Thermal Concept for Planetary Ice Melting Probe

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To support NASA future Ocean Worlds Exploration missions, Advanced Cooling Technologies, Inc (ACT) is developing an innovative thermal management concept for a nuclear-powered ice melting probe. The concept consists of multiple advanced thermal features that can offer the most efficient and reliable ice penetration process by maximizing the power fraction used for forward melting and mitigating a series of foreseen challenges related to icy-planetary missions. These thermal features include:

1) **pumped two-phase (P2P) loop which collects the waste heat from the cold end of the thermoelectric convertors, transports and focuses the waste heat at the front end of the vehicle for ice melting with minimal thermal resistance**
2) **front vapor chamber for forward heat focusing and melting**
3) **variable conductance side walls to enable lateral melting capability (only when the probe gets stuck because of refreezing or other obstacles in its path)**
4) **side high-pressure liquid water displacement for probe maneuverability and steering**

Under an SBIR Phase I program, ACT developed a preliminary full-scale probe design and assessed the technical feasibility of features (1) through (4). A lab-scale ice melting probe prototype with selected features was developed. Ice penetration and thermal behavior of the prototype were experimentally demonstrated in an ice environment system. Functionailties of variable conductance wall and vapor chamber were successfully proven.

Nomenclature

DOP = Depth of Penetration
R = Thermal Resistance across each components
ΔT = Temperature drop across each components
δ = Melted liquid film thickness confined between the probe and the surrounding ice

I. Introduction

There is a significant interest within NASA and the scientific community to explore outer planetary ocean worlds[1], including Jupiter's moon Europa. Since the Galileo spacecraft magnetometer data indicated that an ocean of liquid water/slush might exist 30 km below Europa's icy shell, ocean access became of particular interest for future missions in view of the possibility of finding signs of life or life itself. Ice crust perforation can be achieved with a thermal probe that has a hot front that is supplied with enough heat so it can cancel ice subcooling (potentially very large

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degree), melt the ice or even sublimate the ice if ambient pressure is very low. Earth tests of such a vehicle have been successfully carried out as shown in Ref. 2. Thermal probes must be robust, low mass, and capable of transporting various sensors mounted inside the probe structure. As just mentioned, severe challenges however, can impact the melting process in a low-pressure environment, like on the Europa's surface. As the ice gets heated below the triple-point pressure, it immediately sublimes dropping the melting efficiency, or at times preventing it. Experimental studies[2] report that a melting vehicle is able to melt ice under vacuum conditions at 258 K. Also, thermal conductivity of ice can have a significant effect on the melting and thermal drilling process as it is strongly temperature-dependent. It is shown in Ref. 3 that the high thermal conductivity of the low-temperature ice (6.5 $Wm^{-1}K^{-1}$ at 100 K), on Europa, makes the melting-based advancement/penetration more difficult and energy inefficient compared to Mars[3]. For example, a single (and isolated) General Purpose Heat Source (GPHS) module would be able to penetrate ice layers on Earth or Mars, whereas on Europa, due to low temperature ice at the surface, the source would become stuck in the ice with a surface temperature of < 200 K. A feasible melting probe for shallow ice on Europa was recently proposed by German researchers[4]. An energy analysis for a penetration depth of only 10 cm was conducted and showed positive results for a sample size of 7 cm^3.

In order to reduce penetration time, these nuclear-powered ice melting probes must have minimal footprint in vertical direction and the power fraction used for forward melting must be maximized. Advanced Cooling Technologies, Inc. (ACT) is developing a novel thermal management system that can effectively focus the waste heat to the melting front during normal ice penetration operation and mitigate a series of challenges that the melting probe might encounter during a penetration process, including meeting obstacles, probe getting stuck due to ice refreezing etc.

II. Thermal Concept of The Ice Melitng Probe

Figure 1 shows a preliminary ice melting probe with thermal management features. The internal diameter of the probe is 26 cm and it is 3 m long. It contains 32 GPHS modules, which can generate 8kW of waste heat for ice melting. Operation principle of the thermal management system is as follows: heat is provided from the GPHS modules directly to the thermoelectric (TECs), and the waste heat from the TECs is taken by a pumped two-phase (P2P) loop via evaporators interfacing with the TECcold ends. Heat is transported via vapor flow to the condenser that is located at the bottom of the probe. Over there, a P2P condenser interfaces with a front vapor chamber. The front vapor chamber in turn focuses the heat into the front of the probe for forward melting. The same front vapor chamber is extended upwards along the inside of the external wall (cylindrical), all the way to the top, to form a narrow annular space. This annular extension of the front vapor chamber contains a Non-Condensable Gas (NCG) during normal operation and potentially vapor when lateral metling is needed. When thermal resistance between the front and the ice/liquid increases because of lateral freezing or other obstacles, vapor temperature and therefore, vapor pressure in the vapor camber increases, which pushes the vapor-NCG interface upwards to heat the side walls for probe release or lateral motion. It can be seen from Figure 1 that four sets of liquid displacement nozzles are installed to provide probe steering/lateral movement capability to avoid obstacles. A simplified thermal management scheme is illustrated in Figure 2(a) and the associated thermal resistance network is presented in Figure 2(b). The mathmematical expression of the overall thermal resistance is

