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Testing of a 1 meter Mars IceBreaker Drill in a 3.5 meter Vacuum Chamber and in an Antarctic Mars Analog Site

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In this paper we report on the development of a rotary-percussive sampling drill: the IceBreaker. The purpose of the drill is to penetrate at least 1 meter in icy-regolith and in ice, and acquire sub-surface sample for science analysis. The drill was tested at a Mars analog site in the Dry Valleys of Antarctica and inside a 3.5 meter vacuum chamber in icy-soil, ice and ice with 2% perchlorate. In all cases, the drill reached ~1 meter depth in approximately one hour. The average power was 100 Watts and Weight on Bit was less than 100 Newton. This corresponds to the drilling energy of 100 Whr. In each case approximately 500 cubic centimeters of sample was recovered and deposited into sterile bags.

I. Introduction

The ultimate goal of NASA's Mars Exploration Program is to determine if Life ever arose on the planet. There are two strategies to answer the question of life on Mars: (1) search for extinct life in sediments that formed billions of years ago, when conditions on the surface were more hospitable; or (2) search for extant life in carefully selected environments, where microorganisms could have survived in an active or dormant state up to recent times.

Currently missions to search for extant life on Mars are considered ”high risk-high payoff”, and therefore are not given a top priority in the Mars program. This is so because the surface of the planet is seemingly uninhabitable, and the chances of finding extant life are very small (high risk). However, if extant life was found, it would represent one of the major breakthroughs in human history (high payoff). In order to diminish the intrinsic risk of missions that search for extant life on Mars, it is necessary to identify the environments more likely to host extant organisms. Recent developments in our understanding of life in extreme environments on Earth, particularly those that are similar to Mars (cold and dry), suggest that there is only a very limited number of near-surface environments on Mars that could host active or dormant microorganisms until recent times (Davila et al. 2010). Hence, if these environments are accessible, missions that search for extant life on Mars would become “low risk-high payoff” and hence top priority.

For decades, Mars missions have focused on the search for water. This is so because water is the single most important requisite for life as we know it. It is now well established that water exists in the shallow subsurface of Mars in polar latitudes (Smith et al 2009). This was confirmed by the 2008 Mars Phoenix Lander, which exposed,

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sampled and analyzed ground ice in the Martian Arctic. Ground ice at the Phoenix landing site is so close to the surface (up to 4.6 cm below the surface), that during high obliquity cycles the ice table temperature could rise above freezing, and therefore liquid water, and life, would be theoretically possible (Costard et al. 2002; Stoker et al. 2010), particularly since viable microorganisms have been preserved under frozen conditions on Earth for thousands and sometimes millions of years (e.g., Gilichinsky et al. 1992). Additionally, the Phoenix Lander discovered perchlorate (ClO_4^-) at concentrations of 0.4 to 0.6% by mass in the soil (Hecht et al. 2009). Perchlorate is a soluble salt with a low eutectic temperature (i.e., $Mg(ClO_4)_2$ freezes at -68.6ºC). Due to the low freezing point, liquid brines of $Mg(ClO_4)_2$ would be stable for short periods of time at the Phoenix site (Chevrier et al. 2009; Renno et al. 2009), thereby increasing the potential for extant life. Further, microorganisms on Earth can use ClO_4^- as an electron acceptor (Coates and Achenback 2004), hence ClO_4^- could form a viable redox couple with any organic material or iron-rich basaltic rock on or near the surface. Finally, the Phoenix Lander detected calcium carbonate ($CaCO_3$) in the dry soil above the ice at the 4-5% wt, implying relatively recent liquid water reactions that formed carbonic acid and carbonate. Taken together, results from the Phoenix mission suggest that ground ice in the Martian Arctic has the highest potential to contain extant microorganisms (Stoker et al. 2010).

Shallow subsurface ice has also been confirmed by recent small craters in the mid-latitudes of Mars, where the impacts exposed shallow ice (Byrne et al., 2009); the presence of ice at these latitudes was already suggested by the Gamma Ray Spectrometer (GRS) results (Boynton et al., 2002; Feldman et al., 2002). It is estimated that the Viking 2 Lander would have needed to dig just ~10 cm further down to reach ice. At these mid-latitudes, the current conditions are milder than those experienced in the polar regions, however, obliquity changes would also not result in a similarly large increase in maximum summer temperatures. The mid-latitudes of Mars provide a second location of high interest in the search for extant Mars life.

