Modeling of Cryobot Melting Rates in Cryogenic Ice

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Abstract:
There currently is significant interest within NASA and the scientific community to explore outer planetary ocean worlds, including Jupiter's moon Europa. Since the Galileo spacecraft magnetometer data indicated that an ocean of liquid water/slush might exist 10-15Km 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. In this study, both passive and active melt probes (cryobots) have been theoretically analyzed to determine heating power requirements and rates of descent. It is based in part on earlier experimental JPL cryobot studies, as well as more recent system engineering studies, and provides an analytical estimation adapted to the unique cryogenic Europan environment.The Cryobot probe will descend though Europa's ice core until it reaches liquid water at about 10km depth. This analysis corresponds to the melting and descent rate starting at a 3 km location where water jets are used instead of a mechanical drill. The Computational Fluid Dynamics (CFD) analysis was performed using Transient Multiphase Static model in StarCCM+, but was validated with experimental empirical data performed by Honeybee Robotics, obtained from small-scale probe passive melt data in both cryogenic and warm ice, as well as modeling data from CFX and FLUENT performed by U. Pittsburg. The first step of the analysis was focused on the heating power required to form a melt a layer around the probe. Based on earlier passive thermal melt models developed by Stone Aerospace for the conceptual probe developed for this trade study, it was determined that a minimum of 7KWt would be required to meet a 2yr transit through cryogenic ice. Analysis showed that the water jets at the tip of the probe will significantly increase the melt rate over purely conductive, passive heating. A purely conductive melting probe will descend at a rate of approximate 9cm/hr, while using water jetting the probe will increase this rate to approx. 50 cm/hr. The rate of descent also increases as the probe travels through warmer ice, so case studies at 180K, 200K, 230K and 250K were used to calculate an approximate melt rate through the 10km of ice. The water jet locations and spacing are also a significant factor in the rate of descent, since if they too close together, it could create freeze zones that would slow the probe. The paper will show results of water jet optimization for their location and mass flow rate to improve the probe's descent rate.

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1. INTRODUCTION

Magnetometry and remote sensing data from the Galileo spacecraft of the surface of the Jovian moon Europa indicate the possibility of a subsurface ocean. The surface of Europa is composed entirely of water ice, containing salts, acid(s), and a mix of inorganic/organic chemicals. The surface temperature sits at approximately 100 degrees Kelvin. Additional evidence of tidal heating caused by the immense push-pull gravitational forces exerted by Jupiter led to speculation that the interior of Europa could be heated above the melting point of water **(ref 1).** Figure 1 below shows the predicted makeup of the Europan ice shell (5-30km), ocean (~100km), and rocky mantel. Figure 2 shows the likely thermal profile of the ice shell down to 20km **(ref 2)**. This thermal profile is the profile used for the probe penetration modeling described in this paper.

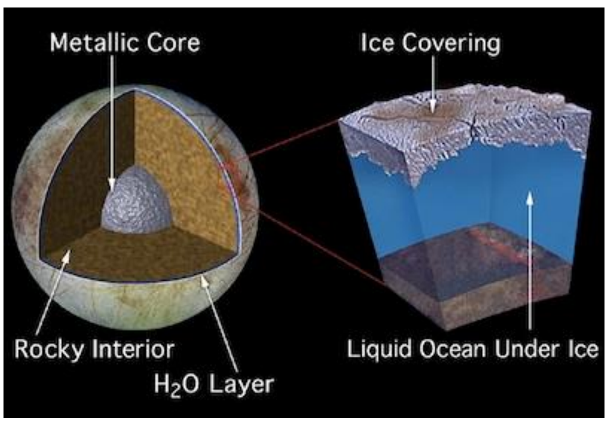

Figure 1. Europa ice shell and ocean

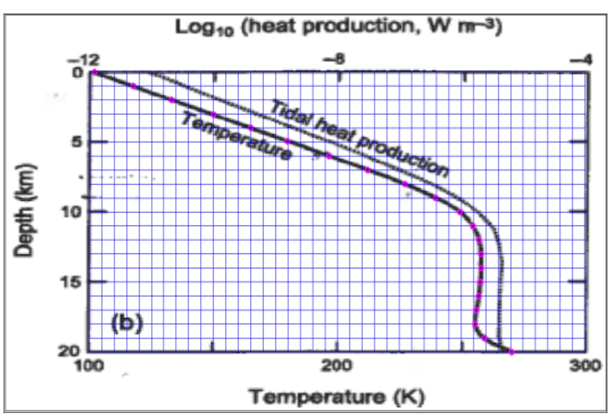

Figure 2. Projected thermal profile for the ice shell

The above Galileo surface data and information shown in the two figures suggest that any probe (cryobot) developed to penetrate the ice shell must be designed to survive the extreme cold environment, a high over burden pressure environment, and have sufficient energy in terms of both stored thermal and electrical power to have any chance of performing an extended ice penetration mission on Europa. Further, long term reliability of the system as a whole, and its primary subsystems makes it essential to design the system to not only survive extreme cold and high surface radiation on landing, but to penetrate at a rate commensurate with the likely life of its components, i.e., typical life targets for extreme environments like Mars or Jupiter icy moons are 2-3yrs. These fundamental design parameters formed the operational envelope for developing our performance models and for doing sensitivity analysis. The next section provides the reader with the background history and research/modeling that formed the foundation for the modeling work described in this paper.

2. BACKGROUND AND STATE OF PREVIOUS MODELING/ TESTING

Thermal melt probes have been in existence since the late 1960's with the development of the Philberth probe by the Army Cold Regions Research Experimental Laboratory (CRREL) **(ref 3).** The probe was primarily developed to study terrestrial polar ice properties, and map the temperature profile to help establish models for estimating ice pack thickness. The underlying mathematical foundation for modeling probe penetration rates was based on Aamot's model of power, heat transfer to the surrounding ice, and probe size, i.e., probe diameter and probe length **(ref 4).** Figure 3 shows a summary of the Aamot approach.

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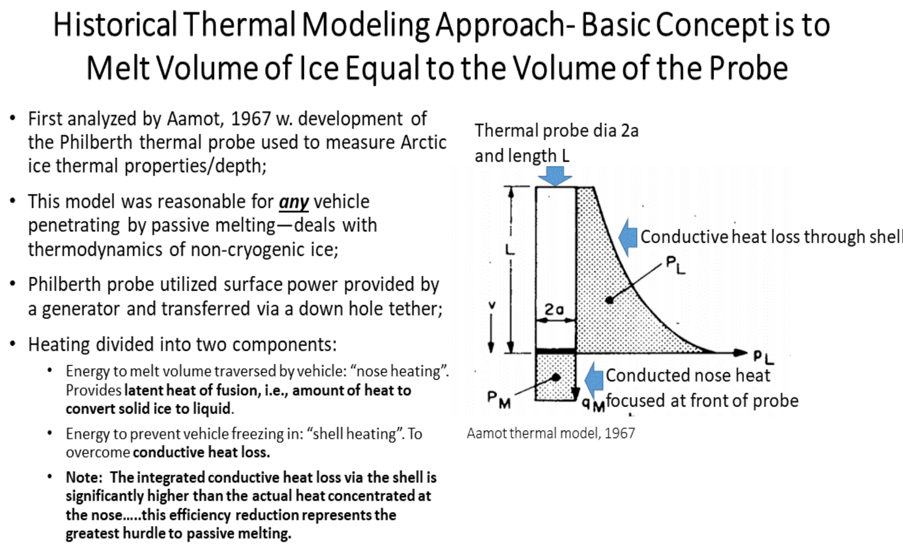

Figure 3. Aamot Passive Thermal Model

The Aamot model was a good predicter for probe performance in terrestrial ice and has been used by many ice reasearchers for designing ice probes and estimating power requirements as a function of desired penetration rates and probe dimensions. Unfortunately, the Philberth probe development came to an end due to the shortcomings of passive melting. Melting in ice containing contaminants like sediment caused debris to settle in front of the probe which in turn acted as an insulator. This prevented the nose heaters from transferring heat to the melt front, causing the probe come to a halt.