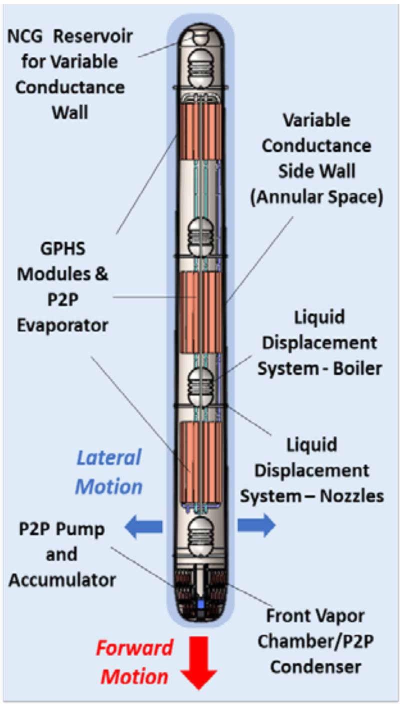


Figure 1. Proposed Thermal Architecture for Europa Ice Melting Probe

$$R_1 + R_2 + R_3 + \frac{1}{\frac{1}{(R_4+R_5)}+\frac{1}{R_6}} \tag{1}$$

In this expression R_6 is a variable component, which decreases when the vapor/NCG front elevates. Three technical goals of full-scale probe trade study are:

(1) To develop a preliminary full-scale thermal management design which is able to minimize the temperature difference between the heat source (GPHS module) and the heat sink (ice) during normal operation
(2) To evaluate the technical feasibility of the proposed thermal feature by calculating ΔT across each component (with 8kW heat load)
(3) To identify pathways to further improve the thermal performances of all the thermal features.

Design and the feasibility analysis of each component are presented in the following sections.

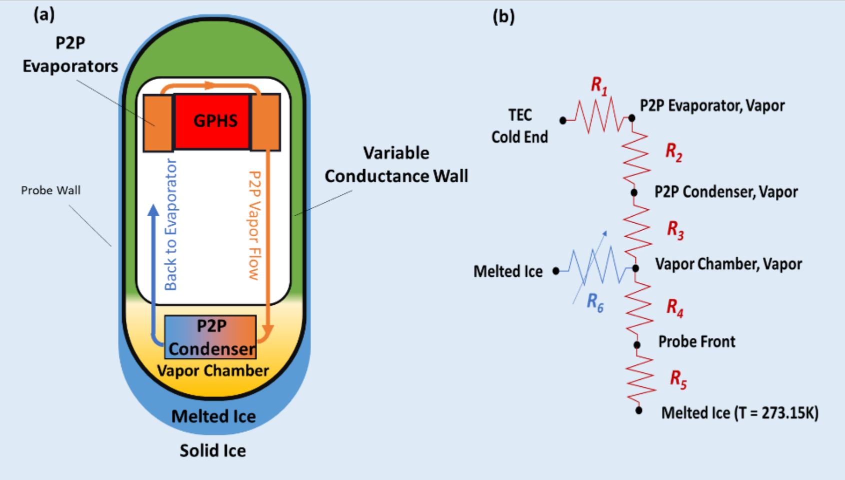


Figure 2.(a) Schematic of thermal concept of Europa Ice melter (not to scale) (b) thermal resistance network

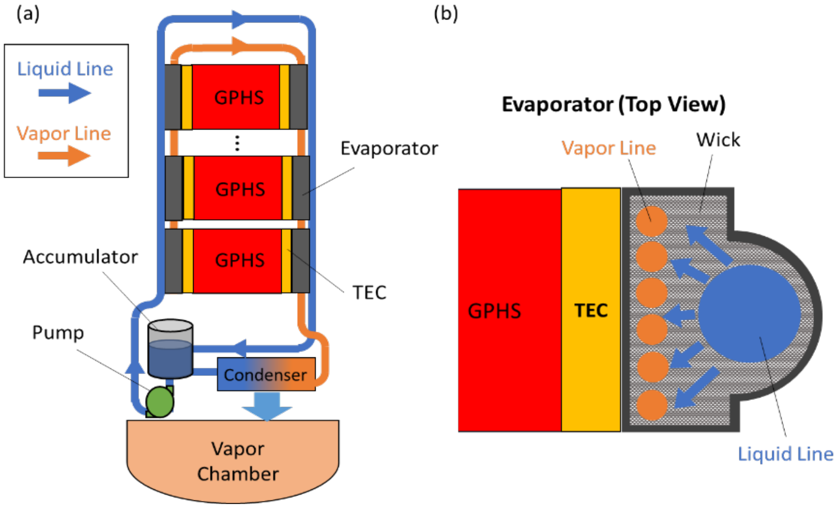


Figure 3. Pumped Two-phase system designed for Europa ice melting probe (a) schematic drawing of the entire loop (b) cross section of the evaporator that can separate liquid and vapor flows

A. Pumped Two-Phase (P2P) Heat Delivery System

A schematic of the pumped two-phase loop system for waste heat collection from the cold end of TECs and heat transport to the front vapor chamber is shown in Figure 3(a). Liquid and vapor phases of the pumped coolant are separated by the wick structure within the evaporator (similar to Loop Heat Pipe evaporator) as shown in Figure 3(b). Liquid phase will be driven by a pump and circulate within the liquid lines. Wick structure of the evaporator will accept liquid from the liquid line into the vapor lines, as needed, through capillary action. Waste heat from TEC cold end will vaporize the working fluid in the wick. Vapor phase will be generated at the evaporator. It will travel along the vapor lines and release its latent heat at the condenser, which is located within the front vapor chamber. Incorporating the P2P loop will offer the following advantages to this system:

- Minimized thermal resistance between the two-phase fluid and the HX tube wall
- Low pumping power
- Isothermality along the entire loop
    - Cold ends of the TECs are seeing the same sink temperature
- Low mass
- Easily managed variable heat loads

A preliminary P2P heat delivery system for Europa ice melting probe is designed. Design inputs are summarized in Table 1. Water is selected as the working fluid because of (1) its high latent heat of vaporization and (2) suitable operating temperatures. The thermal resistance through the evaporator (R_1) is first calculated as 1.5E-3 K/W and the corresponding temperature drop through the evaporator with 8000W of heat load is around 12K (ΔT_1). Pressure drops along the liquid and vapor lines is calculated using the approach described in Ref.5. The volumetric flow rate is assumed to be 200 ml/min and the maximum vertical distance for the liquid to flow against Europa gravity is 1.5 meter (one way). With 8kW of heat load, the maximum pressure difference between the liquid and the vapor lines is 1,913 Pa, which occurs at the highest location of the loop. The capillary pressure that can be provided by the designed wick structure in the evaporator is 2,104 Pa. This means that the capillary pressure is sufficient to separate the liquid and the vapor phases in the evaporator. The vapor temperature drop from the evaporator to the condenser is less than 2°C (ΔT_2).

