Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

Cryobots: An Answer to Subsurface Mobility in Planetary Icy Environments

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Keywords Cryobot, subsurface, mobility, ice, thermal, Earth, Mars, Europa, water, tether, life, in-situ

Abstract

Exploration of the deep subsurface ice sheets of Earth, Mars, Europa, and Callisto has become a major consideration in addressing scientific objectives in climate change, extremophile biology, chemical weathering, mineralogy, planetary evolution and ice dynamics. Similar exploration on Earth has been accomplished through ice coring, for chemical, biological, and crystallographic analysis, and sounding radar, for structural analysis [1]. The results from these studies have elucidated the temporal circulation history of climate change on Earth. For some applications, coring and remote sensing techniques are not optimal; these applications include situations in which the ice cores are too warm for successful core retrieval, investigations that require strict sterilization [2], and planetary environments for which in-situ observations are the only measurements technologically possible. We will discuss scientific goals, design issues, and test results including the fluid dynamics of hot-water jetting, approaches to maintaining vertical attitude, and tether management.

1 Introduction

1.1 Science Goal

The fundamental answers to key questions and scientific objectives in planetary science, such as climate history, exobiology, and volcanic history are possibly hidden in the largest reservoirs of water found on terrestrial planetary bodies, the icy environments of polar caps and icy moons. Therefore, in-situ study of icy environments, including an examination of geology, chemistry, and biology are required. A vertical profile of measurements through 10's to 100's of meters of ice can best address the desired science objectives. The knowledge gained will aid in the understanding of solar system evolution and planetary body evolutionary processes.

1.2 Exploration of New Environments

Figure 1: Hypothetical subsurface mission deploying a thermal probe.

Subsurface environments are protected from the radiation, chemical, and meteoritic processes that occur on or near the surface. Therefore, a subsurface environment would retain the time dependent vertical stratigraphy of information. On Earth, this type of exploration has been accomplished through ice coring and sounding radar. As mentioned above, coring and remote sensing methods are not practical to achieve these science objectives on remote planetary bodies. In-situ investigations of remote planetary environments remain the most technologically feasible method.

Europa, an icy moon orbiting Jupiter, has revealed an environment that re-ignites the imagination for the possibilities of life on other worlds. The Jovian environment extends to include Europa, inundating the surface decimeter with high radiation exposure, limiting the opportunities for biologic activity in this zone. However, the protective icy shell extends at least several kilometers, and below there likely exists a salty ocean several kilometers deep, which may be home to organic life. The daunting question, in response to this discovery, was how to explore this complex world. A possible answer to this challenge is a cryobot or subsurface thermal probe to explore both the ice crust and subcrustal ocean (See Fig. 1). As luck would have it, there is an Earth analog to the Europan environment. Subglacial lakes exist in Earth's polar regions which lie under +3km thick ice sheets [3,4]. This is of great interests to scientists seeking to explore the ice and liquid environments to characterize not only the Europan environment but also to aid in the understanding of our planet.[13]

Another planetary body currently scrutinized for the possibility of liquid water and life is Mars. Recent missions have kindled a growing interest in the Martian polar caps. Polar missions below the surface are desirable as climate history is likely recorded in the largest observed reservoirs of water/ice on Mars, the ice caps. Ice flow, sublimation, sediment deposition, and wind erosion are believed to be the most important processes that shape the caps; however, little remains known about the composition, porosity, density, and layering of Mars polar ice [10]. Geochronology may be recorded in the ice cap by volcanic layers similar to K-T boundary on Earth. Lastly, the search for biology on Mars should begin with the largest known body of water, the north polar cap. Because of the cryobot's unique method of mobility, the polar ice can be penetrated enabling scientific studies.

1.3 Access to New Environments

The exploration of new subsurface ice environments requires a tool to enable access. The requirements imposed upon that tool are daunting at best. The first challenge is to pass through ice that is potentially laden with particles of unknown sizes and volumetric concentrations. Deep penetration into the subsurface is desired. However, the change in rheologic properties associated with high pressure ice overburden, chemical processes, porosity, and possibly meteoritic obstacles, remains unknown. Other problematic issues for non-terrestrial operations are mass, power, communications, temperature, and achieving the downward mobility required to access regions of scientific interest.

1.4 Cryobot

Figure 2: Cryobot.