The next step in the search for extant life on Mars is therefore to drill into the ground ice, sample the ice-rich soils, and search for evidence of life in them. Drilling into ground ice is not only a means to obtain ice-rich samples, but it is also a strategy to access samples that are relatively protected from the high levels of radiation that reach the surface of the planet. Based on results from the Phoenix Lander, drilling into ground ice at high- or mid-latitudes on Mars requires the drill to be compatible with heterogeneous regolith (i.e., dry soil above ice-rich ground), with hard embedded volcanic rocks or impact breccia, and capable of drilling through frozen materials, which could however liquify due to the presence of low eutectic salts such as perchlorate.

In this paper we describe the IceBreaker Drill, a one meter class drill and sample acquisition system enabling subsurface exploration of Mars. The drill employs rotary-percussive action, which reduces the Weight on Bit (WOB) and also energy consumption (Zacny et al., 2007; Paulsen et al., 2010). This is especially important if the drill is deployed from a low-mass platform in a low g environment. The passive sample acquisition system delivers drilled cuttings directly into a sample cup or an instrument inlet port. The IceBreaker was tested in a vacuum chamber and penetrated water-ice at -20°C and water-ice with 2% perchlorate at -20°C to a depth of 1 meter. The system was also field tested at the Mars analog site in the Dry Valleys, Antarctica. The Dry Valleys of Antarctica are the only environment on Earth with heterogeneous regolith similar to that found at the Phoenix landing site, i.e., dry frozen regolith overlying ice-rich regolith with embedded volcanic rocks. The Icebreaker Drill successfully penetrated to 1 meter depth in ice-cemented ground and to 2.5 meter depth in massive glacier ice, and acquired samples into a sample bag. During the chamber and field testing, the IceBreaker demonstrated drilling at the 1-1-100-100 level; that is it penetrated 1 meter in approximately 1 hour with roughly 100 Watts power and less than 100 Newton Weight on Bit. This corresponds to a total drilling energy of approximately 100 Whr/meter.

The drill system achieved high enough technology readiness to be considered as a viable option for future Mars missions such as a Discovery mission to the Northern Polar Regions of Mars.

II. Description of the IceBreaker Drill

The IceBreaker drill system (**Figure 1**) consists of the following subsystems 1) Drill Head, 2) Auger with a bit, 3) Z-stage, 4) Electronic Ground Support Equipment (EGSE) and 5) Sampling Station. The follow on sections will describe each of these in detail.