Table 1. Design inputs for P2P evaporator thermal perforamcne analysis and P2P loop pressure drop analysis

Design Inputs	Value
GPHS Cluster Overall Dimensions	9.4cm x 14.5cm x 109.5cm
Liquid Line ID	3/8 " (0.95 cm)
Vapor Line ID	1/4 " (0.64 cm)
Number of Vapor Lines	30
Number of Liquid Lines	6
Wick Porosity	0.7
Heat Load	8000W
Pore radius of wick structure	20 µm
Total Volumetric Flow Rate	200 ml/min
Permeability	9E-11 m^2
Working fluid	Water
Envelope Material	Titanium

B. P2P Condenser/Front Vapor Chamber

The front vapor chamber is a crucial component of the thermal management system since it is the main "melting" component and the main heat sink of the P2P loop. The heat is received from the P2P loop through a low thermal resistance heat exchanger that has wick at the interface which is always saturated with liquid. The heat evaporates the liquid from the heat exchanger wicked surface. The vapor travels a short distance and condenses in the wick of the inside of the front wall and releases the latent heat. This heat conducts through the wall into the outside ice/water/environment. An optimized vapor chamber design would provide the following advantages:

1. Low thermal resistance interface between the P2P loop and the environment.
2. Uniform temperature distribution at the melting interface.
3. Provide vapor to variable conductance walls.

Figure 4 is the CAD model of a preliminary front vapor chamber design, containing a P2P condenser, accumulator and pump. Probe OD is 26 cm and the probe wall thickness is 5.7mm, made of Titanium. The P2P condenser shown in this design consists of 11 rings of tubing in a rectangular cross section. Vapor coming from the P2P evaporator is divided into 6 branches and enters the condenser tubing. Using rectangular tubing will maximize the dry surface for vapor condensation and the heat transfer performance. Gravitational force on Europa will assist the separation of the liquid and the vapor phases. The condensed liquid film will fall and flow into the accumulator, which is located at the core of the front vapor chamber. Liquid will then be pumped back to the top of the probe and continue to collect waste heat from the heat sources. As Figure 4 shows, the front vapor chamber is elongated to increase heat transfer surface area at probe/ice interface. Also to accommodate more tubes for maximizing the heat exchange area between vapor chamber and P2P condenser, the vapor chamber is compartmentalized. Each level contains three to four rings. The capillary limit, sonic limit and entrainment limit of the vapor chamber design at different working temperature were calculated and plotted in Figure 5, which shows that this vapor chamber design is capable of transferring 8kW of heat at desired working temperature (303 – 333K) with sufficiently large margin.