In the 1990's, with the return of the Galileo magnetometer and remote sensing data suggesting the presence of a salty or slush ocean under the ice shell, renewed interest in revisiting Europa as a possible source of exterrestrial life in our solar system spawned mission concepts for exploring the icy surface and subsurface ocean. Under the Planetary Science Advanced Concepts Program at JPL, a small team of researchers were funded to perform a detailed physics based analysis of what it would take to penetrate the ice shell down to the ocean, sample the ocean for past or extant life, and transmit the data back to a surface lander for relay to an orbiter and Earth. The team did a complete system analysis and design for a Europa cryobot and those results have been published in multiple journal papers. We will only on focus on the melt dynamics for this paper.

The results of that modeling and design effort were based largely on the Aamot model extrapolated to cryogenic ice. Understanding that the model had limitations due to the much higher conductive heat loss through the shell, the team also built small scale heating probes and tested them in colder ice. On a small scale the divergence from the model was not significant. However, the combined modeling and empirical testing clearly revealed the following:

1. Every effort should be made to keep the probe diameter and length as small as possible;
2. Maintaining the primary heat source at the nose in cryogenic ice would result in the probe freezing in due to the conductive heat loss through the shell, i.e., heat transfer to the shell and moving heat cyclically from the nose to the shell was an absolute requirement;
3. A minimum of 1KWt was required to initiate melt for a small probe (i.e., 12cm diameter, <1m long}, thus requiring consideration for power/heat sources that would provide at least that level of heat transfer efficiency;
4. Most important, given the limitations of the Philberth probe in dirty ice, any planetary cryobot would require both passive and

“active” heating, e.g., water jetting/steering, to accommodate ice contaminants;

5. The ice probe would require an autonomous control system to sense/manage variable ice or ocean properties;

The team received funding from the NASA HQ robotic technology program to design, build, and demonstrate via field test, a cryobot system that could not only validate melt performance models but also demonstrate all of the key control functionality needed for a planetary probe **(ref 5).** Figure 4 provides an overview of the early design and subsequent prototype probe successfully built and tested in a dirty glacier (sediment loading on the order of 10-100microns, avg of 60microns) on Svalbard above the Arctic Circle in 2001 **(ref 6).** The JPL cryobot was 14cm in diameter, 1m long, operated on .75Kw, used both passive quad heaters at the nose for melting/steering as well as water jetting with the ability to vary pump flow rate as a function of silt density and penetration rate monitoring. Figure 4 clearly shows that for an extended long duration mission through the Europan ice , the thermal and electrical power needed to both melt, control the probe functions, and perform science would have to be supplied by a radioisotope power source.

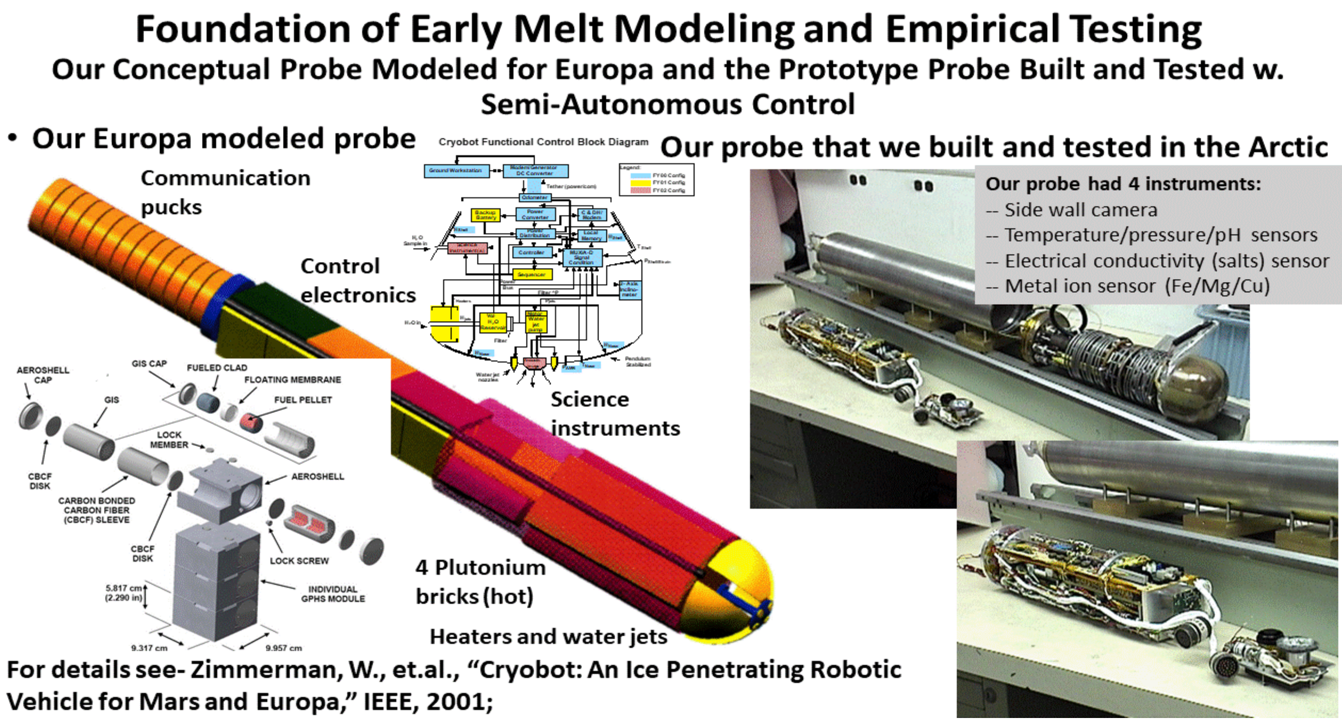

Figure 4. Europa Cryobot Modeling and Prototyping

The research team also did considerable testing with water jetting and how the combination of passive nose heaters, coupled with hot water jetting at the nose, could improve melt efficiency and deal with the likelihood of encountering ice containing contaminants. Figure 5 provides a summary of the test results.