One possible solution to the problem of accessibility is a vehicle that burrows into the ice. Once subsurface access is gained, we must address the issues of mobility and site selection. The vehicle would carry instruments and study the environment at depth. The data could be processed onboard or sent to the surface for analysis. Drill rig concepts have been proposed, but the concepts lack viability due to the mass and volume constraints for non-terrestrial planetary missions. Sampling scenarios, with material brought to the surface for instrument study, were avoided due to sample handling difficulties and maintaining a sample's pristine condition. The best technical solution is a thermal probe that fits within the mass and volume envelope and can carry the instrumentation to the subsurface site for in-situ study (See Fig. 2). The primary challenges are power and instrumentation packaging. Such a probe would be similar to surface rovers with the needs of navigation, autonomous control, and hazard avoidance. This thermal probe, or Cryobot, would melt through the icy environment.

2 Background

2.1 Historical Background

Following the International Geophysical Year (1957-58), there was strong interest in deep (> 1 km) drilling in ice sheets, but there was no established technology. Adaptation of exploration rock coring produced an ice coring drill that worked but was costly and slow and given to seizing in the hole. In the early 60s the Philberth brothers devised an approach for the acquisition of temperature profiles by using a thermal probe which carried and paid out its own tether [5]. The goal of this system was to acquire an understanding of ice motion and deformation through measurement of what was then the key variable, temperature profiles, at less cost that a full coring operation. The Philberth Probe descended by melting through ice until it reached a depth of interest, whereupon the heating was turned off and the probe allowed to come to equilibrium temperature with the ice sheet. For a review of the history of thermal probe development, see Kelty, 1995.

The Philberth probes were 3-4m long and consumed 3-4kW during descent operations. The primary method of descent employed a heated tip to melt through the ice. A control system was developed which used a mercury bath and differential heating to maintain a vertical orientation for the nose sections; later a system of multiple heaters was developed at the University of Nebraska. One of the Philberth Probes managed a descent of about 1000m, but in general they failed due to heater burnout or tether failure. The method for obtaining temperature profiles involved allowing the probe to freeze into place. Yet, that method was also a source of problems. The failures occurred trying to restart the probe's descent following such a freeze-in. At the present time, temperature profiles are no longer the prime objective of deploying thermal probes. The key motivations are the optical examination of the undisturbed ice near the ice-water interface of the melt

void through which the probe is moving in a downward direction (See Fig. 3).

Figure 3: Sediment layering at 1219m depth in an Antarctic ice stream. [12]

The Cryobot improves on the Philberth probe by employing a method of hot water jetting to drill into the ice. The ice drilling community has been using electro-mechanical core drilling and hot water drilling successfully for 30 years. Hot water drilling has been a very effective method to gaining deep subsurface ice access due to drilling fast, straight holes; the JPL program has incorporated the hot-water drilling concept into the thermal probe. Other design tasks at JPL have also influenced the development of the Cryobot. A mission study called CHIRPS addressed the design of a thermal probe for planetary use; the study determined vehicle size, mass, and power necessary for deployment into the icy shell of Europa [9]. JPL's work to develop a hydrothermal volcanic vent probe helped define instrument packaging and environmental constraints for the general case of probes, like the Cryobot, which operate in liquid environments with possible exposure to extreme temperatures and pressures.

2.2 Past Development Activities

This technology development began with studying thermal and fluid dynamics of a thermal probe melting through ice and theoretical models were generated. Lab melting tests were performed to validate and evaluate the theoretical models. The tests created an empirical performance parameter matrix (See Table 1) and were used in designing the vehicle's melt systems. A prototype was created using the melt systems and its system performance was evaluated.

3 Motivation

3.1 Why Melt?

The decision to achieve deep subsurface access through melting is the result of specific requirements from exploration of icy environments. In general the Cryobot:

- Has advantages over conventional drilling since the hole is frozen closed behind the probe. A sealed hole allows melt pressures to increase above planetary surface pressures (near vacuum at Europa) to hydrostatic levels, which serves to keep the hole from collapsing. A sealed hole also allows the cryobot to acquire data in ice versus retrieving a slushy ice core, and that no exchange, takes place between the surface and the probe, for example of microbes.
- Requires no drilling fluid beyond the meltwater produced locally by the probe.
- Drilled debris are not mechanically removed.
- Has a smaller heat consumption and produces a smaller thermal shock in the ice than a traditional hot water drill and less heat is dissipated into the ice sheet.
- Is cheaper, generally, than a full coring operation by approximately a factor of 10.

The cryobot currently has some difficulties. One challenge is directly sampling the ice by retaining ionic and particulate impurities from the ice in the melt-water cavity. Another challenge is the method of recovering subsurface samples for ground based studies.

