THERMAL & FLUIDS ANALYSIS WORKSHOP

TFAWS

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Autonomous Melting Probe for Icy World Exploration

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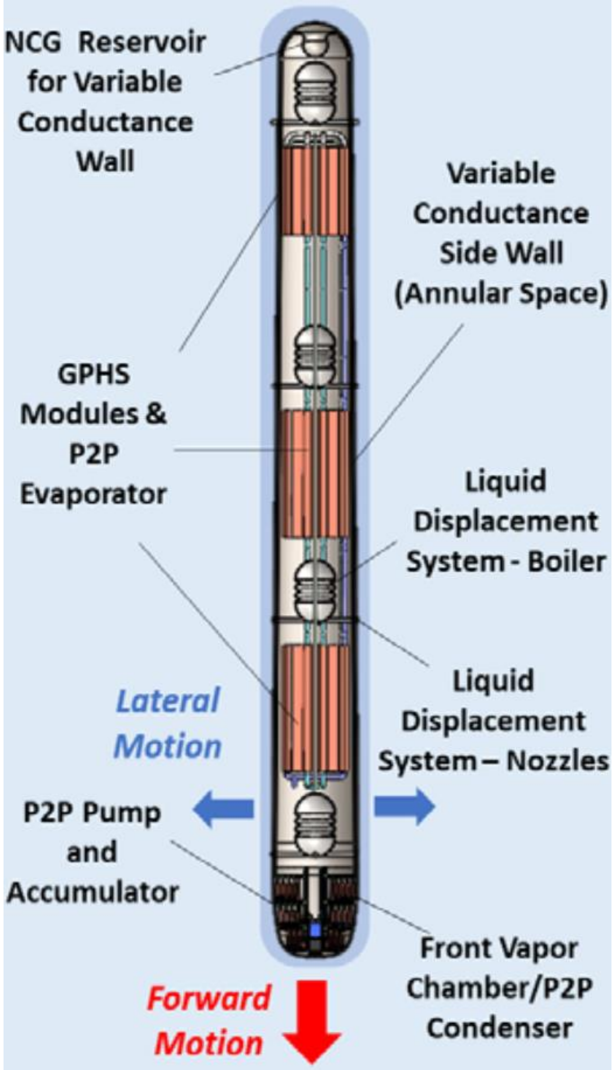
Introduction

- Extraterrestrial ocean worlds are the most promising places for any signs of life beyond our planet Earth
- NASA, ESA and other space agencies have shown considerable interest in studying them
- Of specific interest is Jupiter's moon Europa
  - NASA JPL's Galileo spacecraft indicated liquid water may exist ~30 km underneath icy surface
- One technique to penetrate icy crust is to use thermal probe with heated front
- Environmental conditions on Europa present unique challenges for thermal probe
  - Low pressure on icy surface leading to sublimation after melting
  - High thermal conductivity of low-temperature ice makes melting process difficult
  - Heat "runs away" from source, not allowing surrounding ice to reach melting point
- Key requirements for radioisotope-powered ice melting probe
  - Minimum penetration time and vertical footprint
  - Maximize forward melting heat
- Advanced Cooling Technologies, Inc, (ACT) developed a thermal management concept for the ice melting probe
  - NASA Phase-II SBIR Program

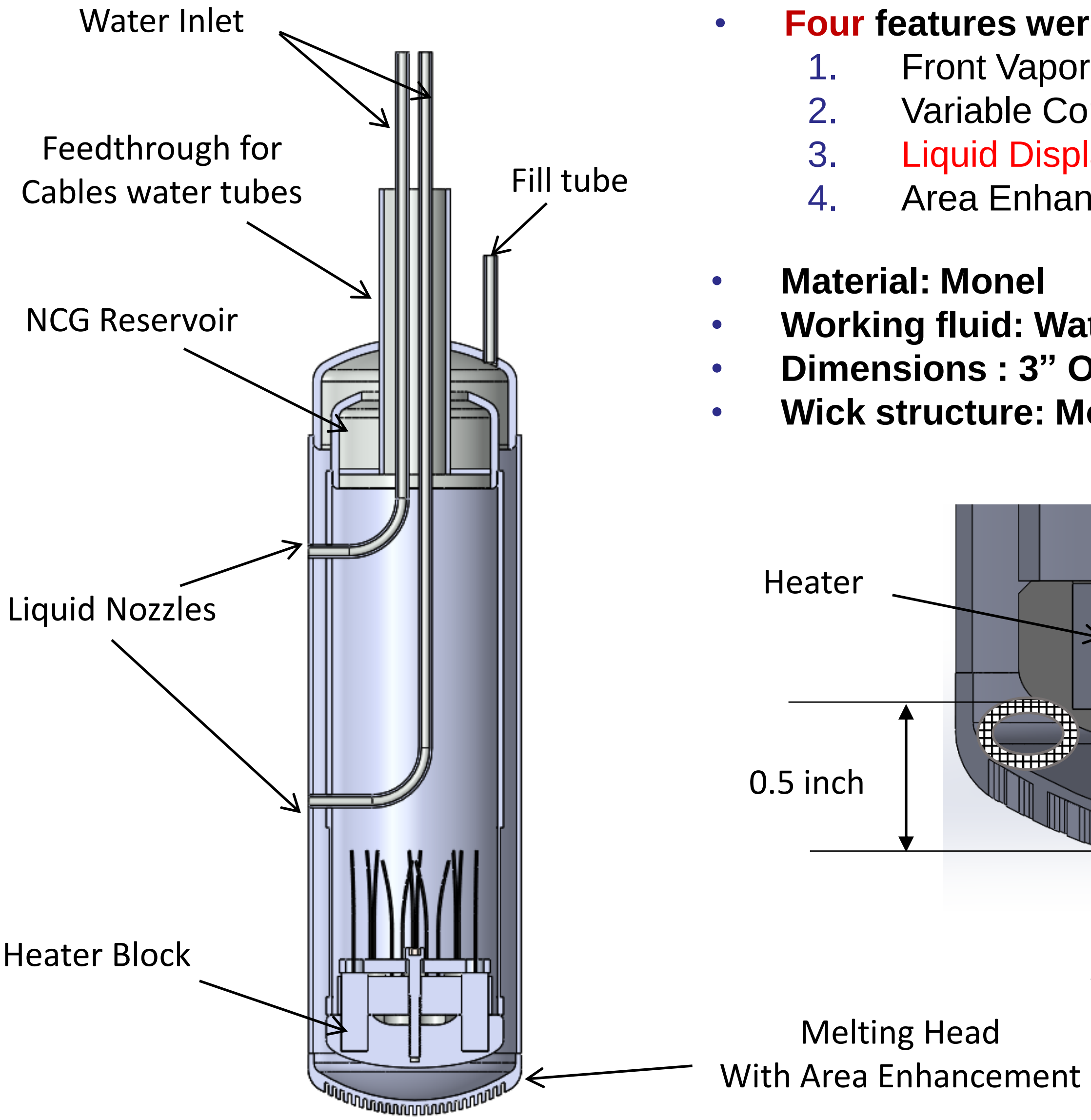
Melting Probe for Icy Planet Exploration

- ACT's proposed thermal features inside the probe for efficient and reliable ice penetration :
  - **Pumped Two-Phase (P2P)**
  - **Vapor Chamber**
  - **Variable Conductance Walls**
  - **Liquid Displacement Steering System (LDSS)**
- Heat Source modules (GPHS or CPHS) provide heat to thermoelectric converters (TECs)
- Waste heat (~9 kW) is collected by P2P evaporators in contact with the cold end of the TECs
- Heat collected by P2P loop is transported to P2P condenser located at front end (melting front)
- P2P condenser rejects heat into the front Vapor Chamber
- Vapor Chamber focuses heat to front end of the probe for forward ice melting
- Tubular extensions from vapor chamber to top end of probe form Variable Conductance Walls
- Variable Conductance Walls provide side wall heating if:
  - Probe is stuck due to lateral freezing
  - Probe is stuck due to nonmeltable obstacle (and steering is needed)
- Liquid Displacement System provide lateral steering capability for maneuvering/steering



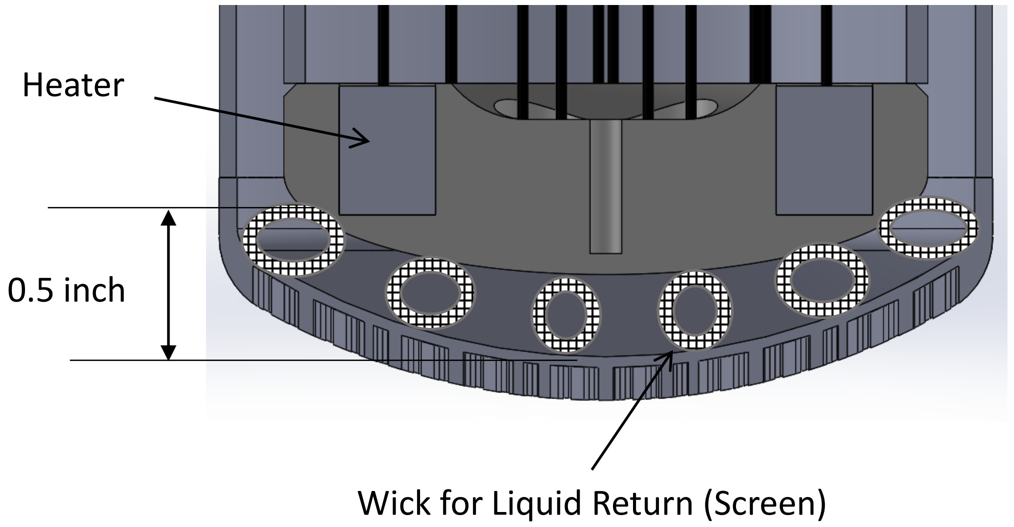
Phase I work

Reduced-Scale Ice Melting Probe for Concept Demonstration

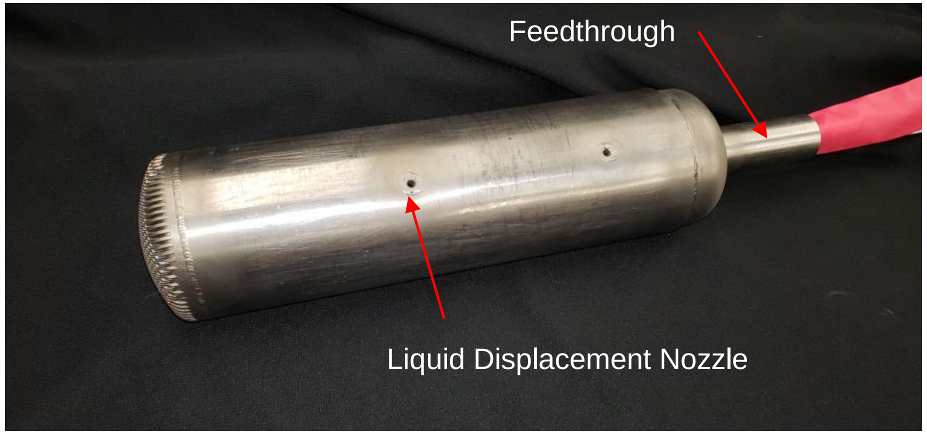


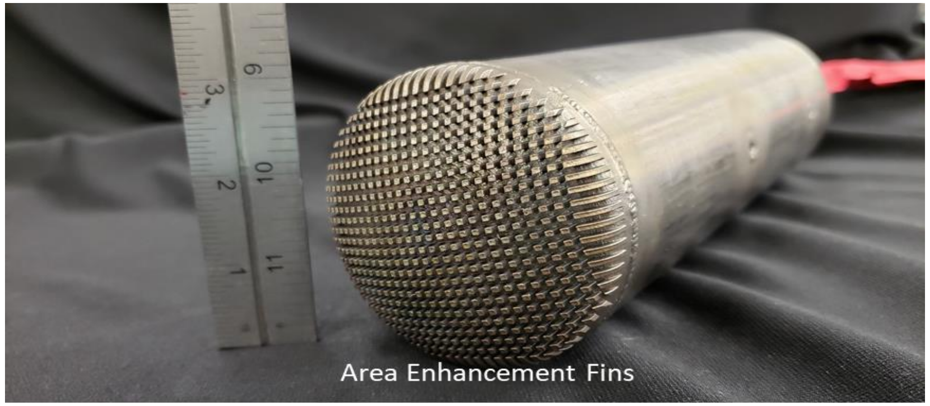
- **Four features were incorporated in this prototype:**
  1. Front Vapor Chamber (Simplified)
  2. Variable Conductance Wall
  3. Liquid Displacement Nozzle for Steering (not used)
  4. Area Enhancement Melting Head