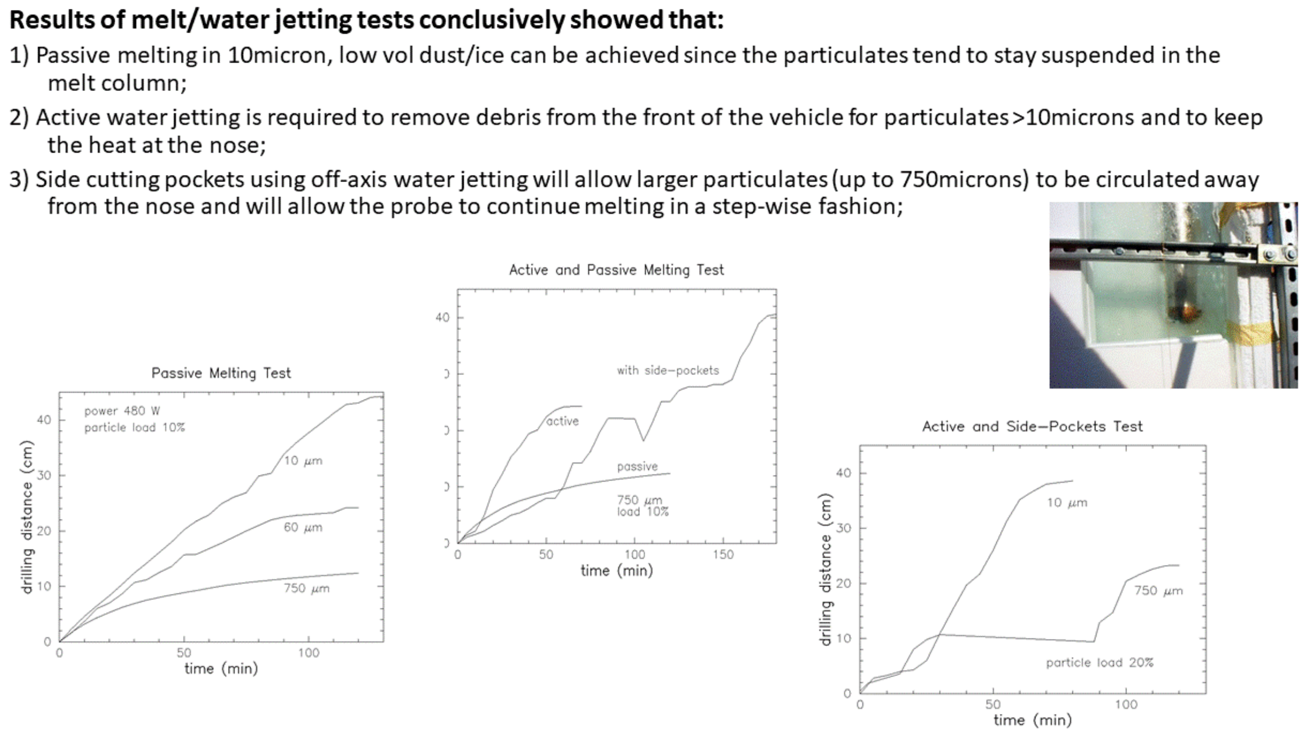

Figure 5. Results of Water Jet Testing in Ice of Varying Sediment Loading (JPL)

In the mid-2000's planetary mission design for Europa saw a hiatus due to the projected high cost of a Europa surface mission and renewed interest in returning to Mars, and, in particular, the Mars N. Polar Cap. However, most recently, new results from Casini's Titan remote sensing and imaging data of rich organic lakes, coupled with images of plumes showing the possibility of water on other icy moons like Enceladus, along with Europa, spurred renewed interest in the icy moons.

With the advent of the NASA HQ Icy Moons ColdTech research program, new modeling and technology development research tasks were spawned. Recent re-examination of the Aamot model to understand and quantify the differences between warm ice heat transfer during the melt phase, vs. cryogenic heat transfer and melt dynamics, has become high priority to better quantify energy and power requirements for Europa ice. Besides the early modeling/testing done by the JPL cryobot team, research organizations like Honeybee Robotics, University of Washington, Stone Aerospace, and a new JPL group have actively been exploring analytical models that help correct the lower projected power predictions of the Aamot model when compared with actual cryo-ice empirical test data. **It should be noted that the bulk of the recent modeling has been concentrating on "passive" heat transfer via the probe nose with no water jetting and no assumptions of embedded contaminants.** Honeybee used a numerical approach to solving the integrated equations for power as a function of variable ice properties, ice temperature, probe diameter/area and length and determined that the Aamot equation underestimated power by factors of 2-4 in 100K ice as a function of probe size **(ref 7).** Similarly, University of Washington has also been modeling only passive heat transfer with a focus on warmer ice where there is good convergence with the Aamot model. In support of a recent design/technology tradeoff study done at JPL, Stone Aerospace did an extensive modeling and tradespace analysis weighing the impact of probe frontal/shell volume and length vs. power to establish an envelope of penetration rates for a range of ice temperatures **(ref 8).** To understand the melt/fluid dynamics across the complete surface area of the probe, Stone and his team used Solid Works finite element analysis/CFD composite model to calculate heat transfer melt rate progression along the probe length in a step-wise manner via mesh linkages. The key results of that analysis are shown in the following figures. The results of that modeling effort also confirmed that the Aamot model underestimated the thermal power needed to penetrate cryogenic ice at 100K. One of the most important results of the Stone model was the development of a "slenderness ratio= probe volume/dia" which optimizes the penetration rate for a given thermal power input. For the purpose of this most recent tradespace analysis, the Stone team used the probe geometry derived from the design parameters /developed for a probe concept that exhibited all the desired functionalities, science payload capacity, and fully redundant electronics/sensing for a "potential" flight-like system. No effort was made at this early conceptual stage to make the design efficient in volume or mass. The result was a probe concept that was 23cm in diameter and 2.1m long (volume of ~ 81-87L), with a 7.5KWt radioisotope power source. The Stone plot shown in Figure 6 highlights where the tradestudy concept fell in the family of sensitivity plots.

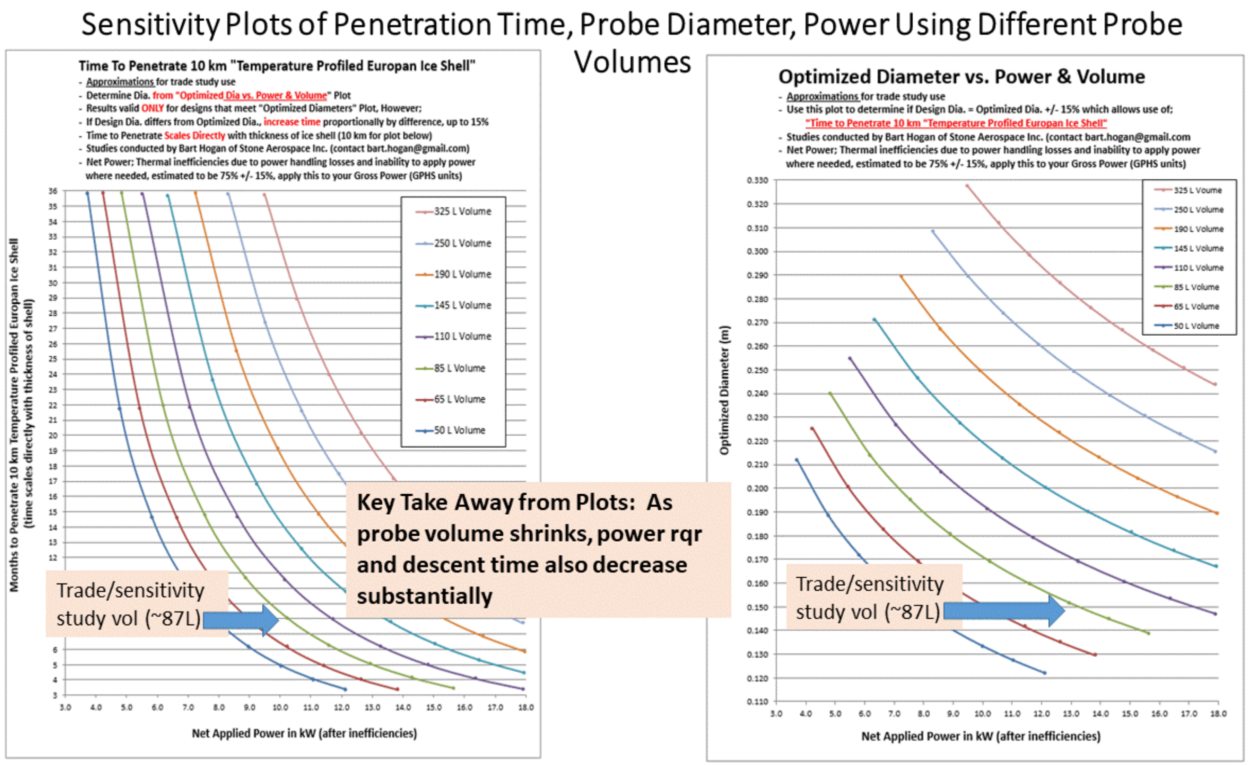

Figure 6. Sensitivity Analysis Showing Melt Rate as f(Power Input and Probe Geometry)

