot model modified to handle temperature dependence of ice thermal properties shows that probe efficiency was below expectations, especially for high power probes. A detailed comparison of the experimental results to full finite volume numerical models results in better agreement and reveals the parameter range over which the Aamot model is valid. These results validate the core of the Aamot model while giving insight into its regime of applicability and the important factors governing deviations from its assumptions. The result of these endeavors is a deeper understanding of the dynamics of cryogenic ice penetration, directing future technological development and mission planning to enable direct exploration of environments that may harbor extraterrestrial life.

REFERENCES

[1] Aamot, H. W. C. 1967, Heat Transfer and Performance Analysis of a Thermal Probe for Glaciers, Technical Report 194, CRREL, Cold Regions Research and Engineering Laboratory, New Hampshire, USA.

[2] Do Vale Pereira, P., et al. Experimental Validation of Thermal Modeling of Subsurface Melt Probes for Ocean Worlds (TBC). To be submitted to The Planetary Science Journal.