- **Material: Monel**
- **Working fluid: Water**
- **Dimensions : 3” OD, 11” Long**
- **Wick structure: Monel mesh with 100 mesh size**

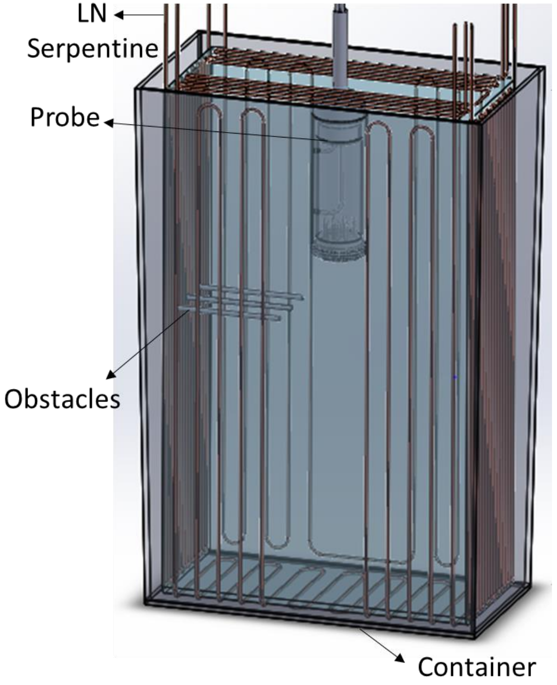


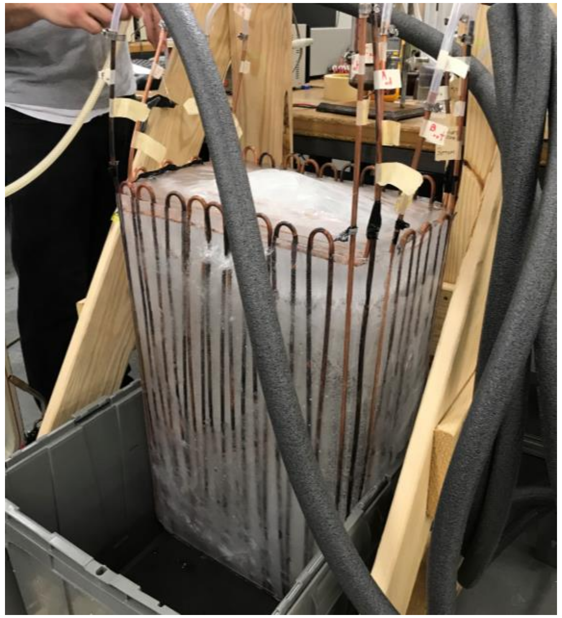
- Ice melting probe prototype features



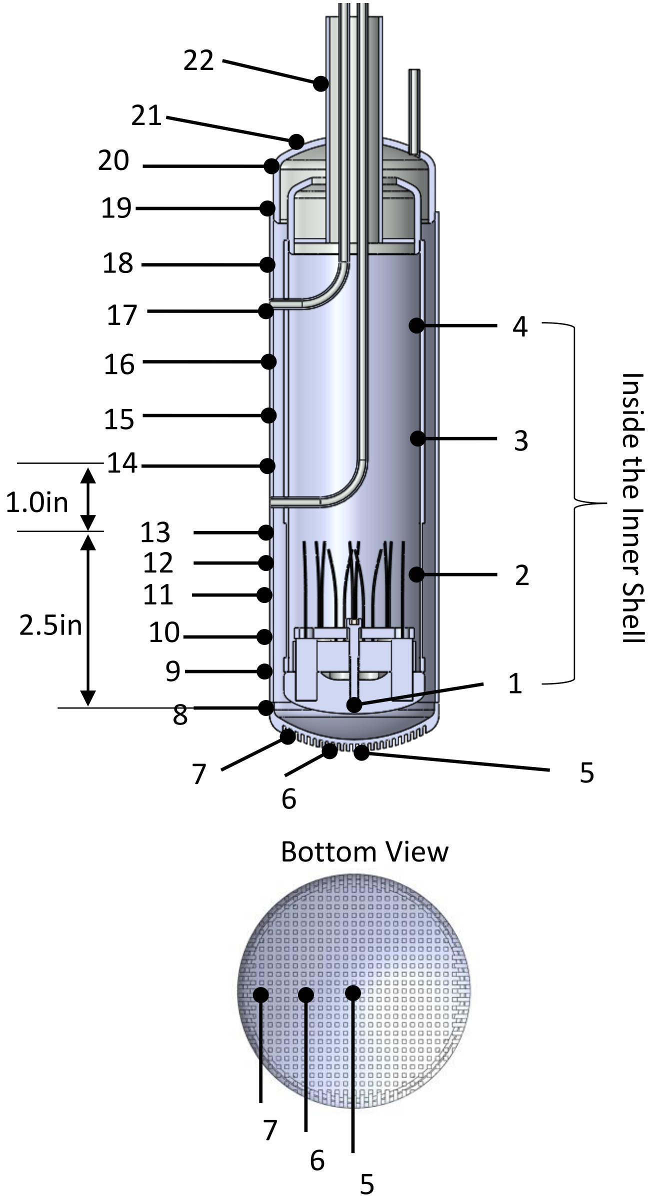


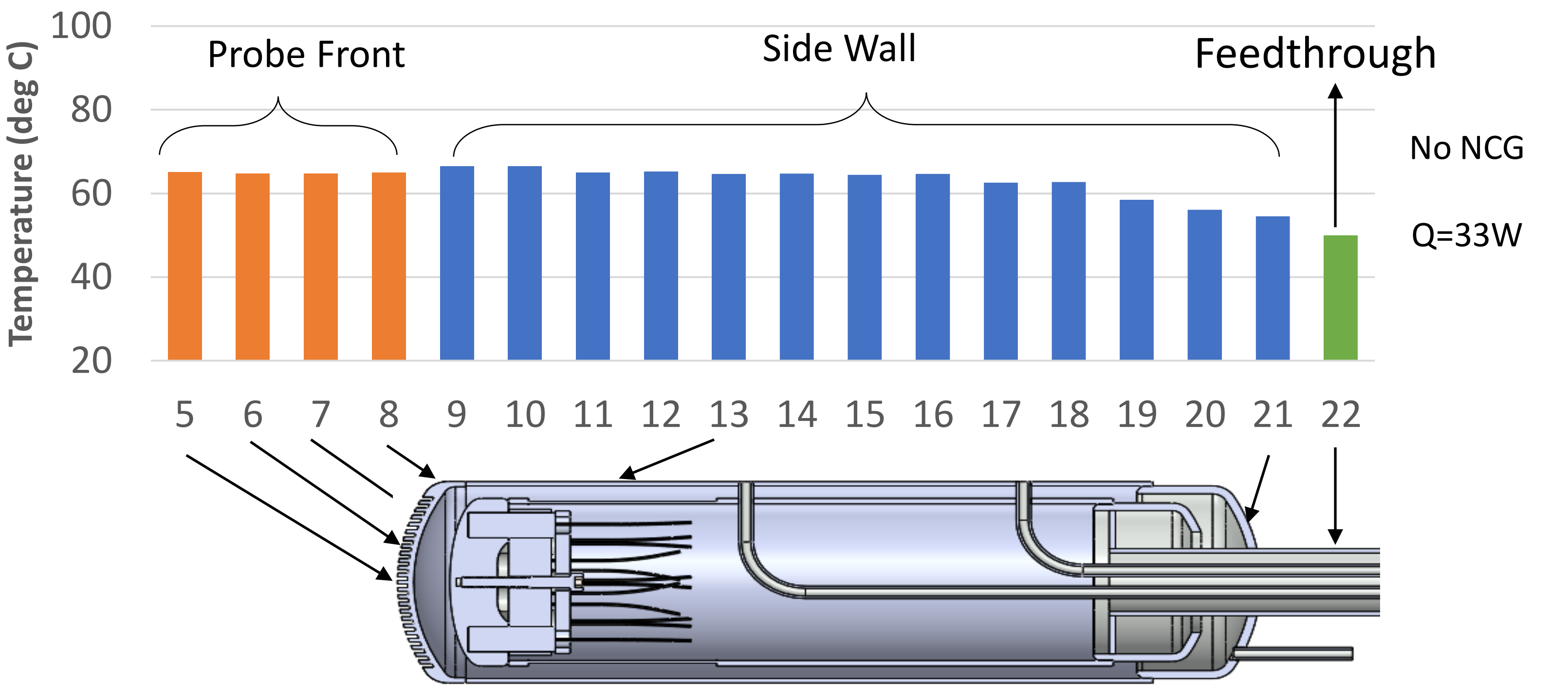
- Ice block dimensions: 16” x 8” x 36”
- Enclosed by 6 LN serpentines (i.e. heat guard), which can provide subcooling and refreezing capability
- Can reach -160° C subcooled ice condition