3.2 Science Motivation

Scientists are eager to employ the cryobot to study such relevant scientific objectives as terrestrial climate history, paleocirculation [6,7], and ice dynamics, Europan ocean and ice in-situ exploration, and Mars climate history, mineralogy, exobiology, and operational access to water. The mix of strong terrestrial and planetary science interests is crucial in supplying testing opportunities for robotic systems at terrestrial sites. In addition, costs may be shared among agencies and programs.

Since subsurface environments are protected from many surface processes, there is a science motivation to detect biosignatures of past or extant life in subsurface ice and melt-water. Just as Earth's polar regions teem with microscopic life, so may evidence of life be found under the Martian poles. Indirectly, the polar ice profile may reveal whether past climate conditions were more favorable to life. By examining the ice near the ice-water interface, the climate record of planetary obliquity excursions, global dust storms, volcanism, and impact events are preserved layers in the subsurface polar ice cap. As dust-laden melt-water

is circulated through the cryobot, the mineralogy of the planet may be revealed in its compositional analysis.

Due to ice structure variability with depth, the thermal probe vehicle needs to adapt to varying environmental conditions during descent. For example, terrestrial firn ice, found in the upper tens of meters of the surface decreases in porosity with depth, potentially requiring different energy input for mobility. The Cryobot must be capable of motion through ice, which is coldest on the upper surface and gradually warms at greater depths and pressures. The vehicle must also be capable of mobility through a liquid water environment, as the probe would be surrounded by water in the melt cavity. Martian polar ice has been seen to contain varying amounts of dust in a layered composition, and some of the dust may be soluble when in contact with liquid water. Ice on Europa and Callisto is thought to have an ionic composition. Therefore the Cryobot must be able to proficiently melt through ice containing varying concentrations of dust, sediment, and possible ionic compositions.

3.3 Engineering Motivation

The challenge is to send a subsurface device to another planet, have it perform autonomously in an unknown environment, and send data back to Earth. A Cryobot vehicle design has a good design trade balance within the known mission constraints. The current design envelope can accommodate a vehicle 1m x 0.12m diameter, a mass of 25 kg, less than a 1KW power consumption, descend >4km, penetrate ice/particle mixtures, and avoid obstacles (See Fig. 3). The Cryobot concept is also attractive because a limited number of mechanical devices are employed such as drill rigs and sample return systems. Because of this design scope, power generation and transmission became important. Thus efficient and optimized melting becomes a key driver in the Cryobot development. Many ideas from the oceanographic community concerning underwater remotely operated vehicles in the areas of pressure vessels, instrumentation, and tethers are used.

4 Methodology

4.1 How to Melt

This thermal probe, or Cryobot, will sublimate and/or melt solid/porous ice to change the phase of water to liquid or gas. The vehicle would then pass downward through an ice layer by letting the gas or liquid re-freeze behind the vehicle. The ice-melting behavior has impacts on power consumption. Clever ways of melting the ice were needed to achieve mobility. The main driver was an efficient means of transporting thermal energy to the ice.

The Cryobot moves by melting ice in front of (below) the vehicle and descending under the influence of local gravity. As the Cryobot moves, it is in a lozenge-shaped volume of water, which is freezing at the top as ice is force melted at the bottom. The Cryobot contains many distinct features for its success and development. The probe will have a hybrid of active and passive melting systems. This will be accomplished through combining a heated tip, water heating subsystem, and a jetting subsystem. Hot-water drilling relies on hot water being forced against a melting front so that there is enhanced heat exchange as well as the sweeping away of granular material [11]. The combination of passive and forced turbulent melting should address the principal problems, and modern techniques of fluid dynamics, monitoring, telemetering, and control will aid in improving design elements.

4.2 Passive Melting

Passive melting, accomplished by simply heating the nose of the probe, will accomplish the desired goal of melting the ice beneath the probe; it was the original approach of Philberth and the follow-on groups, and it worked. It has the drawbacks of being directionally unstable and of losing efficiency in the presence of significant particulate ice loading, when the thermal conduction from the probe to the ice is impeded. Passive melting is essential in porous ice, such as is found in the uppermost, or firn, layer of Earth's ice sheets, and of course it is the backup melting subsystem; therefore it is required in the Cryobot design.