While the bulk of the above modeling focused on passive thermal melting in clean ice, the Stone team did consider how the presence of salts, e.g., MgSO4 as detected on Europa, might effect probe rate of penetration. The current thinking on the addition of salts like MgSO4, is that it makes ice more dense which decreases the energy needed to raise the temperature of ice to the melt temp (specific heat) which in turn lowers the needed conducted heat—this would suggest that a probe could either live w. less power or melt faster with the same amount of stored thermal energy. This is the same phenomenon we see in terrestrial ice when salt is used to remove ice from icy roads. The Stone team plot shown in Figure 7 highlights the possibility that a 10Km penetration could be done in half the time if, in fact, the Europa ice shell is salty ice.

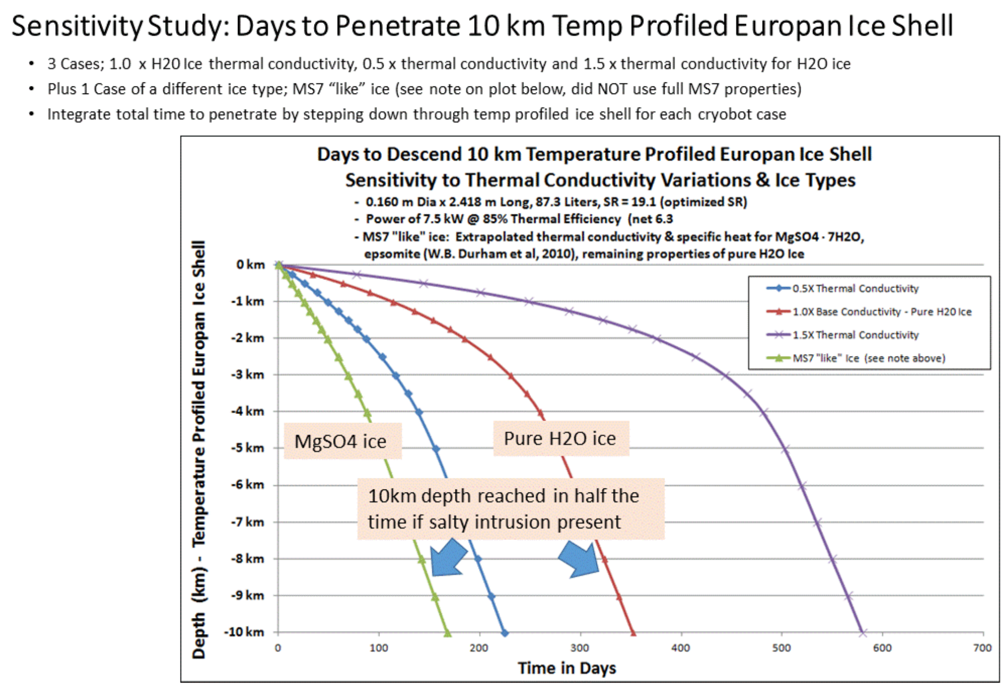

Figure 7. Projected Differences in Rate of Penetration in Presence of Salts

And the last, most recent work using Computational Fluid Dynamics Modeling, from the University of Pittsburg, was used in conjunction with the modeling described in this paper as a means of comparison/validation of our approach. The CFD model analyses two main cases: purely conductive melting and active heating (water jets.) For simplicity, the multiphase model only uses pure H_2O and a laminar flow. The thermal conductivity, specific heat and density vary depending on temperature as shown in Figure 8.

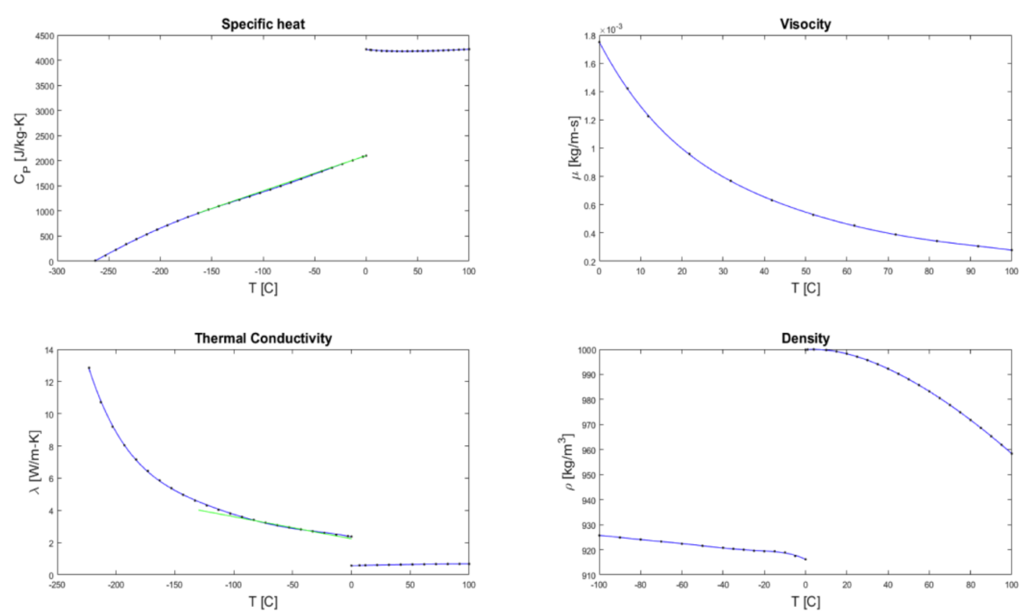

Figure 8. Temperature Dependent Material Properties- Graphs by U. Pittsburg

The above summary of thermal modeling and testing is not meant to be exhaustive because there are now many university participants studying the problem of how to penetrate cryo-ice as efficiently as possible. Some of this research also considers hybrid approaches such as mechanical cutting and melting, e.g., Honeybee and JPL (Wilcox, B). For purposes of this paper, the focus on the next stage of thermal modeling revolves around validating some of the recent empirical testing for passive melting, with a major expansion in the modeling of water jetting, and quantifying how the combined use of passive heaters with water jetting improves heat transfer efficiency and penetration rate. The modeling effort described in the following sections is also part of an effort to obtain closure and convergence of the various modeling techniques as a means of developing a strong proof-of-concept melt probe predictive performance structure. This structure will hopefully guide the design for an actual deep ice probe flight configuration.