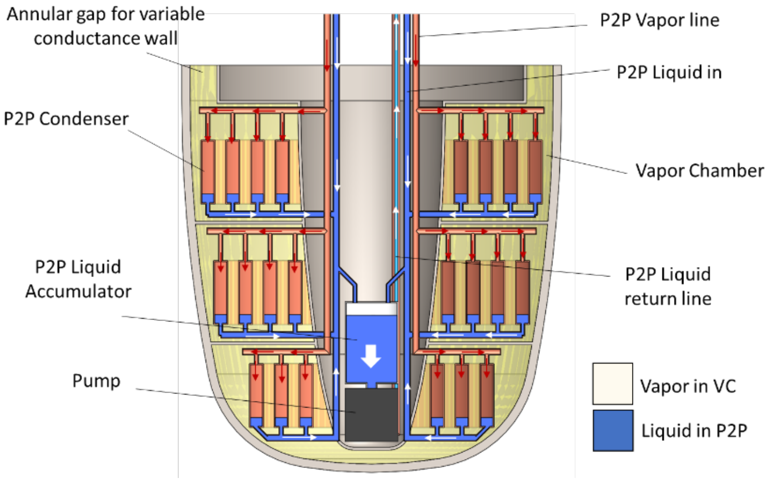


Figure 4. P2P Condenser integrated within a vapor chamber

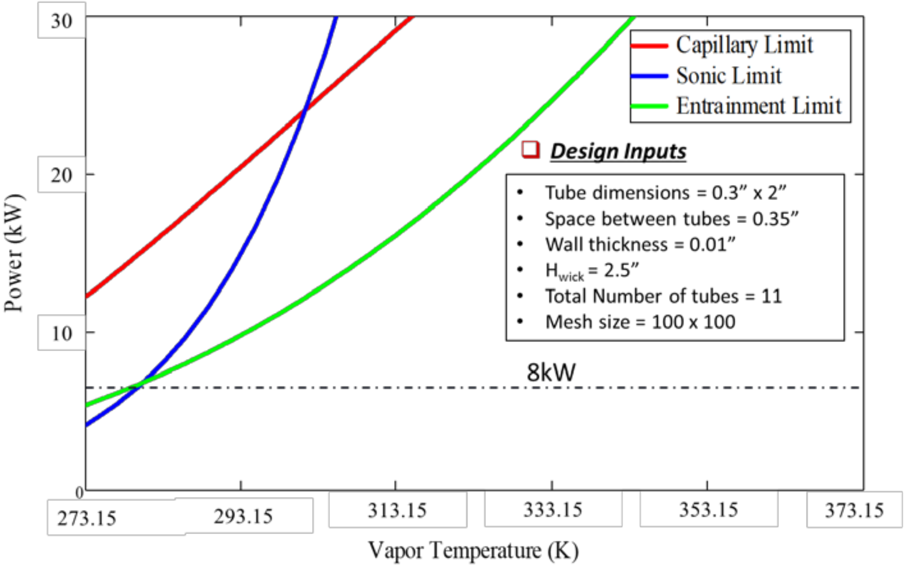


Figure 5. Heat transfer capability of the vapor chamber

Thermal resistance across P2P condenser can be calculated with the given designed inputs listed in Table 1 and Figure 5. The condensation heat transfer coefficient at inner surfaces of the condenser tubing is 20,000 W/m^{2}K (Ref. 6). With 8kW of heat loads, the corresponding temperature drop across the P2P condenser can be determiend as 2.5K(ΔT_3). Heat transfer from the inner surface of the vapor chamber to the probe wall outer surface consists of two components: (1) vapor condensation at the inner surface of the probe head (2) and conduction through the titanium probe wall. Condensation heat transfer coefficient on the probe inner surface with screen attached is assumed to be 7,000 W/m^{2}K. The wall thickness of the probe wall is 5.7mm. This thickness is determined based on a simple stress analysis to make sure that the probe can withstand an external pressure of 500 atm with a factor of safety 2. As mentioned above, heat flux across the probe head is reduced by elongating the probe head. The resultant temperature drop (ΔT_4) is 18.9K.

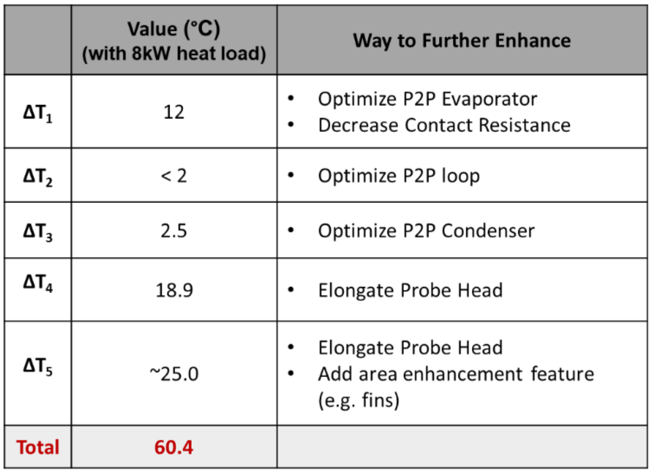
C. Heat Transfer Between the Probe and the Surrounding Ice

Heat transfer between the probe head and the surrounding liquid layer/film (melted ice) is considered to be the “bottle neck” of the thermal resistance chain. An analytical model was recently developed by Schüller & Kowalski[7].

In their physical model, ice melting is considered to be a quasi-steady process. During this process, a thin liquid water film with constant thickness δ forms at the melting front and separates the melting nose and the solid ice. In this configuration, portions of heat dissipated from the melting head are carried away by a lateral outflow velocity and the remaining heat is used to melt the bottom ice. Their model couples heat transfer, hydrodynamics and solid-liquid phase transition to describe the thin-film flow region confined between the probe surface and the solid subcooled ice. Four governing equations associated with the laws of conservation within the thin-film flow region and the force balance between the liquid and the probe are derived and solved[7]. ACT employs their theoretical model to predict the film thickness and the melting velocity of the current full-scale probe under Europa ice environment. Film confined between the probe head and the solid ice is very thin (less than 0.25 mm) and the average melting speed is around 0.15 mm/s. Probe will accelerate as it goes deeper because the surrounding ice is less subcooled. With 8000W of heat load, temperature of the probe head is around 298.15K. Note that in this analysis, the contact surface between ice and probe is assumed to be hemispherical. For an elongated probe head design, heat fluxes out from the probe surface will be much smaller than the hemispehere probe head design. This will lead to a smaller ΔT_5. In addition, the contact surface area can be further enhanced by addinga a fin structure. Since the fin structure might change the confined flow pattern between the probe surface and the solid ice, the theoretical model presented above might not be applicable. More detailed numerical investigation will be performed in the future to clarify the benefit of adding area enhancement fins outside the probe head.

Table 2 below summarizes the temperature drops associated with different components of the thermal resistance network shown in Figure 2(b) (based on the design and analysis presented above). During nominal forward melting mode, if all 8000W of waste heat is dissipated through the front vapor chamber, the vapor temperature in the vapor chamber will be around 54°C and the TEC cold end temperature will be maintained around 60°C. The key of mitigating overall ΔT is to optimize the form factor of the probe head and the front vapor chamber. It is also beneficial to introduce area enhancement features to maximize probe head/ice contact area.

Table 2. Overall temperature drops from TEC to the surrounding ice based on the preliminary thermal management design for a full-scale probe



	Value (°C) (with 8kW heat load)	Way to Further Enhance
ΔT_1	12	• Optimize P2P Evaporator • Decrease Contact Resistance
ΔT_2	< 2	• Optimize P2P loop
ΔT_3	2.5	• Optimize P2P Condenser
ΔT_4	18.9	• Elongate Probe Head
ΔT_5	~25.0	• Elongate Probe Head • Add area enhancement feature (e.g. fins)
Total	**60.4**	

D. Variable Conductance Wall

This feature involves an annular extension of the front vapor chamber upwards, all the way to the rear (top) and connected with an NCG reservoir. In other words, almost the entire probe would be blanketed by vapor and NCG that share the same volume/space. The vapor-NCG front location will be determined by vapor and NCG temperatures. Below, the feature is presented and explained based on the challenges that are solved.