4.3 Self-contained Active Melting

Self-contained active melting, in which the heat is exchanged into the ice through the turbulence of the jet, has not previously been attempted. It has the advantage of being easy to direct downward, and heat transferred is by vortex flow (See Fig. 4). The melt zone forms a parabolic shape in front of the cryobot. Measured thermal melting efficiency is approximately 80%. For a site such as the Mars polar caps, active melting has a crucial advantage of being able to function with substantial levels of particulates in the ice. On the other hand it is more complex than passive heating and requires pumping which generates electrical and mechanical noise.

Figure 4: Demonstration of Active Melting.

5 Thermal and Fluid Dynamics

The modeling performed for vehicle melting was thermodynamic and fluid dynamic analysis. The first step was to characterize passive melting dynamics. The next step was to understand water jet melting dynamics and develop performance parameters. We desired to have predictable and optimal performance capability. These parameters were compared with a matrix of tests thus creating a set of performance parameters to define the baseline design of the vehicle (See Table 1). System tests were completed to characterize the overall performance of the prototype vehicle and evaluate the performance of various subsystems (See Table 2).

Table 1: Cryobot Design/Penetration Parameters. [8]

Design Parameter	Value
Test ice temperature	-10 ºC
Available melt power	0.6-0.8kW
Cryobot length	1.25m
Cryobot diameter	12cm
Penetration rate (measured)	
-Passive melting	0.4m/hr
-Active melting	1m/hr
Water temperature (inlet)	5-6 ºC
Water temperature (nozzle)	20-25 ºC
Return water pressure	1-2bar
Jet velocity	10-20m/sec
Jet flow rate	1-1.5liters/min
Drilling efficiency	80-90%

5.1 Thermal Study

The first study characterized the icy environment thermally. Basic parameters of the far field ice were assumed for various applications, Earth, Mars, and Europa. The overall heat loss to the far field was calculated based on vehicle dimensions. We artificially constrained available power to 1kW to make the analysis realistic for various applications. Subtracting the far field heat loss from available power determined the resultant power for melting and thus descent (See Fig. 5). The next step was to study the passive melt methodology and determine the heat load required to melt ice for a given surface area and ice temperature. The assumptions were perfect contact with ice interface and that the melt water was squeezed out to flow up the sides of the cryobot. Descent rates were derived and compared with laboratory test data. These calculations gave a preliminary understanding of vehicle descent performance. The same analysis methodology was carried out for active water jet melting. The results showed slightly better descent performance over passive melting. From laboratory test data, it was determined that the smoothness of the resultant melted cavity revealed efficiency in melting. The passive melted cavities were more uneven, whereas the jet melted cavities were smoother. The last set of analysis helped us understand the re-freeze rate of the melted cavity. Thus a "wake distance" was established, which enable us to determine if the vehicle would descend too slowly and re-freeze in the melt cavity.

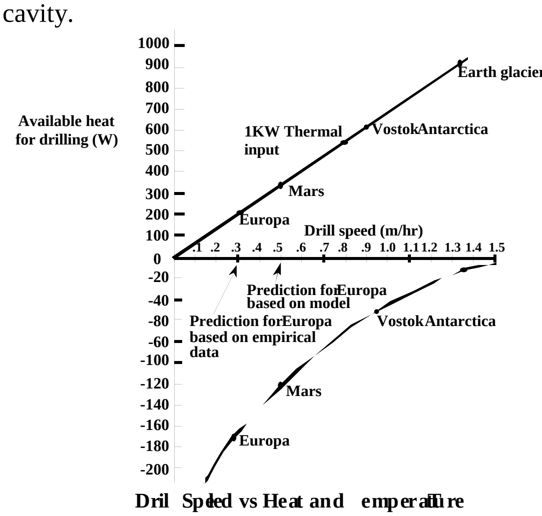

Figure 5: Drill Speed vs Heat and Temperature.

5.2 Fluid Study

From the encouraging results of the water jet melting performance, we needed to understand how the jet method transferred heat to the ice interface. A single jet stream down the vehicle's center to the ice was modeled. The model was arrived at empirically. The assumption of cavity shape was use in the modeling, based on previously described test data. Model inputs were jetting velocity, pressure head, jet temperature, and temperature leaving the melted cavity (See Table 1). The flow was assumed to be turbulent and a heat transfer coefficient was determined. The empirical model and lab tests were compared. We also discovered jetting melting performance had some dependence on nose shape. It is desired to continue the

study with a full fluid dynamic model with analytical simulation.