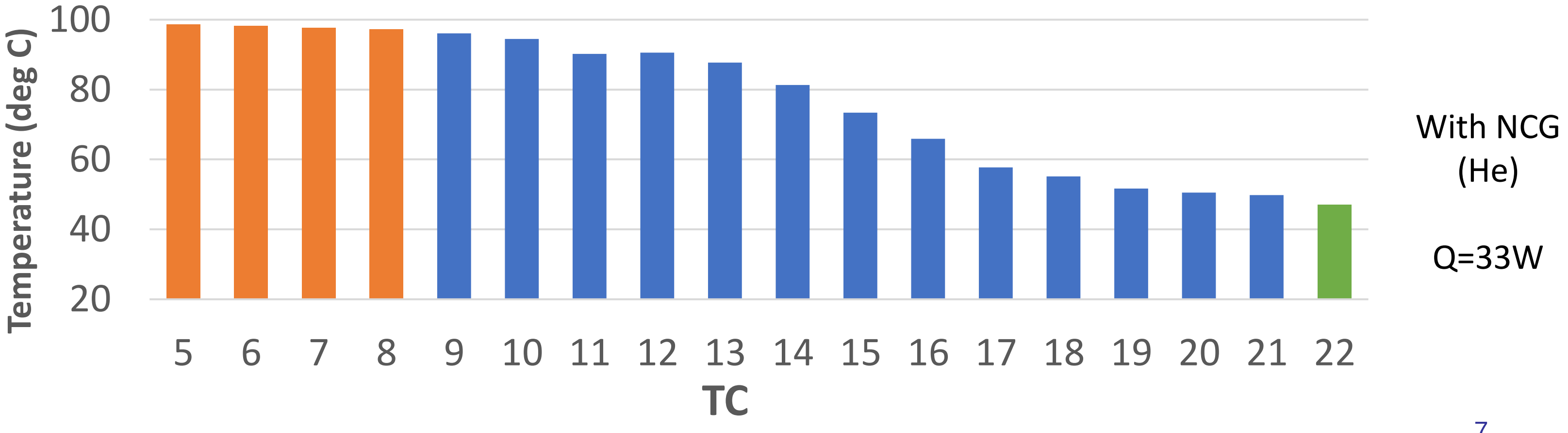




Thermocouple Map and Preliminary Test Results

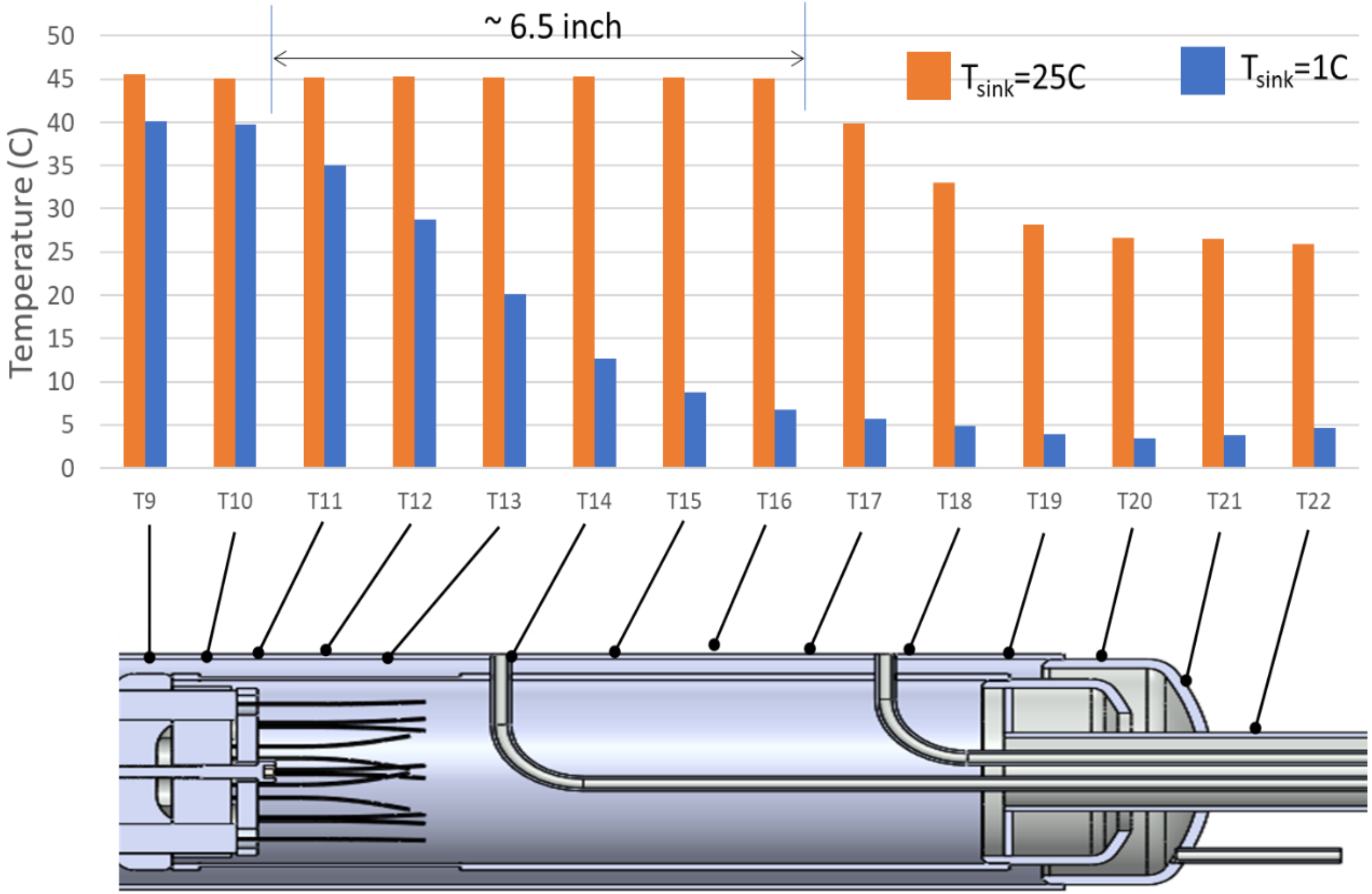






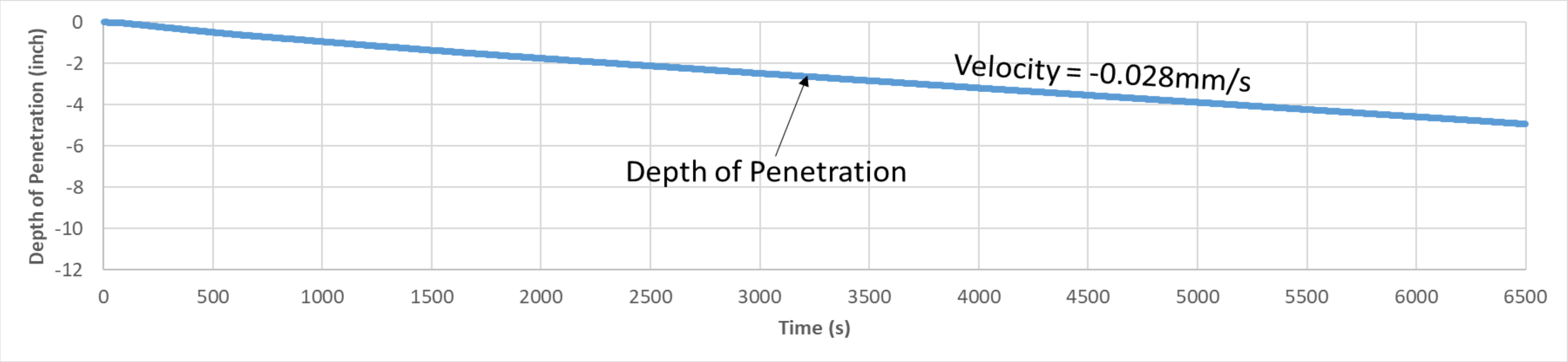
Calibration Test

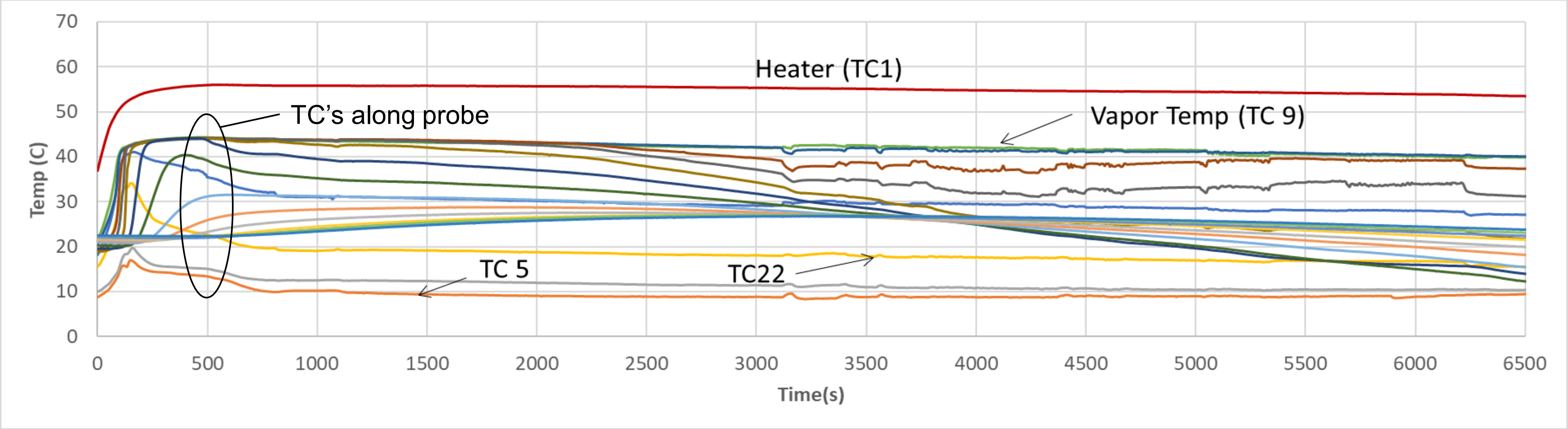
Instantaneous temperature profiles of the probe under two sink (water) conditions



First Ice Penetration Test

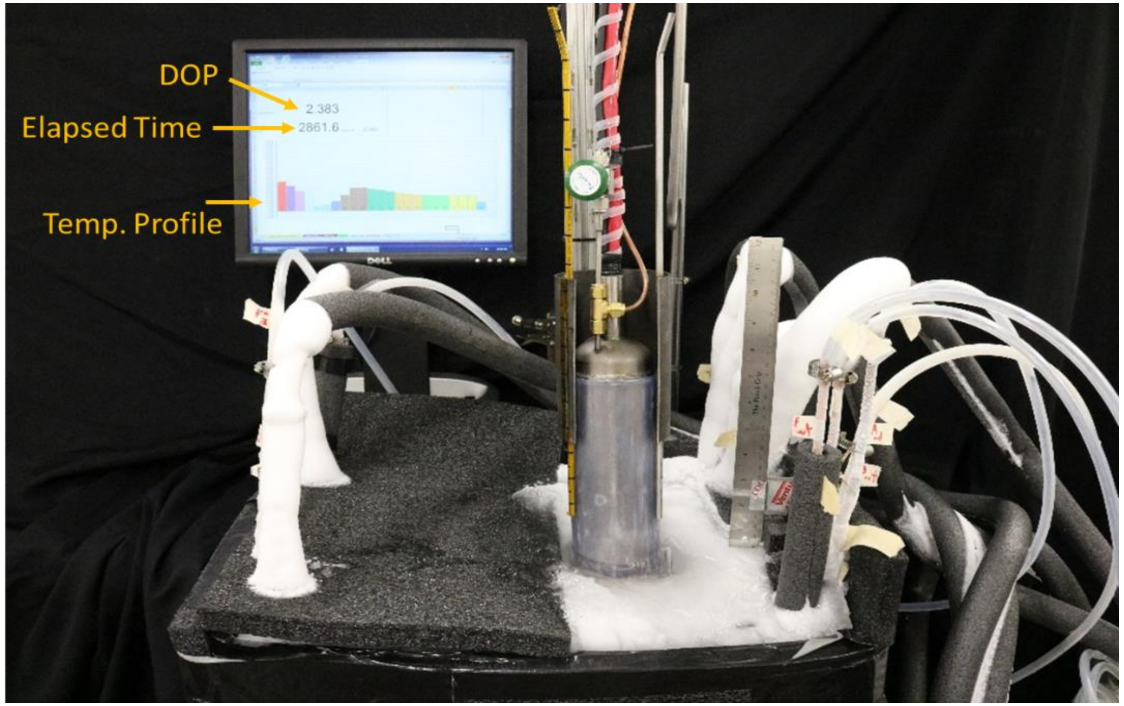
- Comparison between theoretical results and test data **Lower plot shows the corresponding temperature evolution**