3. JPL COMPUTATIONAL FLUID DYANAMICS (CFD) ANALYSIS USING TRANSIENT MULTIPHASE STATIC MODEL IN StarCCM+

The JPL Cryobot modeling was performed using STAR CCM+, a multiphysics simulation tool which includes fluid dynamics, multi-phase, and thermal modeling. The simulation starts at depth of 3km beyond the brittle/porous crust region where sublimation occurs and the use of heat/waterjets is more effective. At this point, the ice temperature and Static Pressure are approximately 160K and 560psi respectively. The 7.5 KW main heat source is near the nose but heat is distributed uniformly through the probe's side walls assuming the use of an internal 2 phase pump fluid system. Two additional localized Heat Sources are also included at the nose of the probe and back side (from radioisotope powered communication pucks.) Figure 9 shows the CFD model boundaries built from an earlier baseline architecture tradeoff study design.

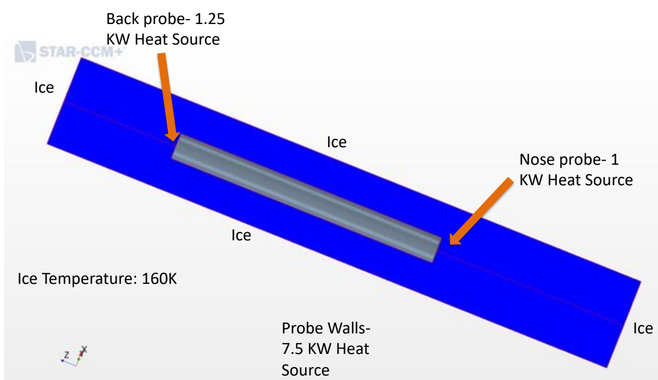

Figure 9. CFD Model Boundaries

The outside boundaries were fixed to be far enough away as to not affect the probe and ice temperatures. The water jet locations were chosen at an arbitrary location for the initial analysis, but were optimized later in the analysis to obtain higher melting rates.

3.1 HEAT SOURCE ANALYSIS/ MELT MODELS

The first part of the study used a 7.5KW heat source as a baseline to create a 6mm liquid layer around the probe. This layer is required for the model because of it's static nature in order for the waterjets to work properly. Although other models indicate that a 2-3mm water layer is sufficient to maintain a melt boundary, the Star CCM physics based model required a thicker melt layer to allow the melt flow pressure to offset the viscous drag as a function of ice-to-liquid phase change density. This simplified the model and removed the uncertainty of the heat transfer rate during this phase change. With the 6mm layer, melting starts in approximately 28 min which is the time it takes for the ice around the probe walls to reach 273K. See Figure 10. The 6mm desired liquid layer is fully developed in approximately 57 min.

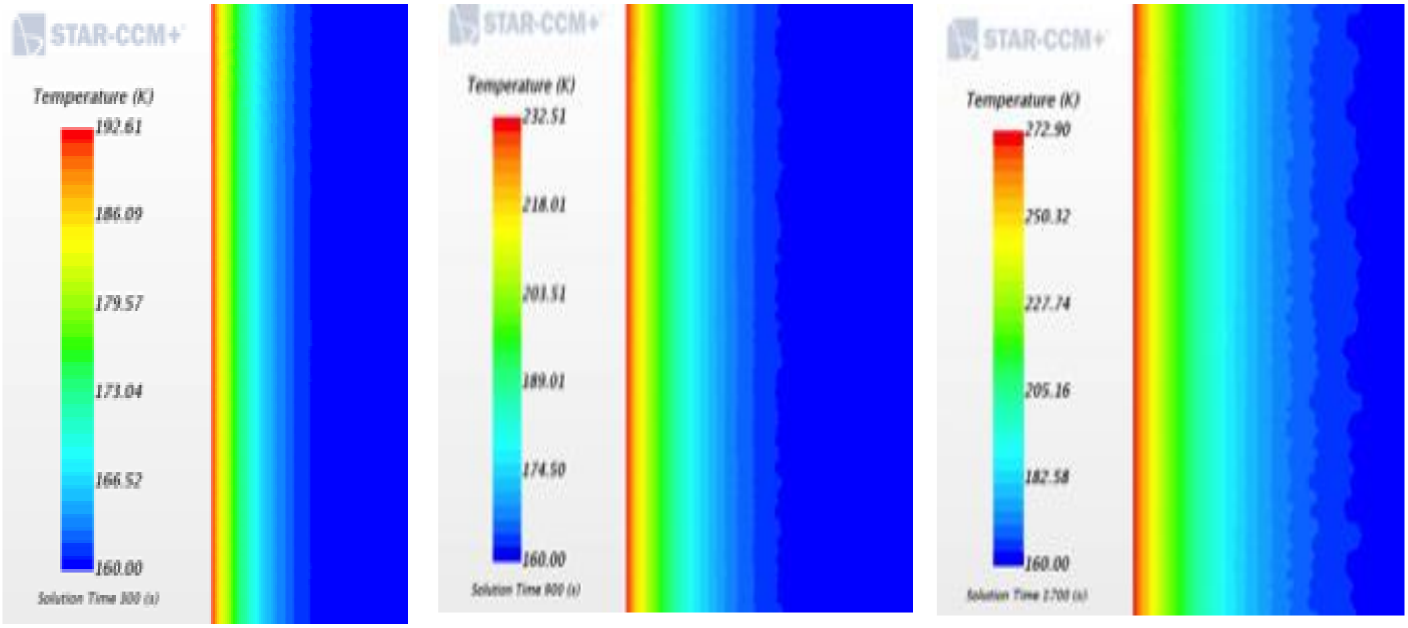

Figure 10. Ice Water Temperature Progression at 5 min, 15 min and 27 min (probe sidewall is on left side of ea. Plot)

Based on this analysis, 7.5 KW provides enough power for the probe to melt a layer of liquid water thick enough for the water jets to work properly. The Cryobot Probe also includes a 1KW Heat Source at the tip of the probe. This is the main driver for the passive melting descent rate. This descent velocity was based on the time interval and velocity of the receding liquid/solid interface. The melt interface was developed until the point in time when the liquid layer rounds the bottom corner of the probe, and is fully formed along the sidewalls. At this point, the probe would sink into the liquid water, pushing it out behind it as shown in Figure 11. By knowing the melt layer elapsed time and the delta-z distance, the descent velocity for a purely passive melt probe is calculated to be 7.2 cm/hr for an ice temperature of 160K. At this rate it would take around 4 years to just travel through the first 3km of ice.

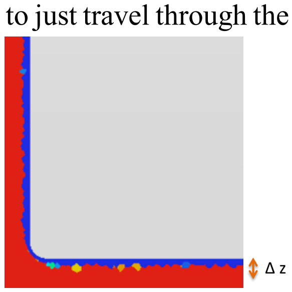

Figure 11. Descent Rate for Purely Passive Melt Probe

Table 1 displays the derived descent rates.

	time	**Δ z**
CASE 1	1.5 min	2.3mm
velocity	**9.2 cm/hr**	
CASE 2	5 min	7.6 mm
velocity	**9.1 cm/hr**	

Table 1- Passive Melting Descent rate calculation

The purely passive melt rate could be improved by directing more heat from the main power source to the tip of the probe. This analysis doesn't include the method of transporting this heat or the amount of heat that is lost due to dissipitaion during the process. The highest descent rate that could be attained is double the initial rate by increasing the power at the tip to 5KW. This would mean only leaving 3.5KW to be uniformly distributed at the probe walls to make sure the liquid layer is still present. This amount of power is sufficient to maintain a 1mm thick melt layer around the probe at all times and stop it from freezing in. See Table 2 results.