6 System Solution

6.1 Cryobot Vehicle

The cryobot is a robotic vehicle that has mobility in subsurface icy environments (See Fig. 2). Mobility is achieved by means of thermally changing the phase of the icy solid to a liquid or gas phase that the vehicle passes through. The nose of the device heats the icy medium. Cryobots are similar to remotely operated vehicles in the ocean. They carry avionics electronics to power and control the system. The cryobot can be used as an instrument payload. In the icy cavity, the cryobot's instrumentation suite can perform imaging, sampling, and a variety of scientific investigations. Depending on the application for a cryobot, the vehicle may be tethered. This enables power and signals to move to and from a surface station to the submerged vehicle. Power can be internal to the cryobot or surfaced supplied. The control system for a cryobot varies with complexity from manual control from a surface station to autonomous control. The current cryobot technology development has utilized off the shelf hardware.

The basic structure of the cryobot vehicle is cylindrical and divided into Bays: Nose, Pump, Instrument, Electronics, and Tether (See Fig. 6). The nose bay is the passive melt system and jetting nozzle; the pump bay contains the water jetting subsystem. The instrument and electronics bays use a pressure housing very common to oceanographic probes. The tether is used to supply power and serve as a data and command communication cable is spooled out of the vehicle during its descent into the ice; this bay is currently designed to store 500meters of tether. The vehicle must be controlled to maintain vertical orientation during passive melting. The system needs to engage water jet drilling and adjust for varying environmental conditions. The instrument suite will have to coordinate with the vehicle system for data and sampling collection. Currently a simple ground station is used for commanding the probe and recording the data telemetry.

6.2 Nose Bay

The nose bay helps achieve both modes of melting, passive and active. There are 4 quadrants of heater plates for passive heating and a centrally mounted nozzle for active melting (See Fig. 6). The four heater plate quadrants play a role in sustaining vertical orientation during passive melting. This is accomplished by differentially heating the quadrants to maintain vertical orientation. The cryobot's nose is capable of dumping 1000W of heater power onto the ice interface, or into the thin film of water under the nose. The shape of the nose and nozzle help play a role in active melting. The nozzle maintains the pressure and flow for warmed water and the nose shape aids in developing the vortex fluid flow for melting.

Figure 6: Nose Bay.

6.3 Pump Bay

This bay is used to heat and expel the warmed water through the nozzle in the nose. The melt water passes into the pump bay cavity for heating. Water immersion heaters can dump 1000W of thermal power to the water. The heated water passes thought the pump system to the nozzle. The pump bay is instrumented to monitor the performance during active melting. The measured parameters are flow rates, temperatures, and water pressures.

6.4 Instrument Bay

The instrument and electronics bays are housed inside a pressure vessel, where-as the other bays can function in the ambient temperature and pressure. Much of the pressure vessel technology is borrowed from oceanographic community, who use pressure vessels to house their instruments at the bottom of the ocean. Ports through the housing shell are provided to perform optical interrogations using windows, lenses, and illuminators. Thus, image detectors are mounted inside the cryobot. Sampling mechanisms can be added to sample the icy environment. For example, materials can be extracted from the ice wall matrix or water samples can be acquired through a port-membrane aperture.

6.5 Electronics Bay

The electronics bay contains elements to regulate power to the subsystems and to provide command and data handling for engineering instrumentation and communications. The cryobot uses a 400VDC bus voltage. This powers the heaters for passive and active melting. A shunt regulator is employed to protect the

electrical systems. Power converters are used to step the voltage down to 48VDC for use by the computer, instruments, and pump system. Signal conditioning is implemented to reduce noise in the electrical systems and to isolate the science instrumentation. The engineering instrumentation consists of multiaxis inclinometers, magnetometer, temperature sensors, moisture detectors, and current sensors.

6.6 Tether Bay

A critical element for the cryobot is the tether system. The tether bay holds the umbilical between the ground station and the subsurface vehicle. The tether passes power and signals by using wire conductors and fiber optics. The key issues in tether development are tether construction and packing the tether in the bay. The drivers in the design are temperature, mass, power, conductor size, data rate, and depth. Tether systems are practical for terrestrial operations of modest depth <4km. For operations on planetary missions, it is best to employ a tether for communication only. Planetary missions that are deeper, >4km, it is best to utilize an ice transceiver concept by sending signals through the ice medium. For those remote missions, advanced research is needed to place the power on board the cryobot.