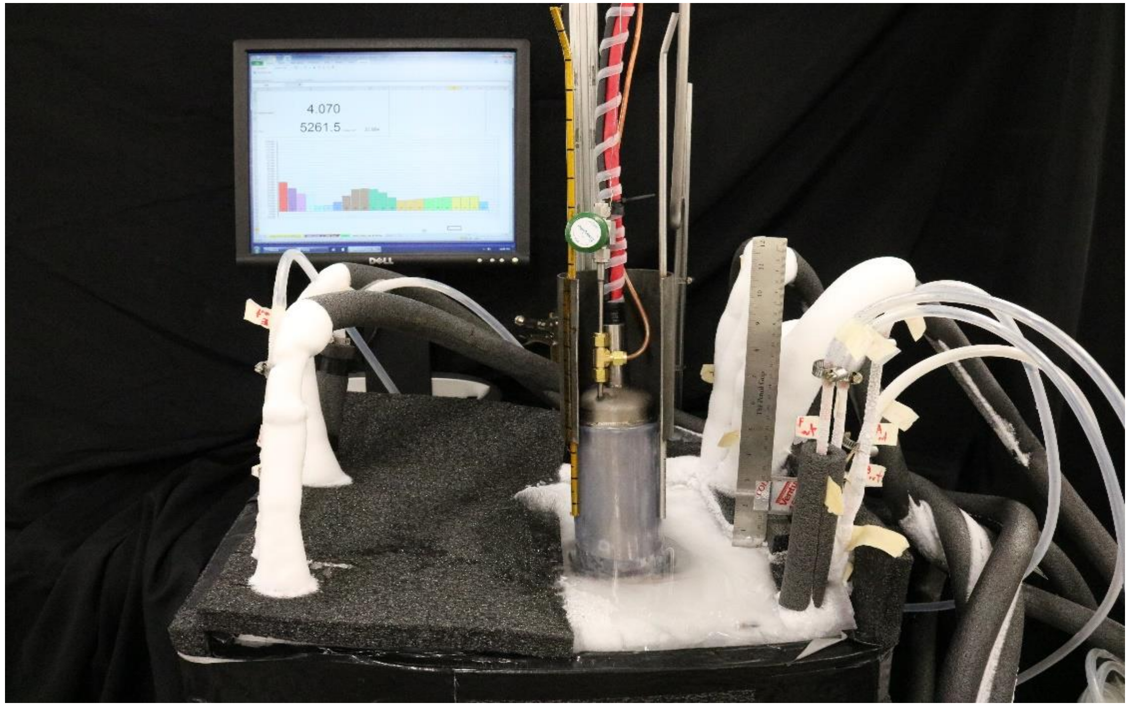


First Ice Penetration Test

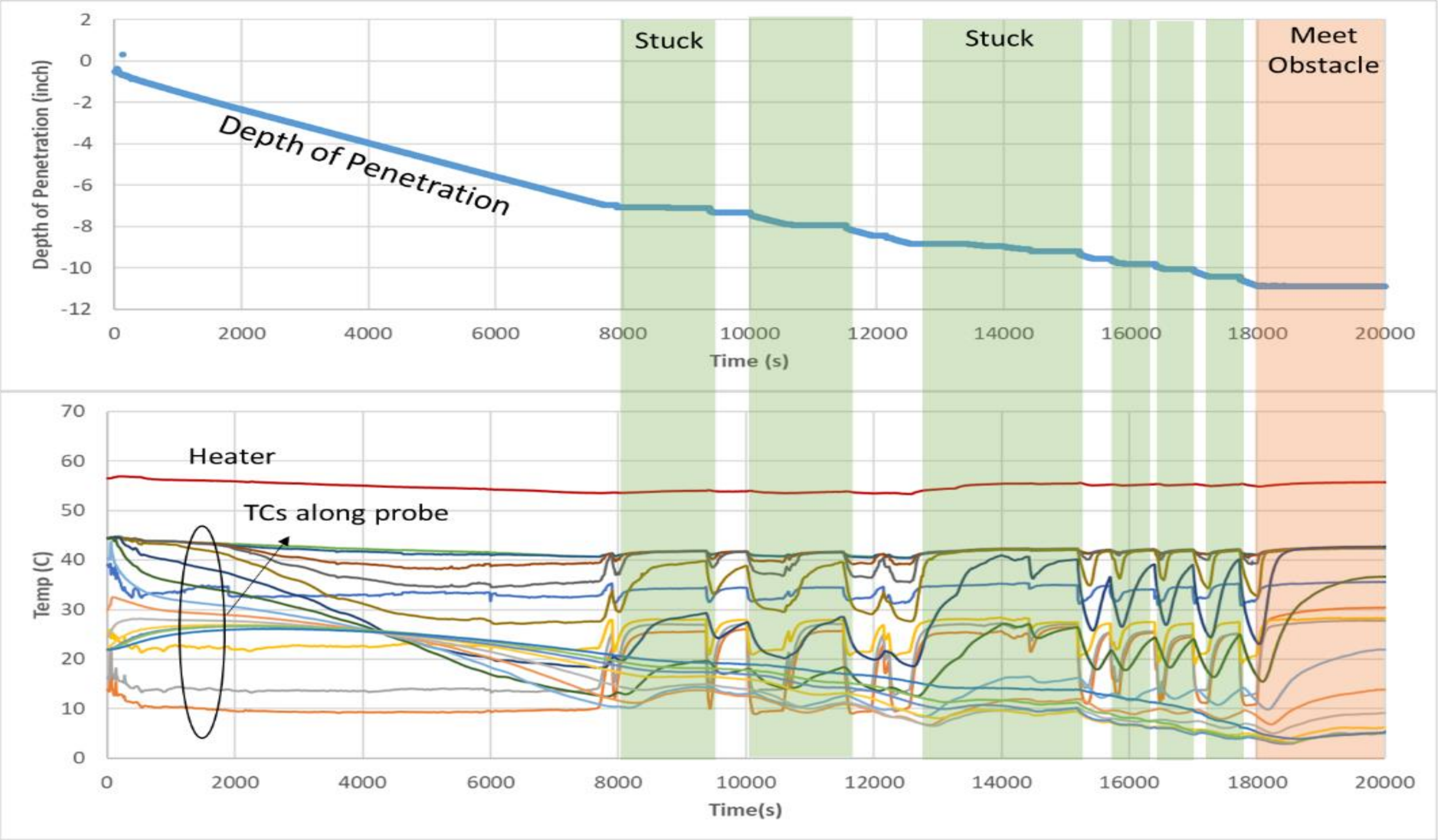
Probe status during normal ice penetration (t=2800s)



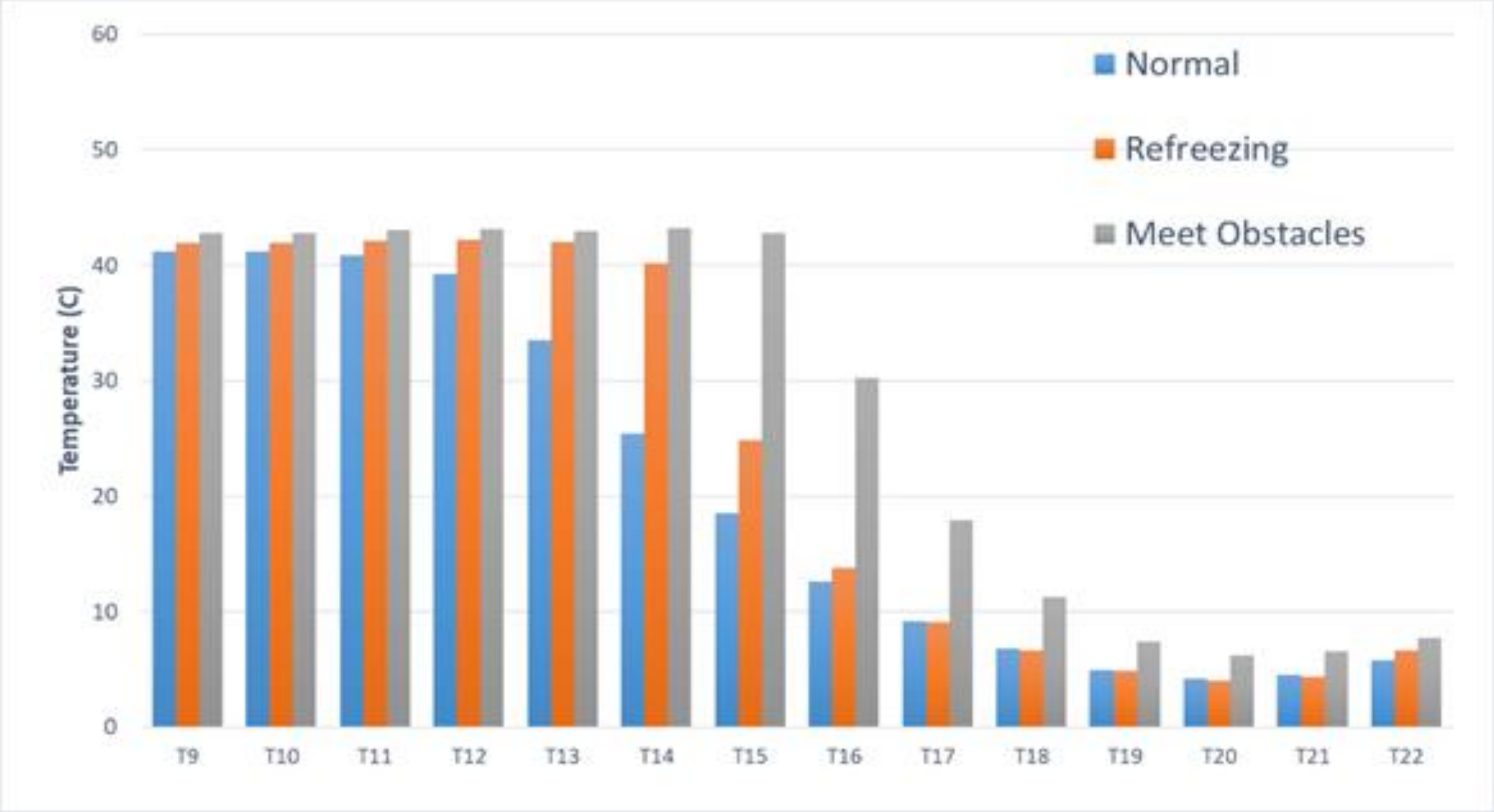
Half of probe body is submerged into the ice (t=5281s)