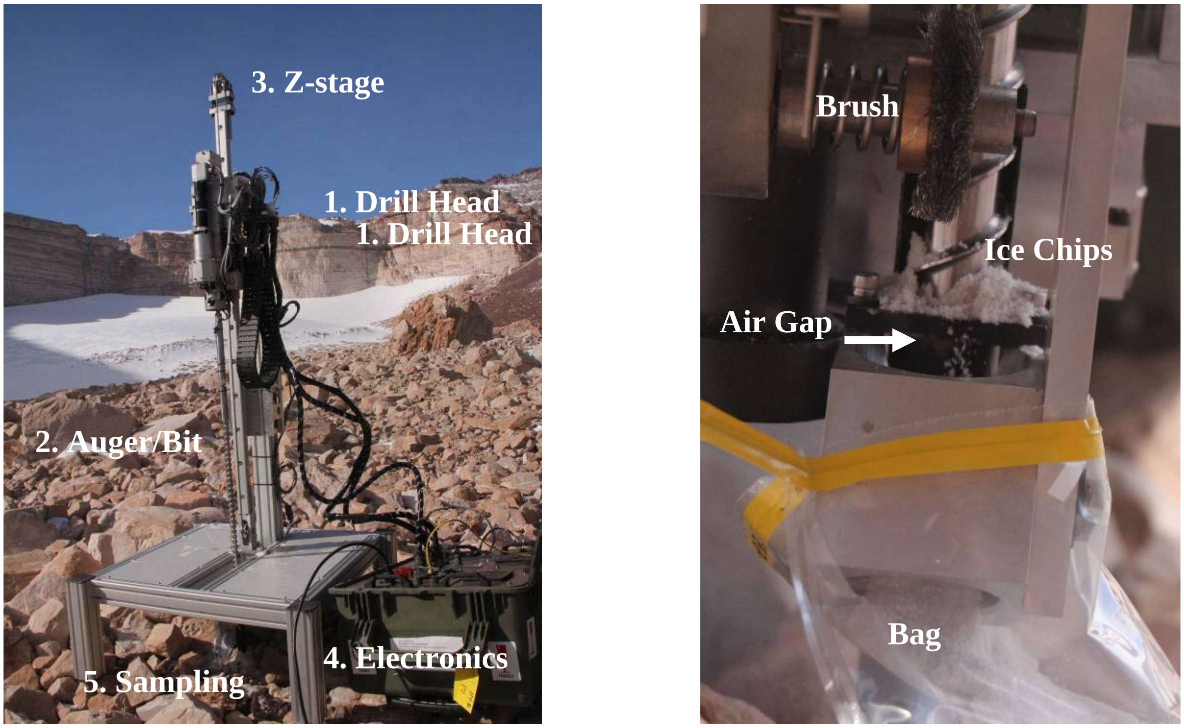

Figure 1. Left: The components of the IceBreaker Mars Drill: 1. Rotary-Percussive Drill Head, 2. Sampling Auger with a bit, 3. Z-stage, 4. Electronics, 5. Sampling System. Right: Sampling System included a brush and gravity feed. The ice chips gravity fall into a bag. Air gap is clearly visible. The drill is shown deployed in Dry Valleys, in the Antarctica's Mars analog site, in November of 2010.

1. *Rotary Percussive Drill Head*

The drill head consists of two independent actuators for rotating of the auger and for driving of the percussive system. Having two actuators allows three distinct drilling modes: rotary, rotary-percussive and percussive. This is particularly advantageous when drilling in a variety of formations with different strengths. For example, one would use rotary-only drilling in softer formations and by doing so saving the energy. In harder formations, though, the rotary-percussive mode could be engaged. With percussion the drill could efficiently drill as Weight on Bit less than 100 Newton in rocks as hard as basalt. The total power of the drill head is 350 Watt. This is sufficient to deliver 2.5 Joules per blow at 13.5 Hz at rotational speeds of 100 revolutions per minute (rpm). The 350 Watt drill head is 70% efficient, thus 250 Watt can be delivered into the formation (remaining 100 Watt is lost through friction and dissipated as heat).

2. *Auger with a drill bit*

The auger length is just over 1.2 meter and its diameter is 25 mm. Since the auger penetrates up to 1 meter deep, the total volume of formation sampled is ~ 500 cm^3. The lower section of the auger has deep flutes with low pitch to enable retention of drilled cuttings, while the upper part has steeper and shallow flutes to prevent borehole collapse. The bit at the end of the auger is designed for rotary as well as rotary-percussive action. A thermocouple is also integrated inside the bit to monitor the bit temperature and in turn the temperature of the regolith during the drilling process. Monitoring the temperature is important when drilling icy-soils and ice, since overheated ice can melt to form liquid water and/or mud. This mud will travel up the auger flutes and refreeze, blocking the flow of cuttings. It can also refreeze onto the borehole wall, trapping the auger inside the hole.

3. *The Z-stage*

The Z-stage advances the drill up to one meter below the surface and it is also used to retract it. The Z-stage has integrated load cells that monitor the Weight on Bit. The Z-stage in turn limits the WOB to 100 Newton during nominal operations (the 100 Newton limit is motivated by assumed lander mass and Mars gravity). The pull force generated by the Z-stage can be very high, since the force can be reacted against the ground.

4. Sampling System

The Sampling System consists of the auger tube and two independent and purely passive cuttings transfer systems: Passive Brush and Gravity Feed (see **Figure 1**).

The 10 cm auger tube encasing the auger section above the ground extends the borehole above the ground (during the drill deployment, this tube is initially lowered and pressed firmly against the ground). Thus, the cuttings produced by the drill can be augered additional 10 cm the ground (or even to the lander deck if the tube is long enough).

The upper section of the sleeve has a 180° cutout for a passive brush and also allows the cuttings to gravity fall out. The passive brush is co-located with the flutes and forms a “worm gear” configuration with the auger. Thus, rotation of the auger spins the brush.