6.7 Power and Control System

The ground station facilitates the power and control systems. For terrestrial operations, a generator and DC power supply are used. The power supply generates power for the cryobot and has to overcome the resistive losses over the tether length. High voltages are used to compensate for the tether's resistive load due to length. For planetary operations, mass and volume are at a premium. Supplied power would be in the form of photovoltaic hybrid power and/or radioisotope power. Cryobots are best served by radioisotope thermo-electric generator (RTG) power because of the extreme depths pursued and efficient use of heat generated from the radioisotope source. Roughly 200W is needed for electrical power and 800W are needed for dissipative thermal power depending on ice temperature.

In the terrestrial work, the control system is performed from the ground station. The cryobot elements to be controlled are orientation, power, instrumentation operations, descent rate, and obstacle avoidance. Many of these functions can be performed on board the system semi-autonomously. There is an operator at the surface station observing the state of the system and is part of the control loop. Autonomous control is highly desired, if not required, for planetary missions.

7 Testing

7.1 Passive Testing

The cryobot drilling mechanism in ice has two components, a passive drilling mode, and an active drilling mode. In the passive drilling mode, a heated nose piece is melting the ice in contact with it. The melt-water is squeezed radially along a film to the outer edge of the vessel. In the case of permeable firn the water is flowing into the pore spaces. The method is limited by the amount of heat that can be transferred without overheating the heating element. In our test case we reached a heat density of 21 W/cm^2. The passive method has limits in dust or debris laden ice. As the debris in front of the heated nose accumulates, forming an insulating heat shield, the drilling speed is drastically reduced.

7.2 Active Testing

In any environment where dirty ice is expected, an active drilling mode is a necessity. This method uses a vigorous jet of heated water from a nozzle in the center of the nose piece. The water hits the ice and forms a conical water filled cavity in front of the nozzle about 30 cm deep. The warm water rotates in a vortex transferring its heat into ice, causing a phase change before it flows past the outside cryobot walls to the back from where it is recycled to the pump that drives the water jet. This active jet stream also works in debris laden ice because it stirs up the dust and particulates and holds them in suspension. For that reason an active jetting system can drill much deeper that a passive system alone. This method does not work well in permeable firn because the water for recycling is lost.

We conducted a comprehensive testing program to determine the optimal choice for the adjustable parameters, such as power to the heating pads, nose shapes, drilling nozzle sizes, water flow rate, water temperature, drilling speed (See Table 1)(See Fig. 7). For a given power supply of about 1 kW and a cryobot diameter of 12 cm, we obtain a drilling speed of 0.2 (Europa) to 0.8m/hr (Earth), depending on the ice temperature. The drilling efficiency is 80-90% defined by the ratio of maximum attainable drilling speed for ideal borehole diameter to the actual drilling speed.

Figure 7: Cryobot testing lab. Figure 8: 5m Melt Test.

Table 2: Summary of Cryobot Melt Tests [8]

Test Parameter	Results/Observations
Total melt distance	5m
Total elapsed melt time	11.2 hrs
Average power	418kW
Average descent rate	43.4cm/hr

7.3 Field Testing

In addition we conducted field tests on Ice Stream C, Antarctica, using a passive drilling prototype in the upper -26 ºC cold firn layer. This gave us additional insight into the dynamics of drilling in porous cold firn that could not be easily simulated in lab experiments. At low drilling speeds the passive method became very inefficient, because of re-freezing of the water percolating down into the firn. Active drilling tests in ice containing dust of various particle sizes and densities have been initiated.

8 Conclusions

Cryobot technology is a viable answer to gaining access to icy subsurface environments, such as planetary polar regions of Earth and Mars, and icy satellites such as Europa and Callisto. The subsurface presents a unique pristine environment to study exobiology, planetary evolution, and geochemistry. The cryobot moves vertically down by melting ice below the vehicle to. This method of subsurface access is desirable over conventional drilling methods for planetary exploration because of mass and mechanism issues. Thus, the design challenge is power for the cryobot. To reduce needed power, thermal analysis of melting ice was performed to model the heat flow to the ice. The modeling effort resulted in cryobot prototype design parameters. A prototype was built from those parameters and tested. The results have been promising (See Fig. 8)

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10 Acknowledgements

The authors wish to acknowledge the research and development by the Cryobot Team effort. Mechanical engineering: Jason Feldman; Electronics engineering: Greg Pixler, Sung Park, Dr. WaiChi Fang, Robert Ivlev, and Joseph Tosczylowski; Control System: Dr. Robert Bonitz and Dan Helmick; System engineering: Corey Harmon, and Emily Eelkema; Testing environments: Dr. Jacklyn R. Green. The Cryobot website: Adrian Downs (http://fuego.jpl.nasa.gov).
This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).