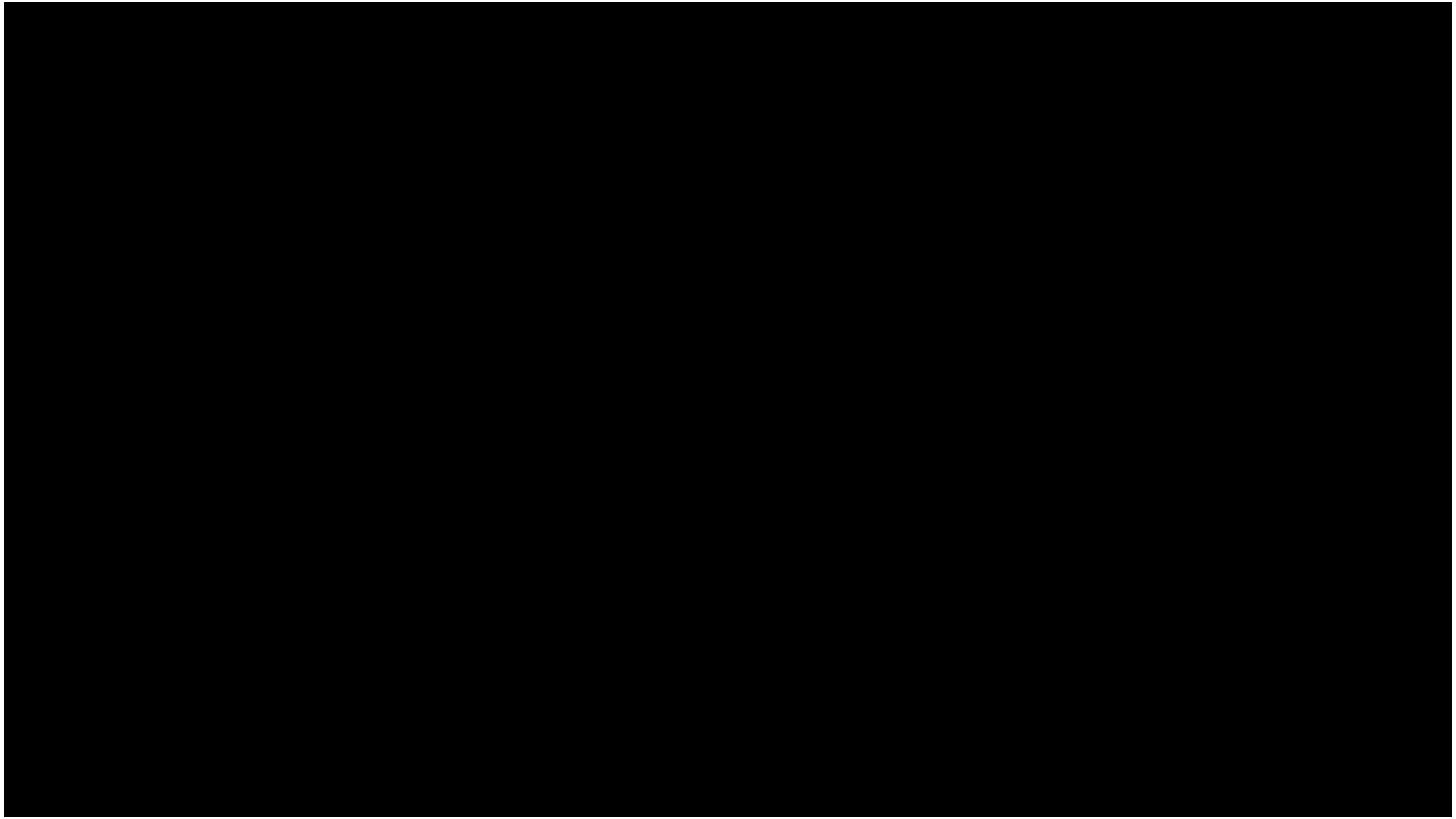


Probe Refreezes and Self-Releases and meets Obstacle



Probe Refreezes and Self-Releases and meets Obstacle

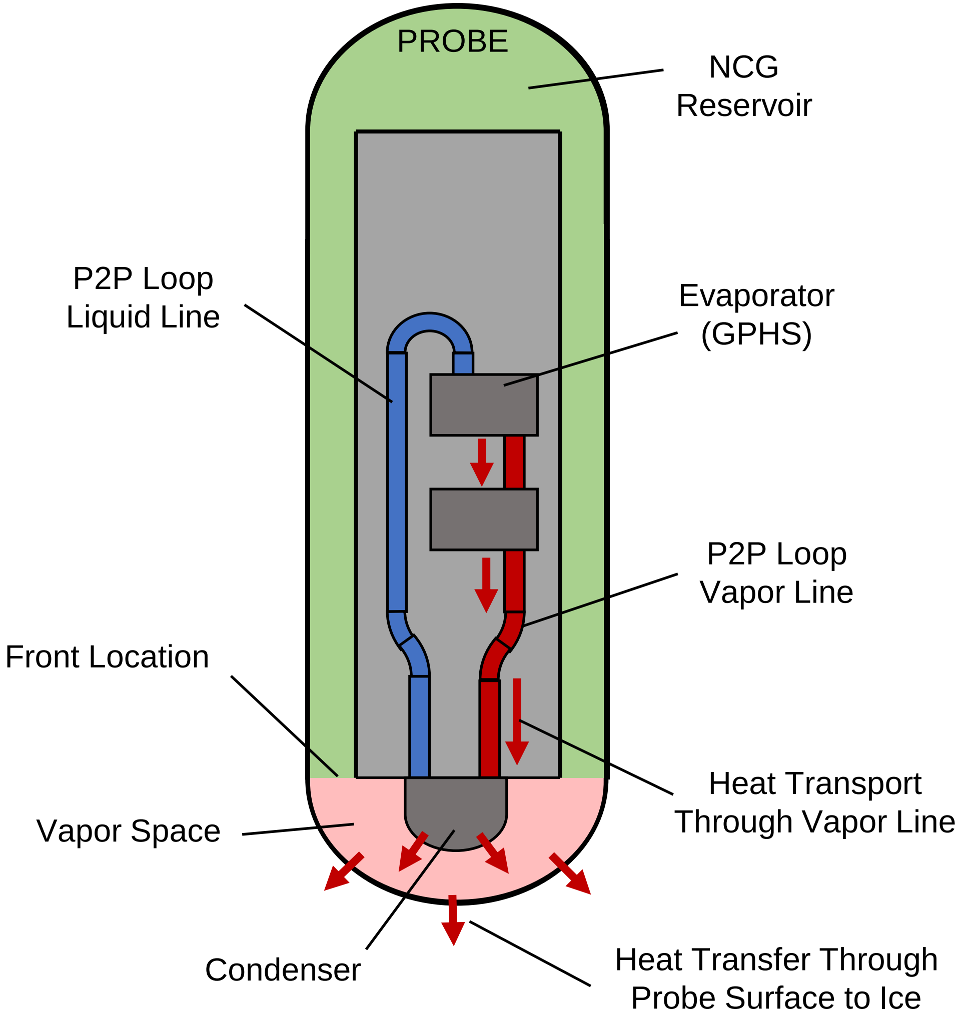




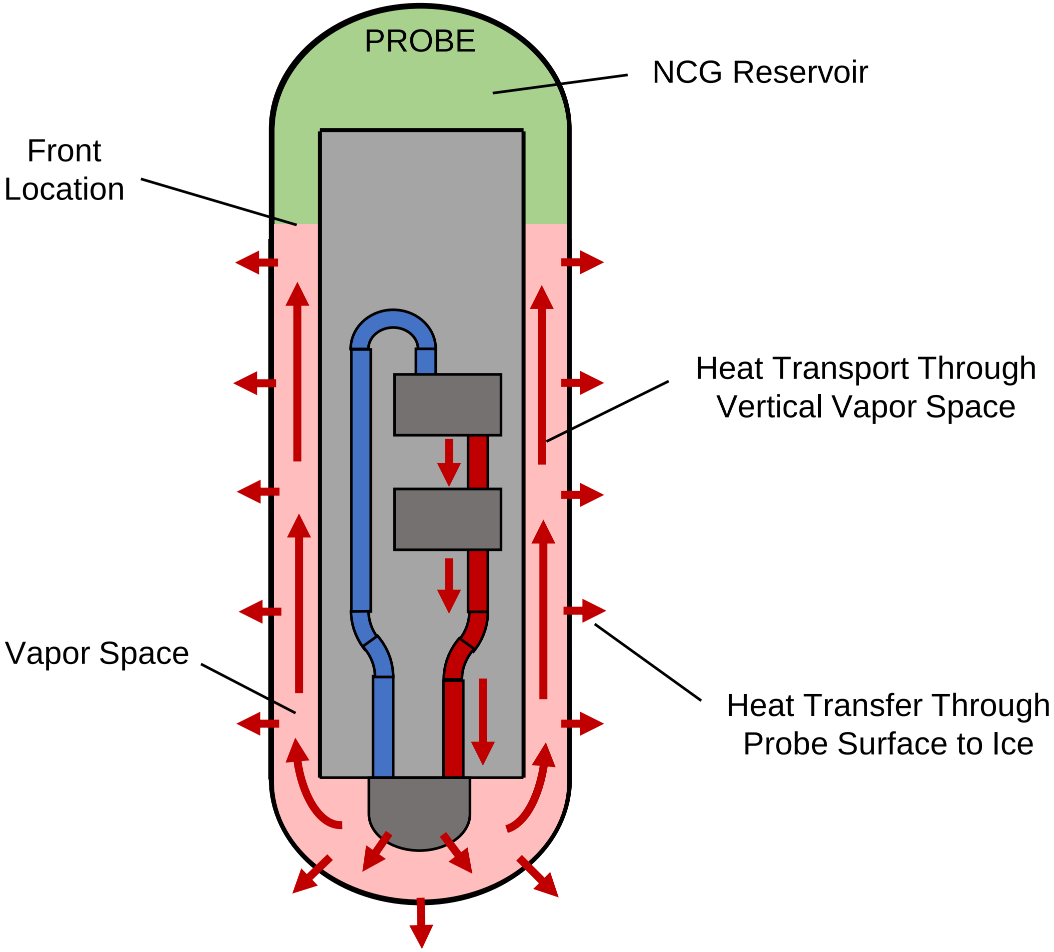
Phase II work

Phase II Concept Overview

Normal Operation

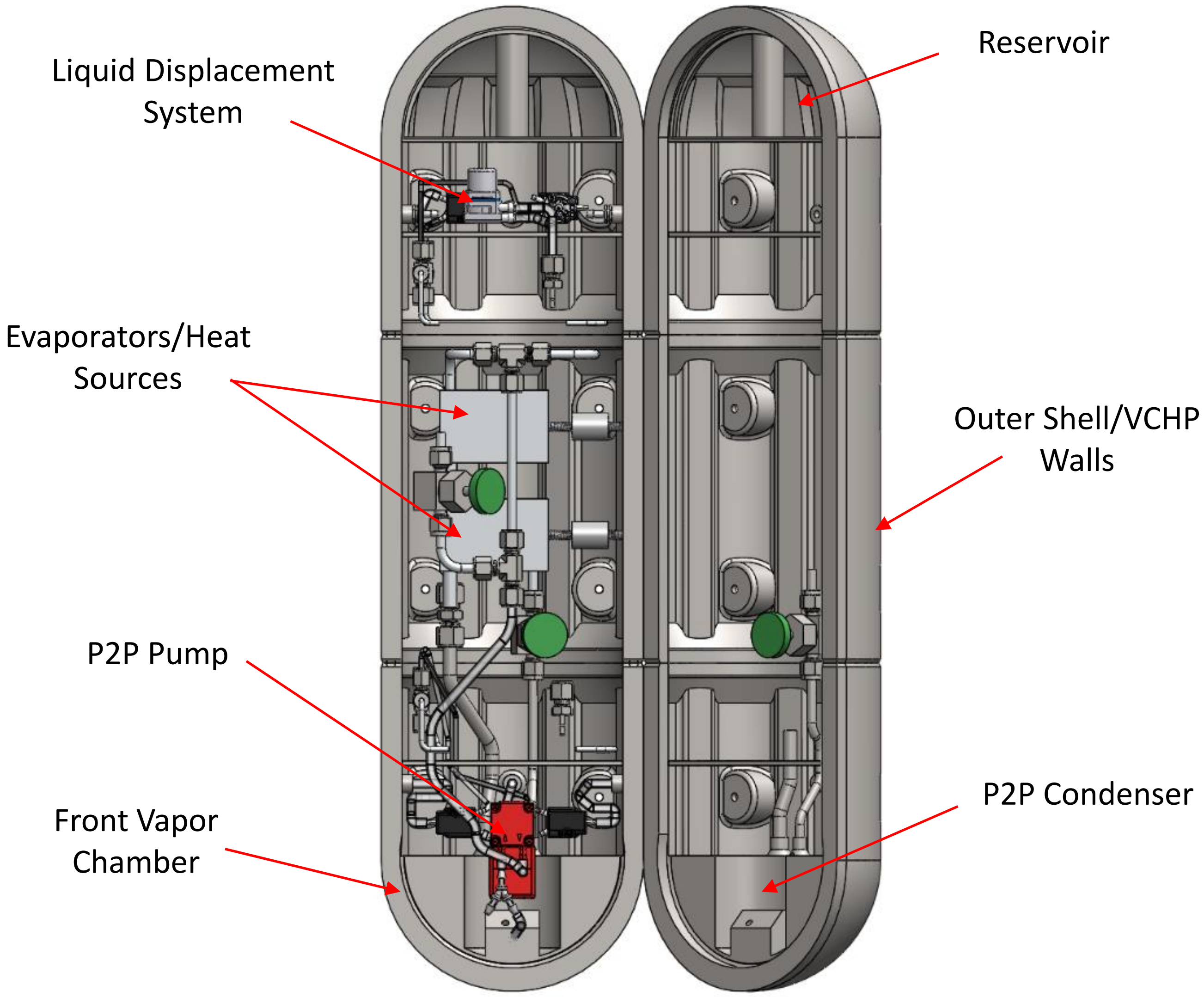


VCHP Wall Operation



Phase II Melting Probe Prototype Development

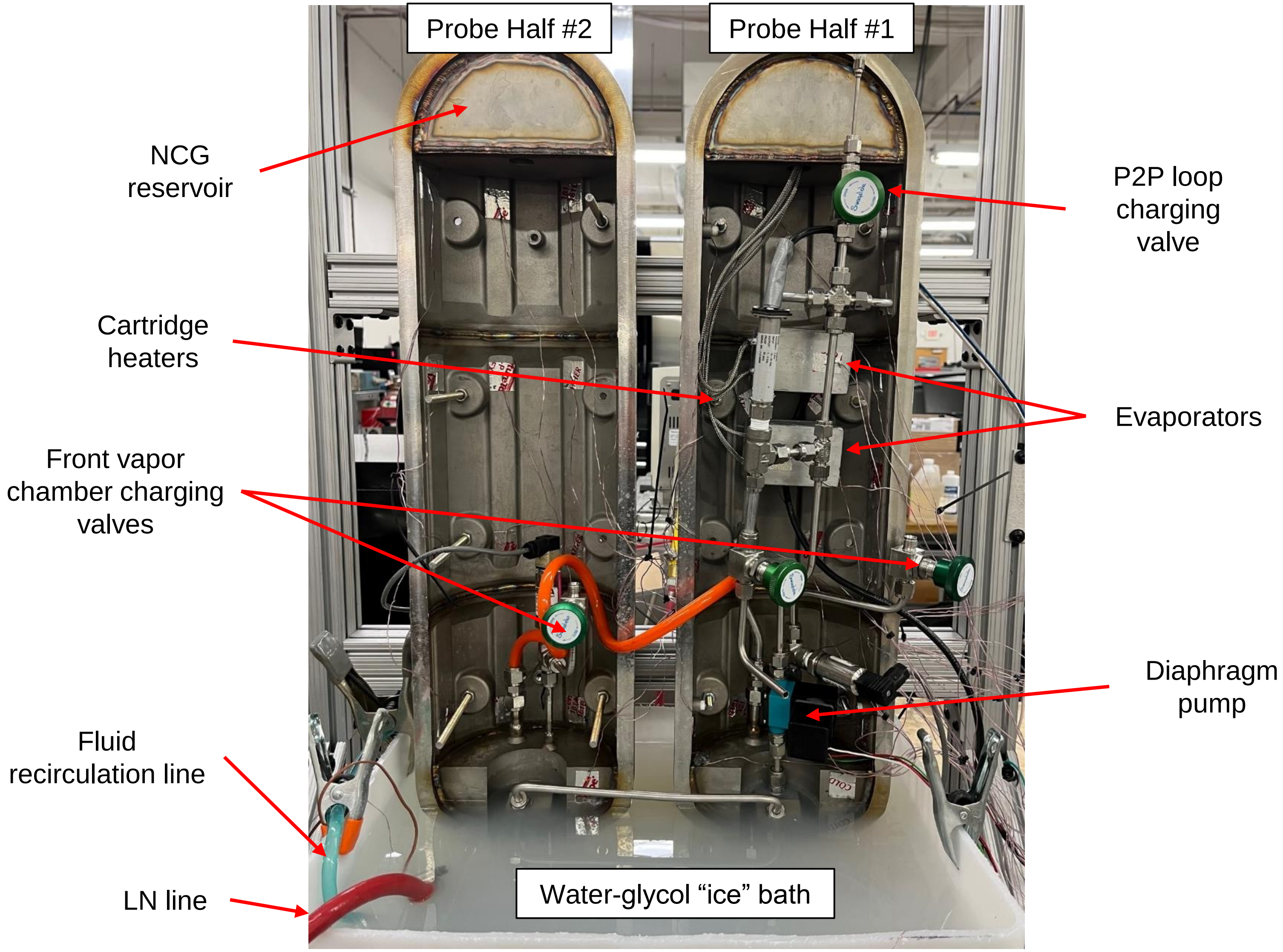
- 1st Prototype Features:
  - P2P Loop
  - Vapor Chamber
  - Variable Conductance Walls
- Total power = 600 W
- Prototype dimensions
  - Height = 27.25 in
  - Diameter = 7.25 in
- SS 316 metal probe (3D printed)
- 2 separate shells (halves)