Heat at Tip	Melted ice in 5 min	Approx descent rate
1KW	7.6 mm	9.1 cm/hr
3KW	11 mm	13.2 cm/hr
5KW	15mm	18 cm/hr

Table 2- Passive Melting Descent rate, 1KW, 3KW, 5KW at Probe tip

3.2 MODEL VALIDATION

This StarCCM+ CFD model was validated using different mesh sizes and time steps. As with the Stone finite element mesh approach, joint modeling efforts by both JPL and University of Pittsburg employed a mesh approach. The U. of Pittsburg mesh approach is summarized as follows. The model was setup similar to the StarCCM+ simulation using ice boundary conditions and the probe heat source. The numerical models included phase-transformation from solid to liquid through the incorporation of the latent heat of fusion. Multi-phase considerations for the formation of vapor phases considering latent heat of vaporization were also included. ANSYS CFX and FLUENT were used to validate results obtained in StarCCM+. A comparison of the execution codes yielded good agreement in both melt rate and rate of descent predictions, with the former compared to results of the one-dimensional Stefan problem. ANSYS FLUENT has a built in utility to model phase change, called the Solidification/Melting Model. The solidification and melting model uses an enthalpy-porosity based Volume of Fluid (VOF) method to track each discrete phase, which are represented by volume fractions. To handle the interface between the solid/liquid domain, instead of using a Lagrangian-based tracking method, a liquid fraction variable that represents the amount of solid/liquid present in a cell is used. The liquid fraction is calculated once the cell reaches saturation temperature, and is based upon the enthalpy in the cell with respect to the latent heat of fusion. In situations where re-freeze momentum is considered, a mushy zone parameter is used to dampen the velocity of the solidifying liquid. In situations where momentum is not considered, the solution is mushy zone parameter independent. In closing this summary, U. of Pittsburg did some internal model validation steps. The U. of Pittsburg in-house FDM model was subjected to a grid independence study. Grid sizes ranging from 1 [mm] to 0.1 [mm] were selected. With the FVM being energy conserving, and considering only conduction and phase change it is expected that the results (such as time to reach saturation temperature, time to form a liquid phase, and time to form a melt pool of desired thickness), could be dependent on mesh size. The main factor of interest is the thickness of the solid/liquid interface, as represented by the mushy zone. The solid/liquid melt pool effects the properties of the mushy zone making it inherently mesh dependent as shown in Figure 12.

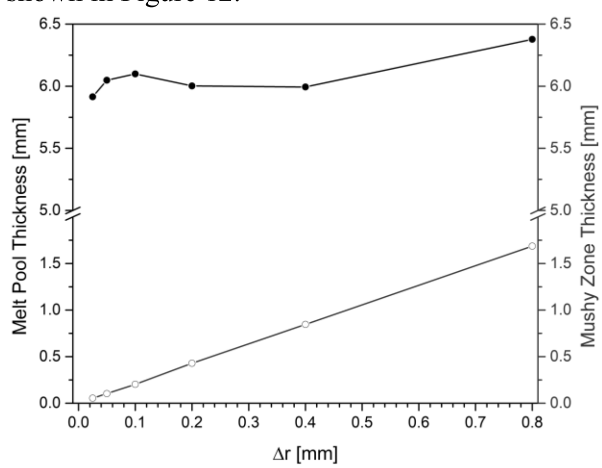

Figure 12. Melt zone growth as f(grid dependence) (bottom plot is mushy zone (variable grid size) and upper plot is melt water zone (single grid size)- both converge towards 6mm- note the shortened y-axis)

The JPL model was compared to results obtained from University of Pittsburg using FLUENT and CFX. Figure 13 compares the results from both programs discussed in greater detail in the following text.

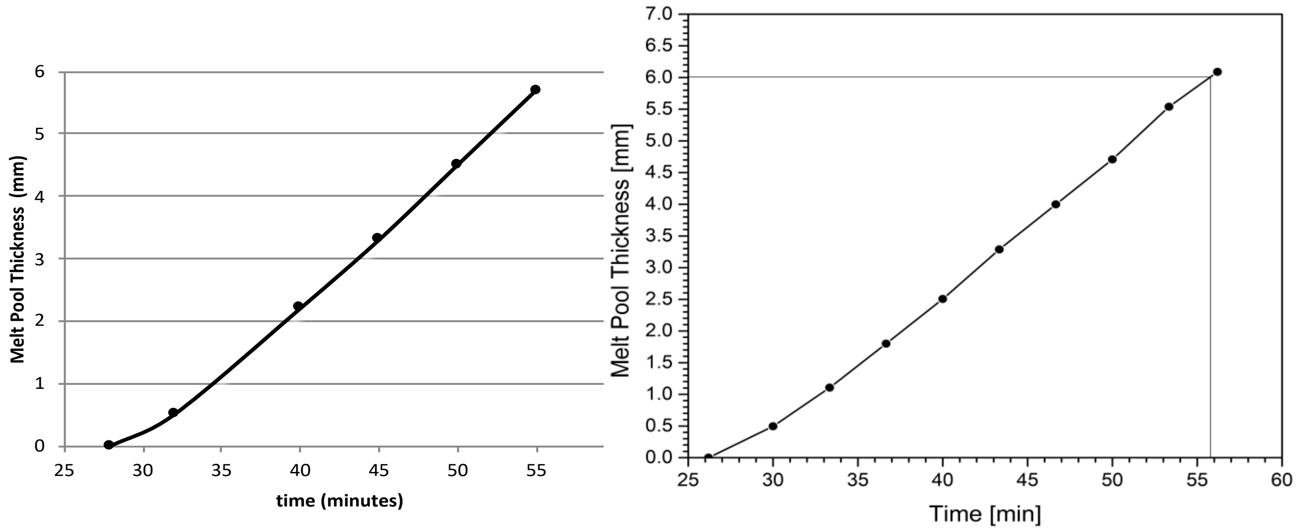

Figure 13. StarCCM+ vs CFX Melt Pool Thickness Results

CFX predicted the 6mm layer to be fully developed in 56 min, while StarCCM+ predicted 57min. The difference between them is less than 2%, and could be caused by the differences in mesh, time step and measurement of the zone between solid and liquid.

As a check on model accuracy we used empirical test chamber data performed by Honeybee as shown in Figure 14. The same physics model was applied, but the probe's dimensions and boundary conditions were changed to match Honeybee's experimental set up. The Heat Flux used in this case is larger than what we would see on the real size probe design. However, it is a good confirmation for the melting/solidification physics model.

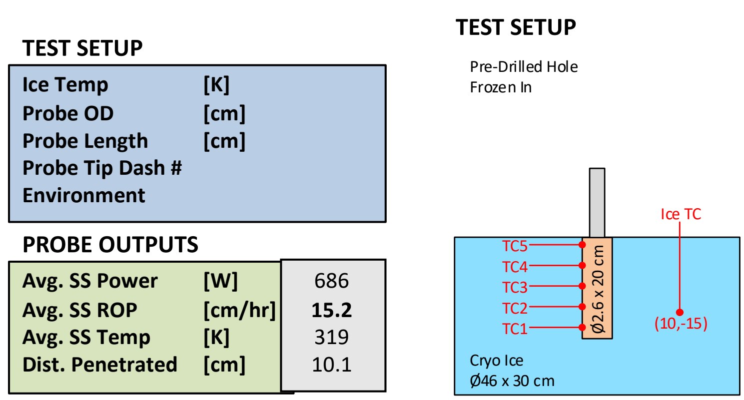

Figure 14. Honeybee Test Set Up (note location of thermocouples (TC) in figure on right)

Table 3 shows the difference between both cases was ~10%. This is an "excellent" agreement between the CFD Model and actual experimental data.. Because of the CFD static nature of the model, the melt rate was calculated after a 1mm liquid layer was formed at the tip of the probe. Another difference is the model uses the temperatures from the thermocouple experiments to assume the Heat Flux by sections.