1. **Releasing the probe from lateral freezing:** The major purpose of this feature is to passively melt the side ice when the vehicle gets stuck as a result of lateral water refreezing. When such an event occurs, thermal resistance in the front increases due to the fact that latent heat is not absorbed and also, the amount of outside liquid water increases its temperature because of sensible heating. As a result, the vapor temperature increases and so does the vapor pressure. Then, the vapor - NCG front moves upwards allowing the advancing vapor to heat the side walls and further melt the outside ice to unblock the vehicle. Once the vehicle is free and

able to continue the forward melting and movement, vapor pressure goes back to the nominal value and the front travels back to the nominal location, just above the front vapor chamber resuming normal operation and forward melting. The system is fully passive and saves energy by minimizing its use during abnormal situations.

2. **Avoiding obstacles - lateral melting:** another serious challenge is the potential presence of rocks/debris/impurities in the path of the probe. In these cases, the forward melting becomes more difficult or even impossible and prevents the probe from its advancement. In such situations, the front vapor chamber, that needs to reject the continuously incoming heat, increases the vapor temperature and the NCG front moves up (as much as needed to enable heat rejection through the side walls). In other words, the probe gets hotter, melts the surrounding ice and creates liquid water all around the probe. The lateral melting and movement can then be started by engaging the liquid displacement nozzles, which are described later.
3. **Minimizing potential skewing:** the vapor – NCG blanket that the Variable Conductance Walls feature provides will significantly increase the wall isothermality in the tangential direction, minimizing the potential for skewness. In turn, this will minimize the length of the melting path/trajectory to the ice-liquid interface.
4. **Heat rejection during transit:** during transit to Europa the probe will be kept in "lateral melting" mode (or hot probe). In these conditions (hot probe), the entire amount of heat is rejected through the front vapor chamber and lateral walls to an external cooling loop (inside the carrier space craft) attached to the probe (and detachable once on Europa surface).

Figure 6 below shows NCG/vapor front location and vapor temperature as a function of environment temperature and total thermal power. In this case it was assumed that the entire thermal power of 8000 W was delivered to the environment through the vapor chamber at nominal conditions. It is true that other factors like environmental pressure and ice subcooling would also influence boundary conditions (mostly heat transfer coefficient) therefore a more complex and detailed model will include these influences.

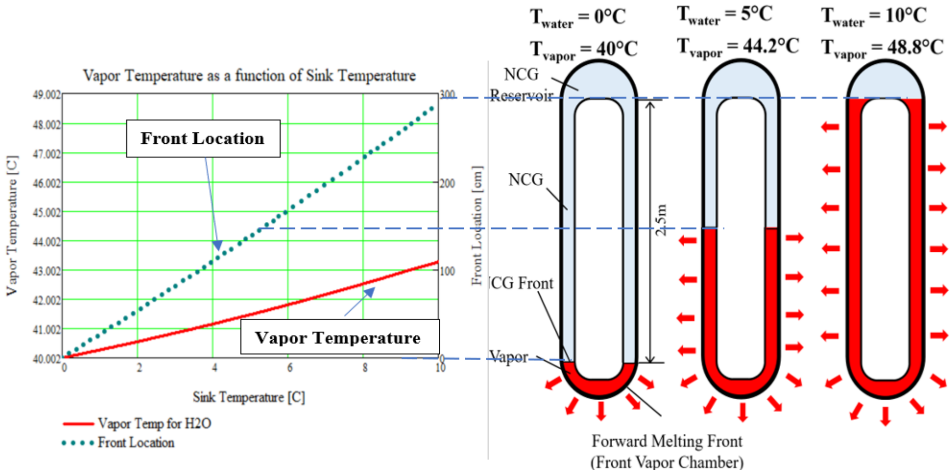


Figure 6. Vapor/NCG locations at various sink (environment) temperatures (full-scale system)

E. Liquid Dispacement System for Lateral Motion

This feature allows the probe to navigate through the ice in a direction other than vertical down when needed. This feature will always be assisted by the variable conductance wall feature that will, by default, always provide liquid water film around the probe. The feature will include a bellow-like boiler capable of high pressure (>500atm) that are provided with nozzles to the outside environment. The high-pressure liquid nozzles would work under two different regimes:

- **Two-phase water regime**: where the liquid is pushed out almost continuously by the vapor pressure. This regime will be used at depths where the environmental pressure is lower than the critical pressure of water (217 atm).
- **Compressed liquid regime:** where the pressure vessel is liquid tight and volumes of liquid are pushed out into the environment intermittently (to allow recharge/refill) by heating and cooling of the pressure vessel.

This regime will be used at depths where the environmental pressure is higher than the critical pressure of water (217 atm). To be noted is that, even though the pressure is supercritical, heating of the vessel will not produce supercritical temperatures so the fluid (water) will always be in a "compressed liquid" state. The probe will be pushed in the opposite direction mostly by the displacement of the liquid out of the probe, because of the difference in liquid density caused by vessel expansion as well as by liquid compression. Preliminary calculations show that, in high pressure environment (500 atm), just by liquid displacement the probe can move entirely lateral at a rate of 0.2-0.3 mm per hour if an average heating power of 350W is applied.

Based on their principle of operation, type of energy used as well as heating and cooling methods available on board, there are several alternative concepts that ACT considered in regards to this feature, including:

- Liquid water displacement by *thermal cycling*.
    - Liquid water displacement by thermal cycling – P2P loop Cooling.
    - Liquid water displacement by thermal cycling – Environment Direct Cooling.
- Liquid water displacement by *electro -mechanical pumping*.