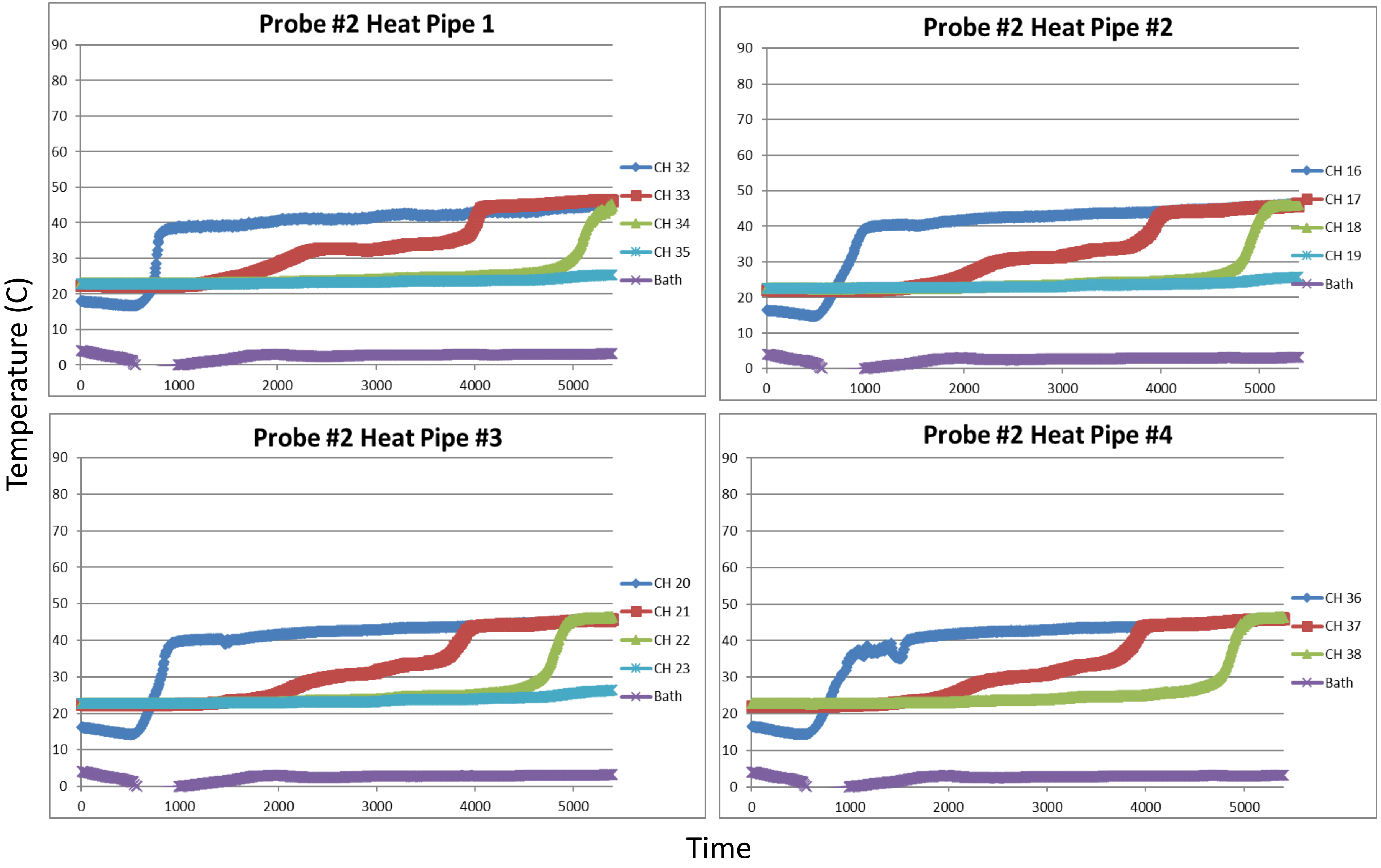


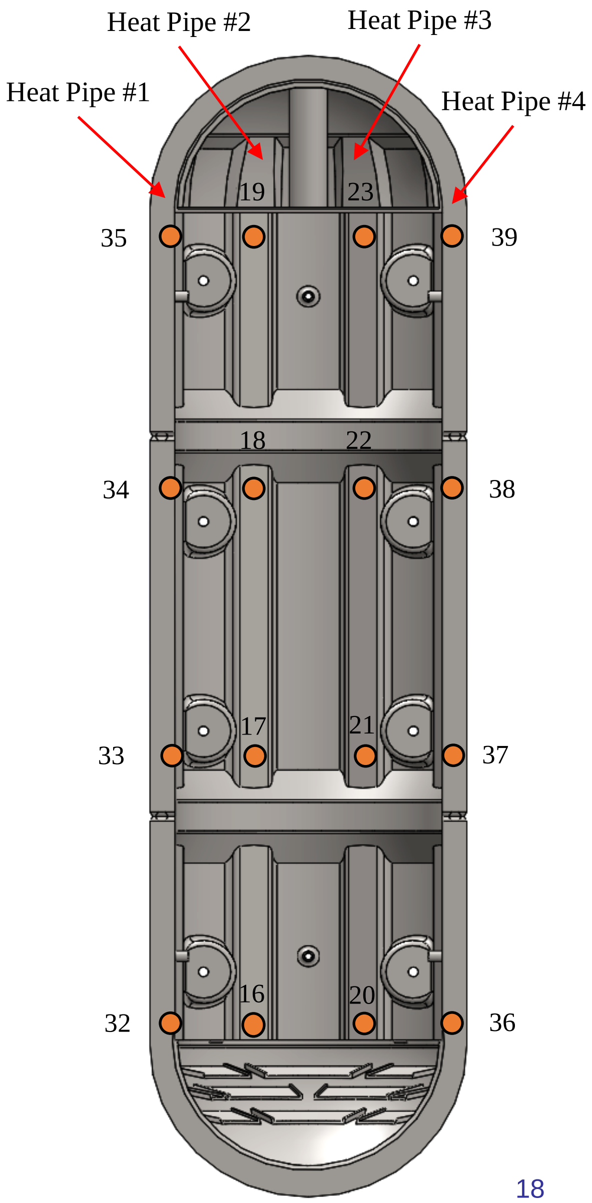
Thermal Performance Testing

Testing Parameters:

- P2P Loop
  - Acetone working fluid
  - 120cc charge
- Front Vapor Chamber
  - Methanol working fluid
  - 40cc charge
- VCHP NCG
  - Argon
  - 4.5 psia total pressure
- Power = 500W
- 0˚C bath temp




Probe #2 Heat Pipe 1
CH 32
CH 33
CH 34
CH 35
Bath
Probe #2 Heat Pipe #2
CH 16
CH 17
CH 18
CH 19
Bath
Probe #2 Heat Pipe #3
CH 20
CH 21
CH 22
CH 23
Bath
Probe #2 Heat Pipe #4
CH 36
CH 37
CH 38
Bath
0 10 20 30 40 50 60 70 80 90
0 1000 2000 3000 4000 5000
Temperature (C)
Time


Heat Pipe #2
Heat Pipe #3
Heat Pipe #1
Heat Pipe #4
19
23
35
39
18
22
34
38
17
21
33
37
16
20
32
36