Study	Star CCM+ 30s run	AVG descent rate
CFD	1.15mm	13.8 cm/hr
Honeybee	NA	15.2 cm/hr

Table 3- CFD vs Honeybee Experimental Results

3.3 ADDING SALTS TO ICE

This analysis was performed using a 3.8% $MgSO_4$ saturated ice. This value was chosen based on recent data of Europa's surface. Adding these salts changed the thermal conductivity into a roughly contant 2 W/mK for the solid ice (Figure 15.)

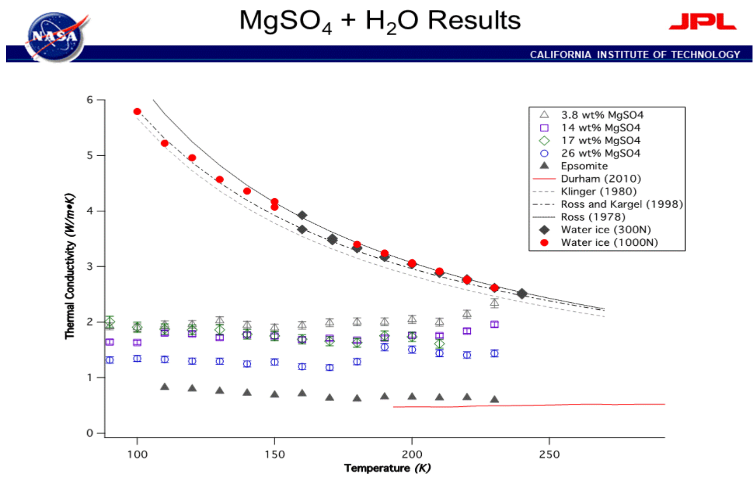

Figure 15. $MgSO_4$ Thermal Conductivity

The Specific heat didn't change considerably for the salt saturation level analyzed. This would have more of an effect if the saturation level was increased (Figure 16.)

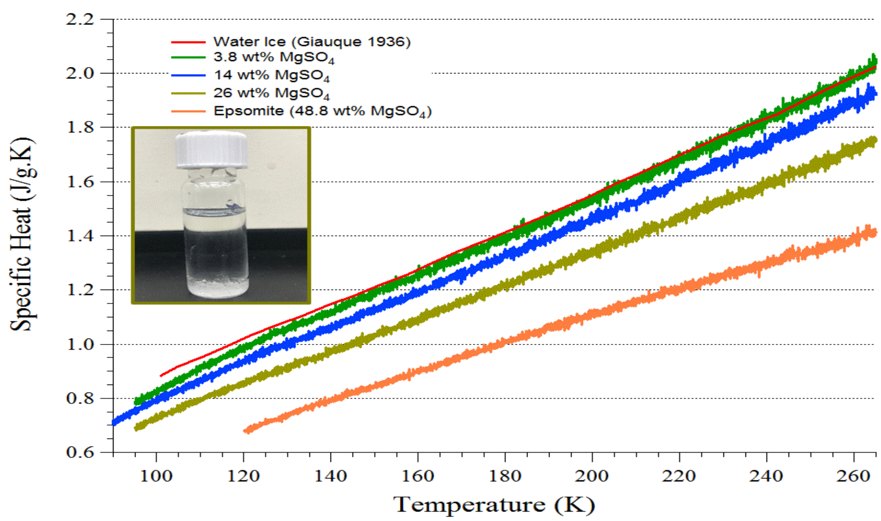

Figure 16. $MgSO_4$ Specific Heat

The salts improve the descent rate by a factor of 4 in most temperatures analyzed. The faster rate is mainly affected by the ice's lower thermal conductivity coupled with slightly lower specific heat. This allows the ice closer to the probe to be heated more rapidly without loosing as much heat to the further ice boundaries. Table 4 compares pure ice vs. salty ice descent rates as a function of temperature.

	Pure Ice (cm/hr)	Salty Ice (cm/hr)
160K	7.2	27
200K	17.1	31
250K	51	55

Table 4 – Pure ice vs Salty ice Descent Rate

This would decrease the descent time to reach liquid water from more than 15 years (pure ice) to approximately 4.5 years (salty ice).

3.4. ACTIVE WATER JETTING

Water jets are one of the options that will increase the probe's descent rate. The baseline design is composed of 3 waterjets at 1.25in from the center, but it could be optimized based on number of jets and distance in the future. Figure 17 is a plot of the velocity profile created by the jets. The liquid water is directed to the center of the probe and then pushed backwards and around the edges. The 6mm liquid layer created by the main heat source allow the liquid to flow through the entire probe walls without a problem.

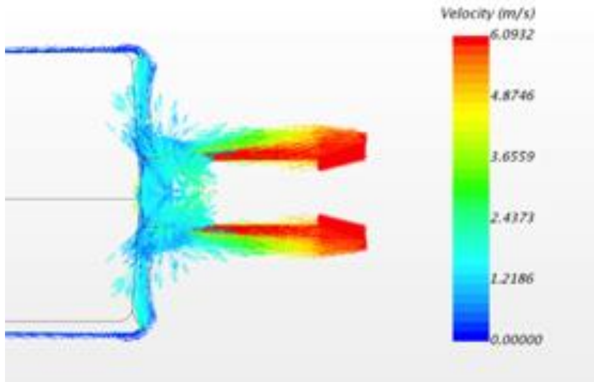

Figure 17. Water jets Velocity Plot

The descent rate was calculated after 1 min of the jets being on using the same method as for the static case. Because of the water jets, the Δz is the highest at the jets level, but this value is not used for the calculation. The lowest Δz value is the main driver for the descent since the probe will only be able to move to the lowest point of liquid layer as shown in Figure 18

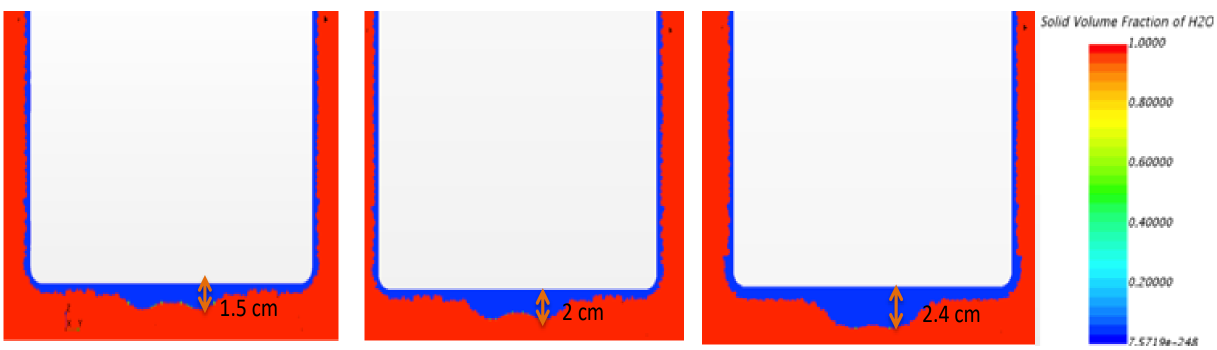

Figure 18. Liquid Layer Created by Water jet after 20s, 30s and 1 min

It was not necessary to run the CFD model for a longer time because the probe reached steady state with the same incremental melt rate. Cases for the jets running 1 min and 5 min are shown in Table 5.