III. Lab-scale Melting Probe Prototype Development

A reduced-scale melting probe prototype is developed by ACT to demonstrate two major thermal features: a variable conductance wall and a front vapor chamber. The sectional view of the lab-scale prototype is shown in Figure 7 and the fabricated hardware is shown in Figure 8. The probe OD is 3 inches (7.62 cm) and the length is 11 inches (27.94 cm). This prototype consists of two shells: The inner shell contains a heater block and an NCG reservoir. The outer shell is the actual melting probe. The annular space between the two shells is the vapor space of variable conductance walls, which is charged with the working fluid (water) and the NCG (nitrogen). The entire probe is made of Monel because of its compatibility with water. It is however envisioned that the full-scale probe will be made from titanium (also compatible with water). As mentioned above, a custom-made heater block is integrated with the inner shell lower dome, which can provide more than 500W of heat. TCs and cables of heater extrude from the top of the probe via a feedthrough pipe. The vapor chamber is located at the bottom of the probe and the liquid return is achieved by rolls of fine screen mesh. The probe head has fin structure to enhance ice/probe contact area (Figure 8). After charging with the working fluid and the NCG from the fill tube, the probe is placed on the ice environment system for testing. The ice envionrment system is essentially a big ice block (40.6 cm x 20.3 cm x 76.2 cm) enclosed by 6 sets of LN serpentine as shown in Figure 9. Temperatures along the probe and the penetration depth are monitored during the test by 17 thermal coupless and a linear depth penetration sensor. In addition, the process of ice penetration is recorded by a camera, taking photographs every 2 mins.

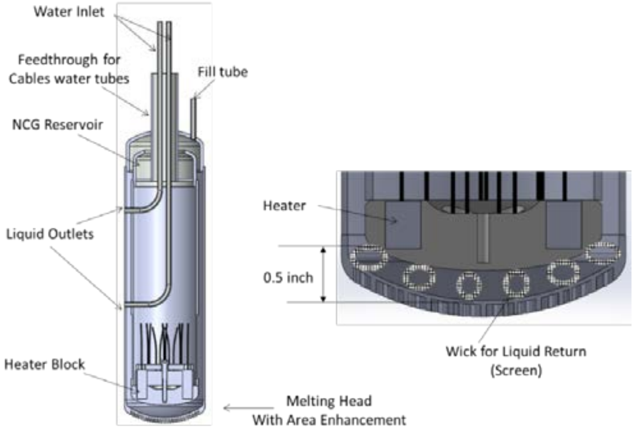


Figure 7. Lab-scale melting probe prototype for thermal feature demonstration

Figure 8. Lab-scale ice melting probe prototype with area enhanced melting head

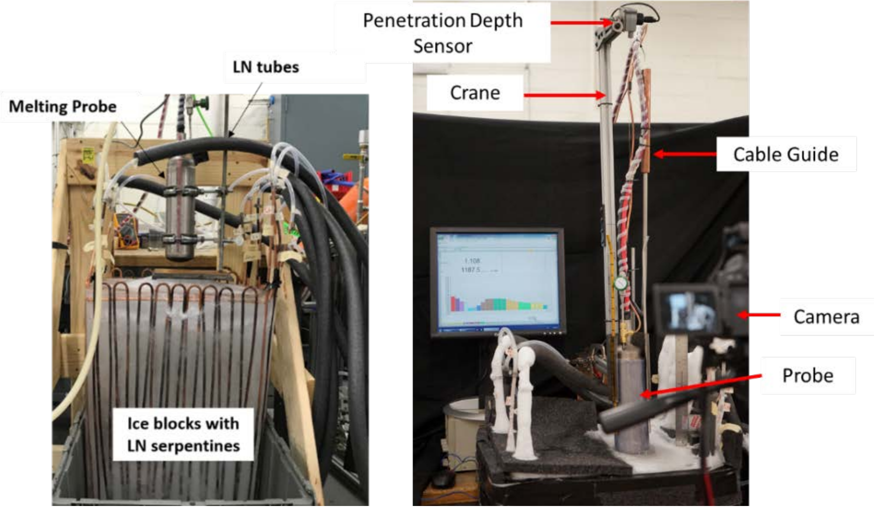


Figure 9. Ice Envionrment System for Prototype Testing

IV. Test results and Discussion

A. Ice Penetration Test

Figure 10 shows the temperature evolution with respect to the depth of penetration. In this test, 95W of heat was continuously applied to the heater. Before refreezing occurs (will be shown later), the probe melts downward in a nearly constant speed, which is around 0.028 mm/s. Figure 11 is a photograph taken at t =2800s. The instantaneous temperature profile along the probe, depth of penetration (DOP) and the time stamp are shown in the monitor in the photograph. The probe sinking velocity and the probe head temperature data was used to validate the theoretical model described in Ref. 7 and the results are shown in Table 3.