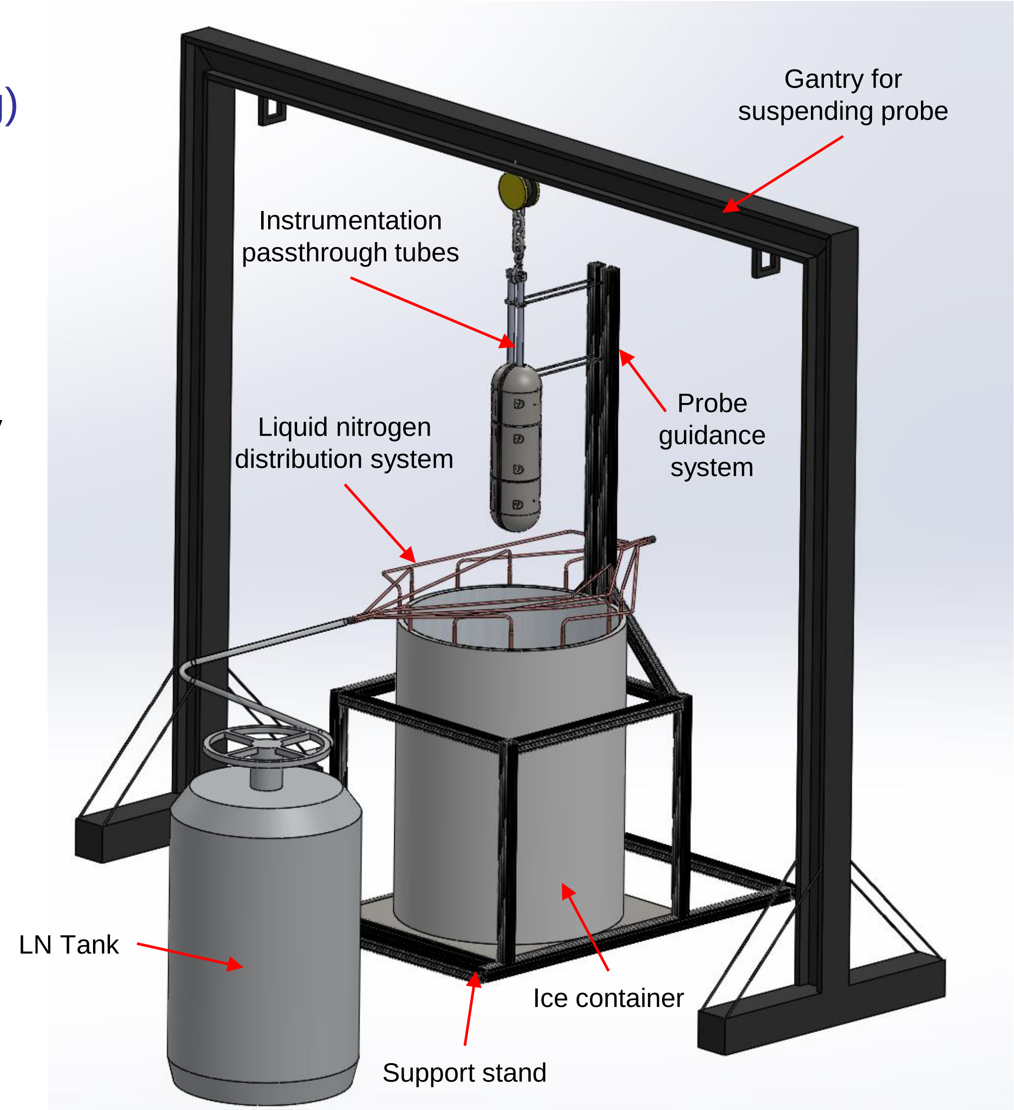
Large-Scale Experimental Setup

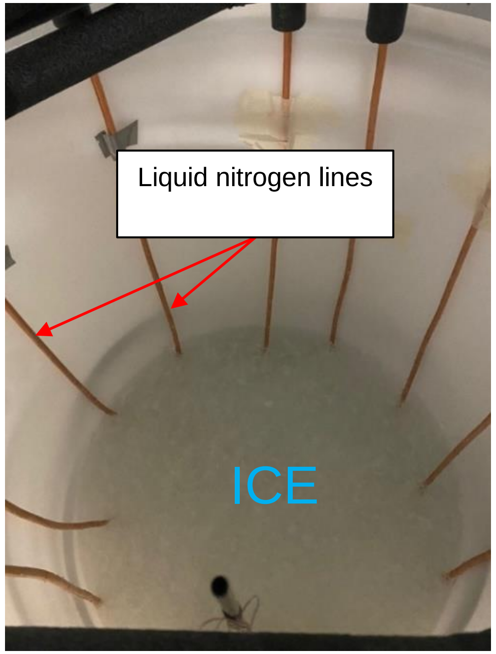
Testing:

- Regular downward descent (low subcooling)
  - Constant melting
  - Both temperature and descent velocity recorded
- Simulated Obstacle
  - Suspend in place once fully submerged
  - Demonstrate VCHP wall/feature functionality

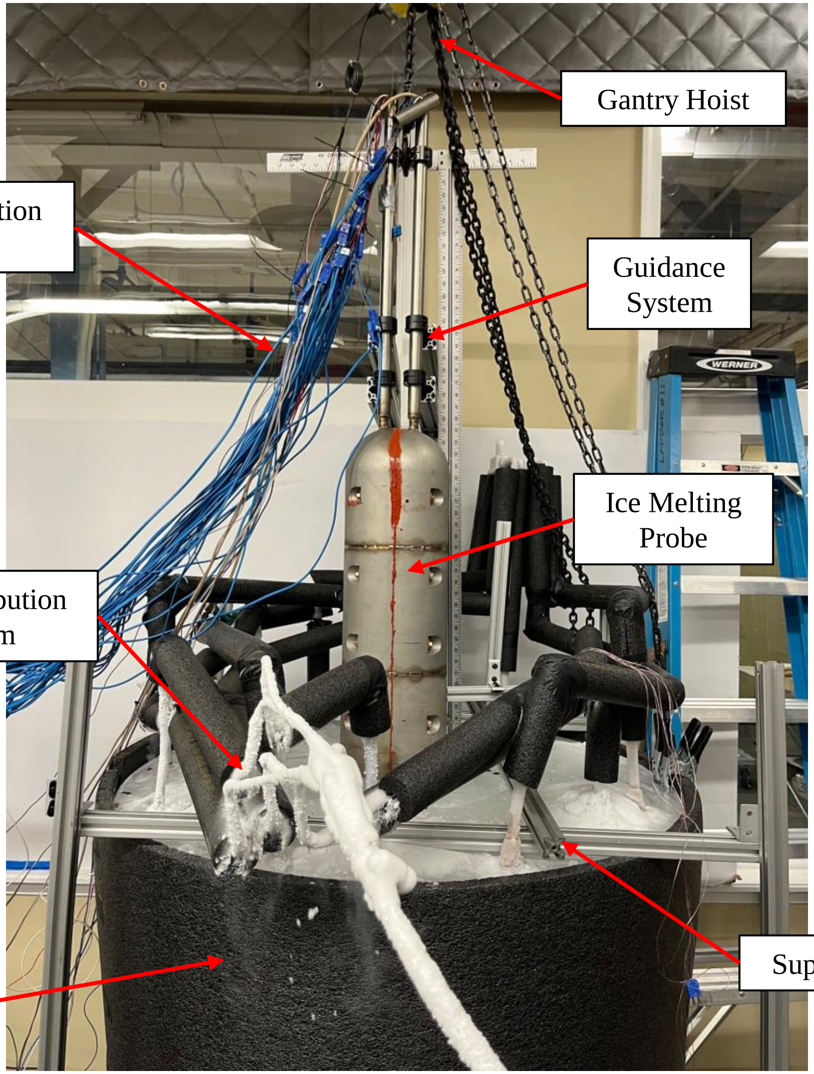
Instrumentation:

- TC placement
  - Key probe internals
  - Imbedded in ice
- Pressure transducer on P2P loop
- Displacement sensor to measure speed of descent