Table 5- Water jets Melting rate calculations

time	Δz (min)	Δz (max)	Melting rate (min)	Melting rate (max)
1 min	0.9cm	2.5	54 cm/ hr	144cm/hr
5 min	4.1	11	49 cm/hr	132cm/hr

The water jets make the Cryobot approximately 6 times faster than the purely melting model. This is a great advantage for a mission aiming to reach liquid water in 2 years which can still be optimized by the location, mass flow rate and number of jets. Making the jets further apart or closer together have different effects on the rate of the descent. The jets being closer together increase the Δz at the highest point, but decrease it at the lowest, which will result in a lower descent rate. When the jets are too far apart, the ice column melts slower than the flow rate. The liquid water does not have enough room to flow around the probe's edges, causing the simulation to crash because of the static nature of the model. These cases demonstrate how changing the sepration of the jets affect the descent rate as shown in Table 6.

Location	Melt rate calculated at highest Δz	Melt rate calculated at lowest Δz
1.25 in	144 cm/hr	**54 cm/hr**
0.75 in	156 cm/ hr	**44 cm/hr**
1.75 in	Water could not flow around the probe corners at these velocities, creating a pressure build up at the tip pushing the probe back.	

Table 6- Water Jets Location Analysis

The descent rate will increase exponentially as the probe descends and the ice warms up as shown in Figure 19. At 6km and 8km depth, the ice temperature will be approximately 200K and 240K respectively. At these depths, the probe will descend at a rate of 168 cm/hr and 480 cm/hr. These values were used to calculate an approximate time to reach liquid water at 10km. This is a very conservative approach, only using 3 reference points: 3km, 6km and 8km. The actual time to reach this distance will be faster because the water properties will be changing to our advantage continuously. This is also the worst case scenerario, using H2O without any of salts added. Once the salts are added to the model, the thermal conductivity and specific heat decrease which allows more heat to be available for melting thus allowing the probe to travel faster.

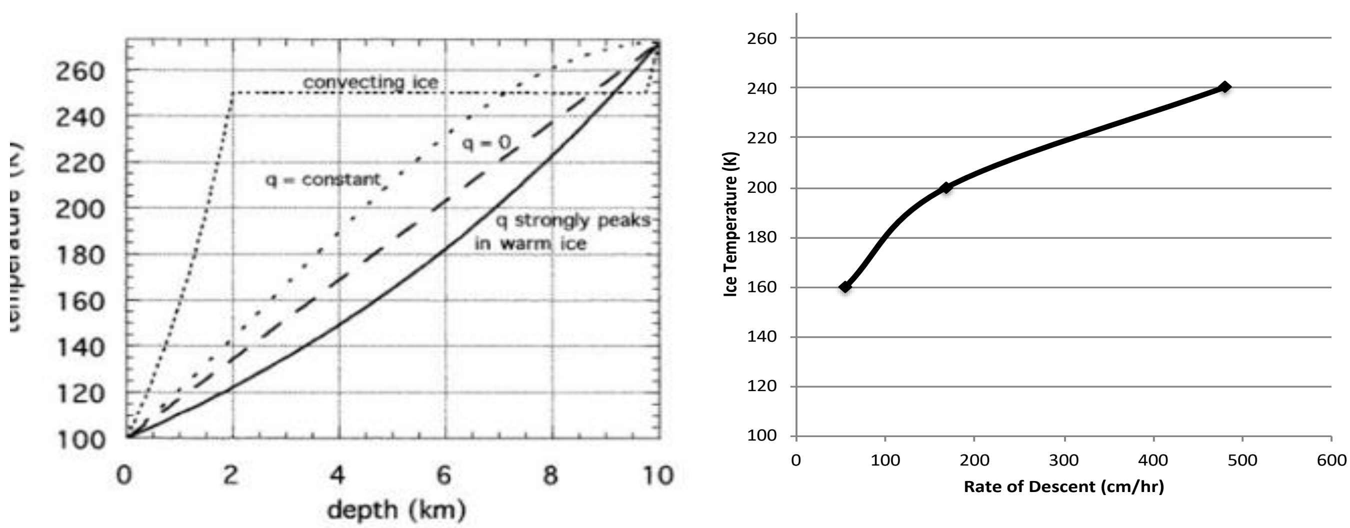

Figure 19. Depth/Rate of Descent vs Temperature profiles

Table 7 shows that based on the three depth reference points, the probe will take approximately 300 days to reach 10km. Most of the descent time is spent at the lower temperatures and only around 17 days consume the last 2km. This analysis doesn't take into account the descent of the first 3km were the drill is being used.

Ice Temperature	Depth	Days
160K	3-6 km	231.5
200 K	6-8 km	49.6
240 K	8-10 km	17.4

Table 7- Time to Navigate to Liquid Water

4. CONCLUSIONS

The above summary of model descriptions and test results provides the reader with a past-to-recent picture of how melt probe fluid dynamic modeling has evolved. Combined, the above results display a rich array of variable dependencies and how those variables affect probe dynamics. The models converge reasonably well on melt rate as a fuction of probe dimensions/power with particular focus on some key aspects of probe performance and design:

- Probe diameter, length, and power drive penetration rates;
- There are critical relationships between diameter and length as a function of power that can be optimized for a desired melt rate;
- In contaminant free ice, passive melt rates are surpassed by factors of 4-6 if hot water jetting is incorporated, and in ice containing sediment on the order of 10-60 microns, water jetting provides both a more efficient way to transfer heat to the nose and circulate debris away giving a factor of 3x increase in melt rate over passive;
- While hot water jetting can substantially improve melt rate, the spacing between water jet orfices is critical to the frontal vortex formation and subsequent transfer of heat to the melt front, namely:
- If the jets are too close to the nose center the ablated side lobes melt at a much lower rate which can slow the descent;
- If the jets are spaced too close to the circumference of the nose, the melt front exceeds the circumference leaving a frozen center zone which again impedes descent;
  The presence of salts increases the density of ice and therefore decreases the specific heat allowing an additional increase in melt rate. This offers designers the option to maintain the same melt rate as clean ice but with less power, or, penetrate at a higher rate with the same amount of power.

The following tables compare the results obtained from the different CFD models and previous waterjet testing. Table 8 shows that using the mesh approach, the first 3 models converge within 1cm/hr for passive melting at 160K. The minor differences are likely due to small details such as different mesh sizes, size of boundaries, time steps, etc. The slightly larger difference with the Stone CFD analysis assumed that all heat was directed to the tip of the probe, not counting on the heat needed on the sides to keep a 6mm layer for the waterjets performance.

There was no specific water jet testing done in support of our modeling. However, the results shown in Table 9 are within the expected relative range for pure vs. dirty ice, based on the previous Cryobot testing performed by Zimmerman, W. et.al. in 2001.

CFD Software	Probe Descent Rate (160K)
StarCCM+	7.2 cm/hr
FLUENT	7.5 cm/hr
CFX	6.5 cm/hr
Stone (FEA)	17 cm/hr

Table 8- CFD Probe Descent Rate comparison

CFD- Waterjets vs passive	~6x (39-45cm/hr) Stone- 37cm/hr
Test (dirty ice)- Waterjets vs passive	~3 to 4 times faster

Table 9- Probe Waterjet testing comparison

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