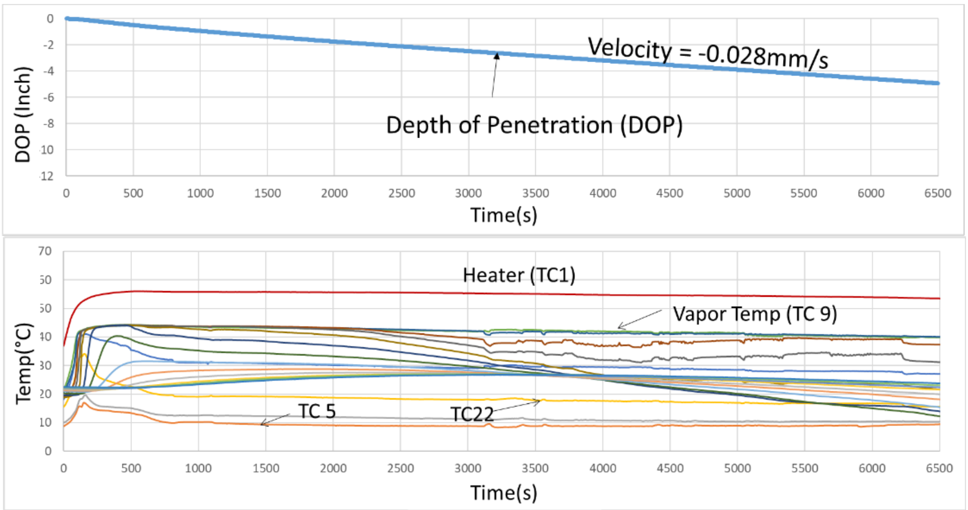


Figure 10. Ice penetration test results. Upper plot shows the depth of penetration and the lower plot shows the corresponding temperature evolution

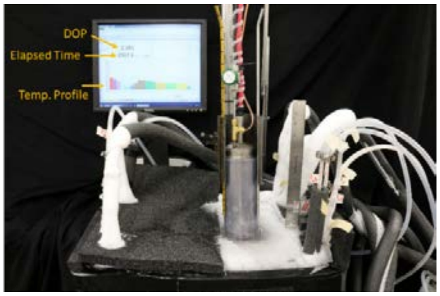


Figure 11. Probe status during normal ice penetration (t=2800s)

Table 3. Comparison between theoretical results and test data

	Measured	**Model[7]**
Melting Velocity (mm/s)	0.028	0.025
Film thickness (mm)	N/A	0.56
Probe Head Temp (°C)	11	9

B. Probe Refreezing and Self-Releasing

One of the critical functionalities of the variable conductance wall is to allow the probe to release itself from a refreezing condition. This was successfully demonstrated in Figure 12 At the beginning of the test, probe was sinking smoothly. As more length of the probe submerged into the ice, more heat started releasing to the environment and at t=6200 seconds, ice around the probe body started refreezing. The probe was getting stuck and unable to melt forward. As predicted, the variable conductance wall started operating: the probe cannot dissipate all the heat through the front vapor chamber and the vapor temperature (and pressure) increases. Vapor expands and pushes the vapor front upward. This leads to the increase of side wall temperature, which can be seen from the transient temperature data shown in Figure 12. Increased side wall temperature melted the refreezing spots and the probe was released. After the probe was released from refreezing condition, probe front temperature significantly decreased and the vapor front retracted.

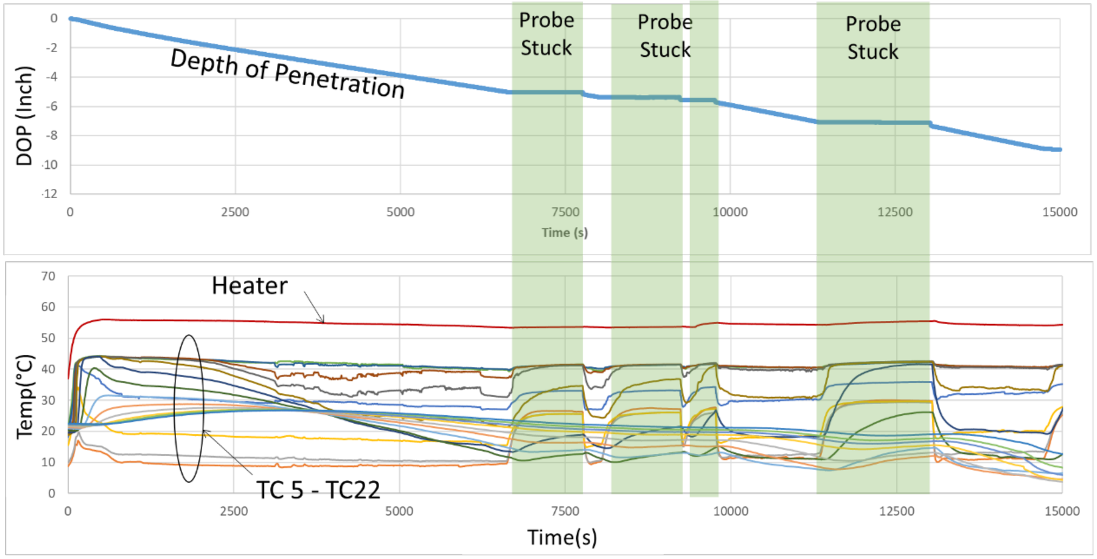


Figure 12. Depth of penetration data and probe temperature behavoir during stuck and self-releasing periods

C. Probe Meets an Obstacle

A third test was then conducted to demonstrate thermal behavior of the variable conductance wall when the probe front meets an obstacle. Testing procedure is similar to the previous test and the result is shown in Figure 13. The major difference is that an obstacle (a polymer plate) was embedded at the depth of 10.8 inches (27.4 cm). In the early stage of the test, the probe smoothly penetrated the ice. During the middle of penetration process, the probe was getting stuck due to ice refreezing and probe released itself using the mechanism discussed above. At t=18,000s, the probe front met the obstacle and could not melt forward. As the temperature data shown in Figure 13, vapor front moved significantly and heated up the side wall. Temperature profiles for the three different cases are shown in Figure 14.