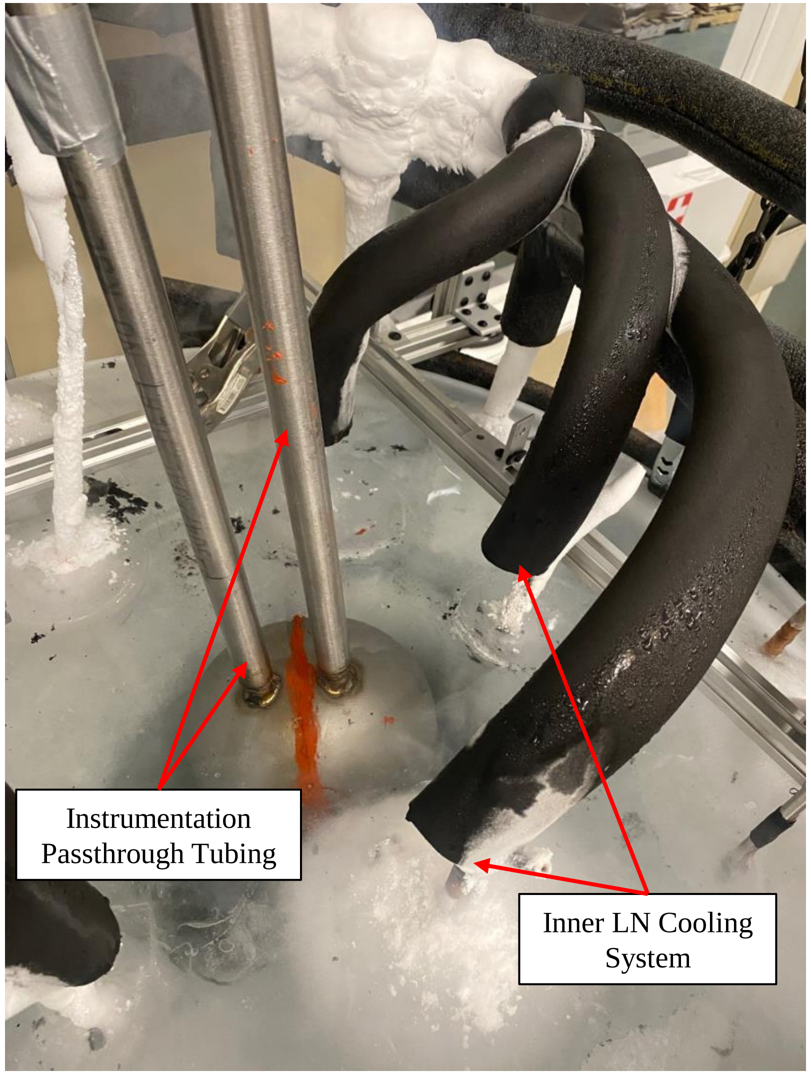




Stages of Large-Scale Ice Melting Test

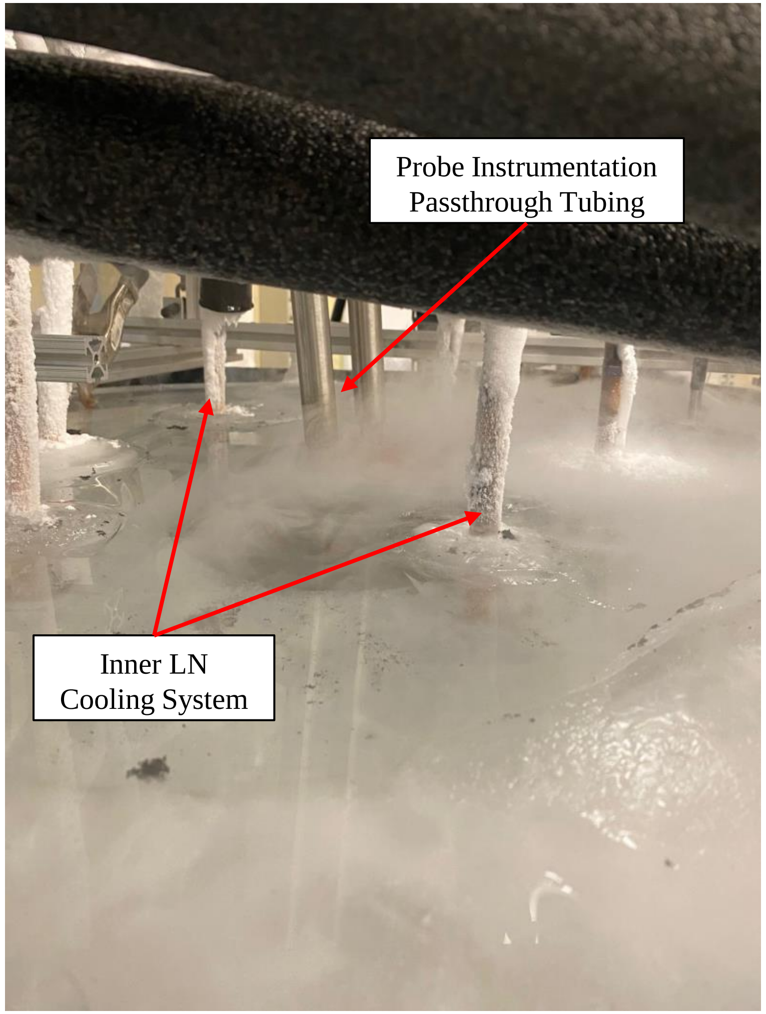


Probe prior to melting into ice

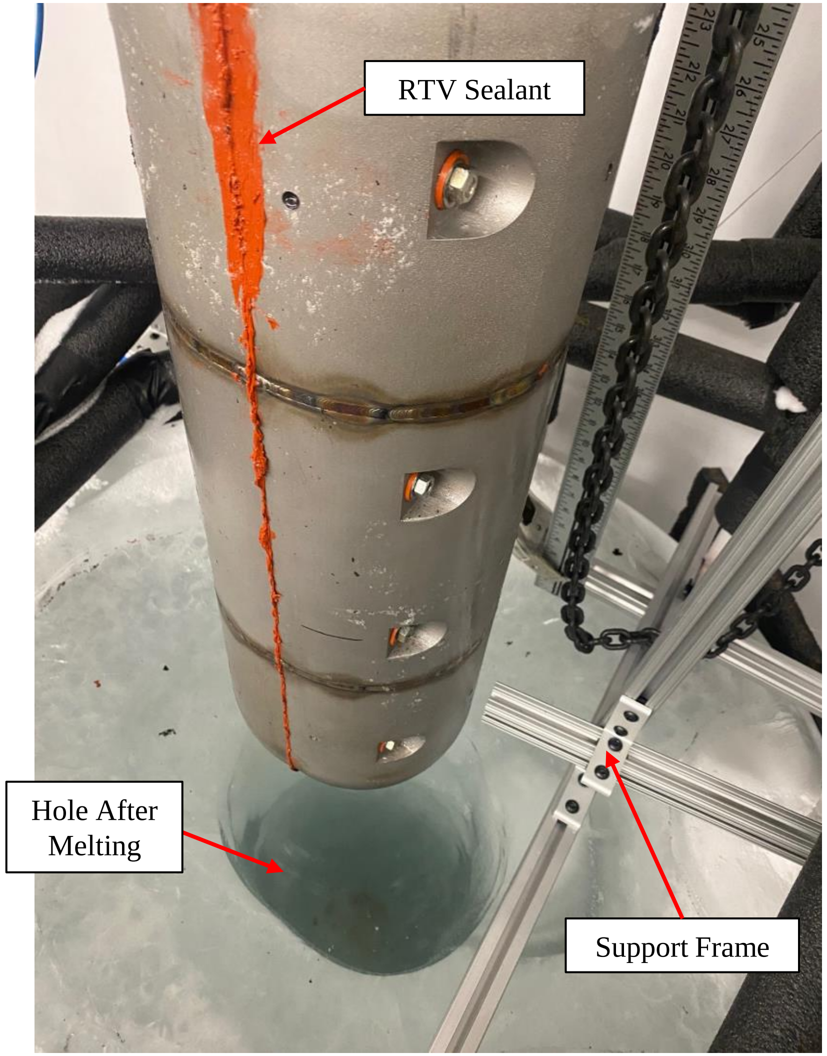


Probe after melting into ice block

Stages of Large-Scale Ice Melting Test

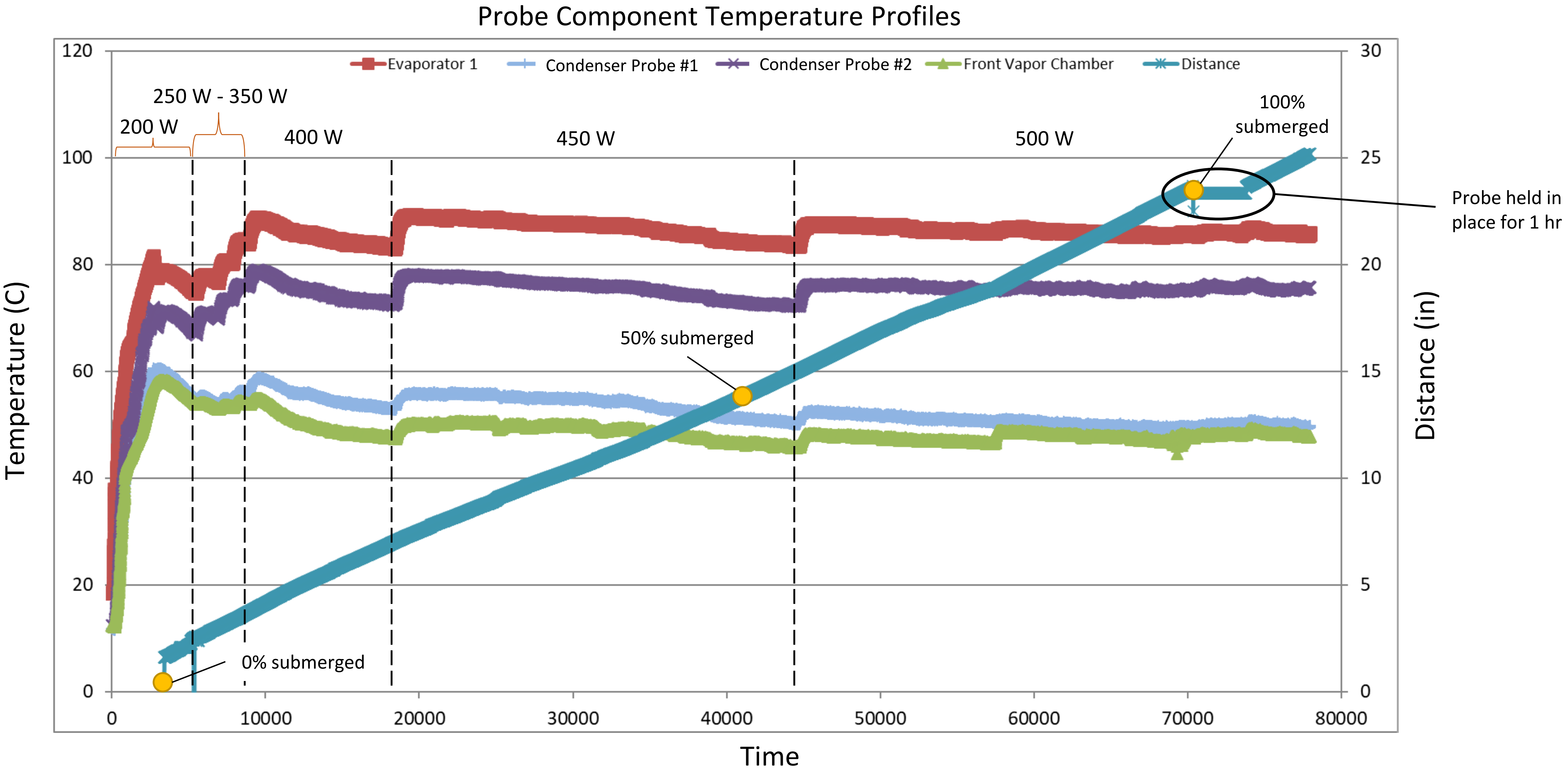


Probe fully submerged under ice surface

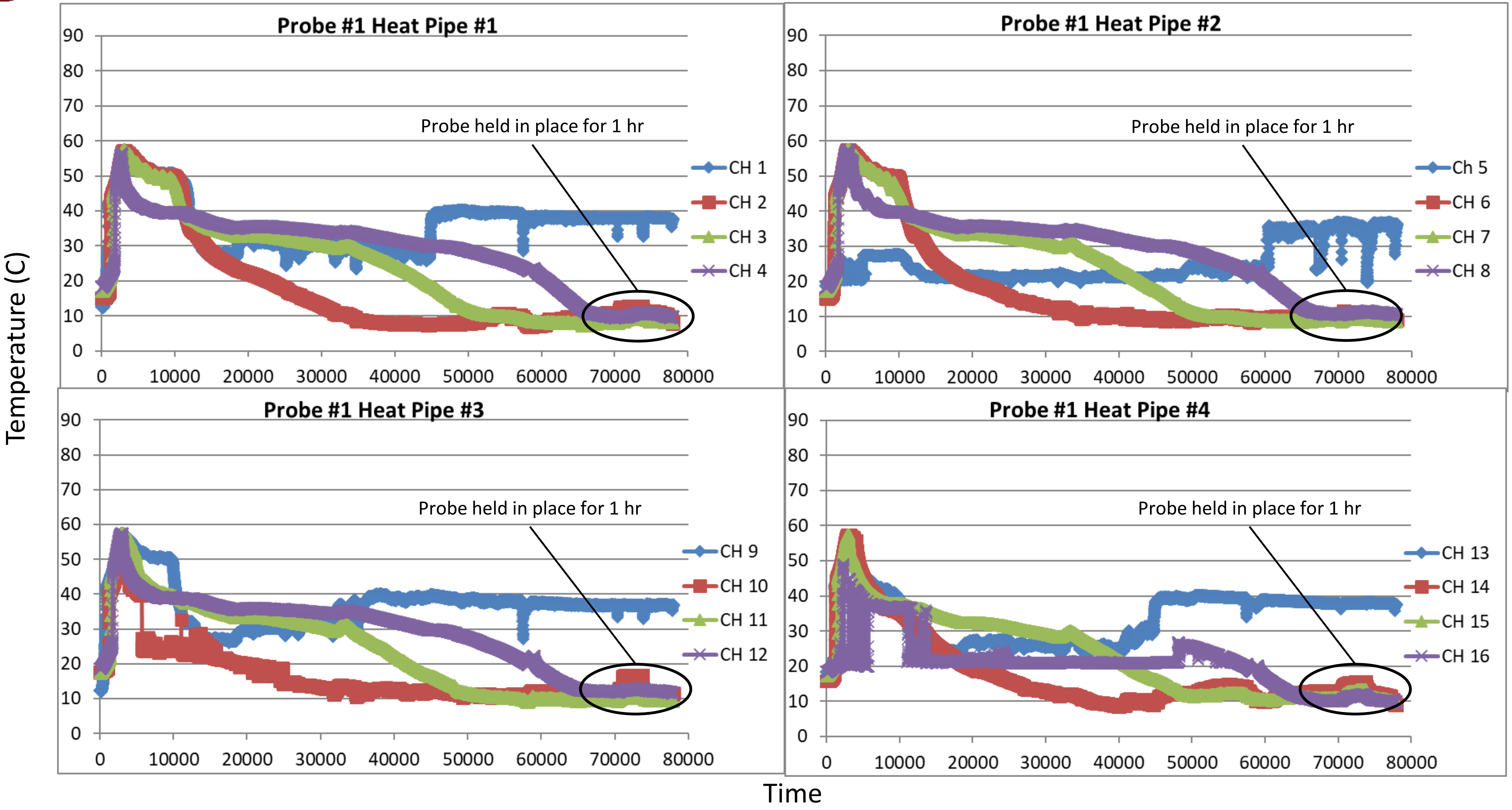


Probe removed after ice melting test

Large-Scale Ice Melting Test @ -26˚C



VCHP Wall Performance @ -26°C Ice Temperature



Melting Speed and Testing Conditions

	Test #1	Test #2	Test #3
Bulk Ice Temperature (˚C)	-26	-21	-2
Total Melt Distance (in)	26	26	26
Max Power Reached (W)	500	600	600
Total Melt Time (sec)	70,000	56,000	54,500
Average Melting Speed (in/hr)	1.34	1.67	1.72
Total Energy Deposited (Joules)	3.04E7	3.02E7	2.72E7
Specific Velocity (in/hr/Joule)	4.41E-8	5.53E-8	6.33E-8

Summary and Conclusions

The thermal management architecture consists of multiple novel features that can offer 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.
- A ***front vapor chamber*** can effectively transfer heat from P2P condenser to the melting head with minimized thermal resistance. The heat transfer performance of front vapor chamber can be further improved with elongated nose design and area enhancement features.
- ***Variable conductance wall*** that can passively control heat dissipating area to achieve maximized forward melting during normal mode and provide lateral melting capability when the probe was stuck in the ice.
- **Liquid displacement-based steering system** was not developed/demonstrated

Acknowledgements

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  - NASA Technical Monitors:
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- Contributors at ACT:
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  - ACT Safety Committee

THANK YOU FOR YOUR ATTENTION