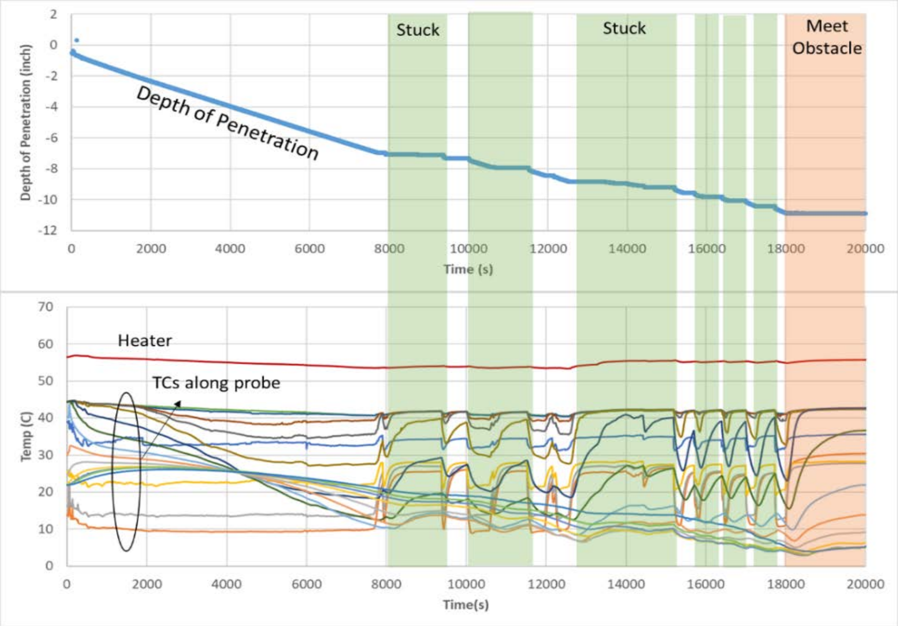


Figure 13. Depth of penetration data and probe temperature behavoir at various conditions, including normal melting, refreezing and meeting obstacles.

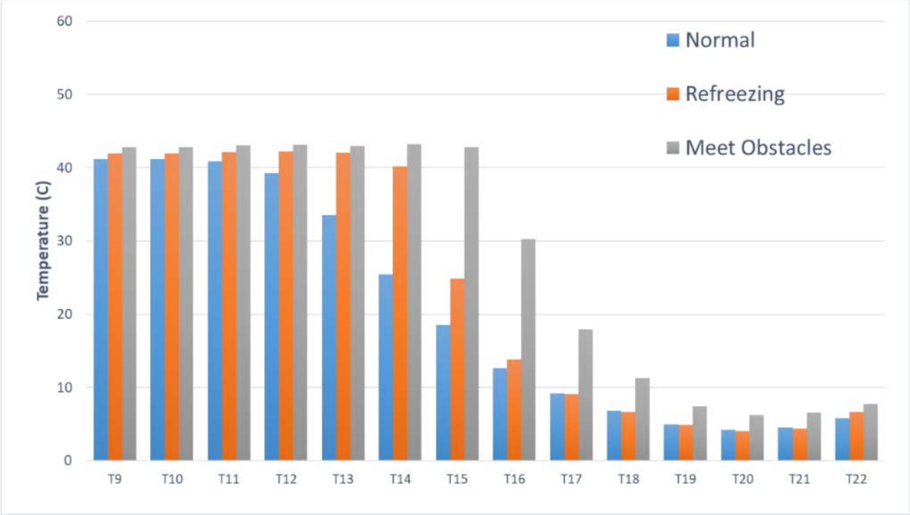


Figure 14. Temperature profile comparison among three cases (1) Normal forward melting (2) Probe Stuck due to Refreezing (3) Probe Stuck due to meeting obstacle

V. Conclusions

Under an SBIR Phase I program, Advanced Cooling Technologies, Inc (ACT) developed a thermal concept for Europa ice melting probe. The thermal management architecture consists of multiple novel features that can offer the following advantages:

- A pumped two-phase heat delivery system can uniformly acquire the waste heat from multiple GPHS modules and transport the waste heat to the vapor chamber with minimal temperature drop and using minimal pumping power. At the same time, it plays the role of aon on board thermal bus for other thermal needs like heating/cooling the pressure vessel for steering/lateral propulsion

- A front vapor chamber can effectively transfer heat from the P2P condenser to the melting head with minimized thermal resistance. The heat transfer performance of the front vapor chamber can be further improved with elongated nose design and area enhancement features
- A variable conductance wall that can passively control heat dissipating area to achieve maximized forward melting velocity during normal mode and provide lateral melting capability when the probe gets stuck in the ice.
    - When the probe gets stuck due to refreezing, variable conductance wall will automatically heat up the side wall and release the probe.
    - When the probe meets an obstacle, variable conductance wall will heat up the entire side wall. With the assistance of the liquid displacement system, the probe can move laterally and avoid the obstacle.
    - A Liquid Displacement System that will enable the probe to move laterally and bypass the obstacle. By strategically designing the boiler and heating/cooling elements, the liquid displacement system will be able to operate in both subcritical and supercritical regimes.

The technical feasibility of above features was assessed in Phase I. A proof-of-concept ice melting probe prototype that has three key features (variable conductance wall, front vapor chamber and liquid displacement system) was developed. Ice penetration and thermal behavior of the prototype was experimentally demonstrated in an ice environment system. Three testing scenarios were conducted (ice penetration, probe refreezing/self-releasing and meeting obstacle). Both variable conductance wall and front vapor chamber concept were successfully demonstrated.

Acknowledgments

This project is sponsored by NASA Jet Propulsion Laboratory (JPL) under an SBIR Phase I program (Contract# 80NSSC190363). We would like to thank Terry J. Hendrick (technical monitor) and Eric Sunada for their supports and valuable inputs to the program. We would also like to acknowledge Philip Texter, Chris Jarmoski, Larry Waltman and Patrick Wisotzkey who have significant technical contributions on lab-scale melting probe prototype development.

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