If the cuttings are not sticky, they will fall down into a cup or an instrument inlet port. If they are sticky (for example due to liquid-water) they will be brushed off using the brush. This dual sampling system has been tested in the Antarctic with sticky and non-sticky cuttings and worked successfully in each case.

III. Testing of the IceBreaker Drill

The IceBreaker drill was tested in two complementary environments: a vacuum chamber and at a Mars analog site in the Dry Valleys, Antarctica. Testing in a vacuum chamber offered a highly controlled environment and conditions similar to what the drill will encounter on Mars with respect to temperature, pressure, and formation properties. Testing in the Antarctic offered geological uncertainty, air (in addition to the ground) temperatures below freezing, and remoteness, which makes drilling operations challenging since the system cannot be fixed easily if something goes wrong.

A. Drilling at the 1-1-100-100 Level

The drilling data was evaluated based on the Honeybee developed 1-1-100-100 benchmark. The 1-1-100-100 benchmark refers to drilling to 1 meter depth in 1 hour with 100 Watts of power and 100 Newton Weight on Bit. Note that 100 Watt power refers to power going into the formation and not the power of the drill head (i.e., does not take mechanical losses into account). The four parameters: depth, time, power and WOB can be used to calculate other valuation metrics such as drilling energy or drilling specific energy. For example, if a drill penetrates to 1 meter in 1 hour with 100 Watts, the required drilling energy is then 100 Whr (i.e., equivalent to a 100 Watt light bulb for 1 hour).

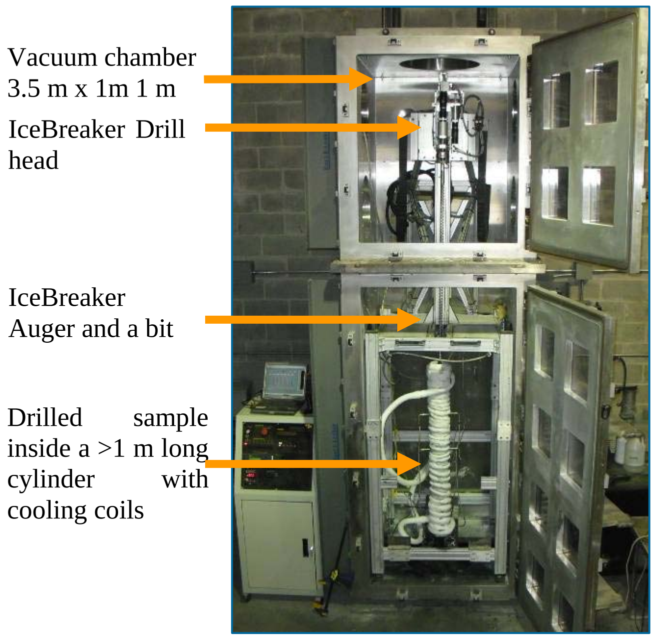

Figure 2. 3.5 meter vacuum chamber with integrated IceBreaker drill. The sample was placed inside a 1 m long cylinder below the drill.

B. Testing in Vacuum Chamber

A number of tests were performed inside a vacuum chamber in ice and ice mixed with 2% perchlorate. The chamber shown in **Figure 2** is 3.5 meter x 1 meter x 1 meter in size, was designed and built specifically for performing drilling and excavation tests under Mars conditions. The chamber is conveniently box-shaped with large doors featuring twelve windows; each 25 cm x 25 cm. The chamber has many electrical and fluid feedthroughs along its side and back walls as well as large 50 cm flanges on the top and the bottom allowing the integration of top or bottom cylinders to extend the chamber length beyond 3.5 meters.

The test sample was placed inside a steel cylinder with cooling coils. Freezing was achieved via 150 Watt cooling capacity at -25 °C.

Figure 3 shows the drilling telemetry to a maximum depth of 100 cm. Note that the Y-axis values have to be multiplied by the scaling factor (0.1 or 0.01) in the legend to obtain the actual values. Auger power refers to the rotary power, Perc. Power refers to the power generated by the percussive mechanism, while WOB stands for Weight on Bit.

During the 100 cm test, the total power was below 80 Watts, the WOB was < 100 Newton, and the drilling time was ~1 hour. Thus, the energy was ~ 60 Whr (average power was 60 Watt). These vacuum tests therefore demonstrated drilling at 1-1-100-100 level, that is ~1 meter in ~1 hour with ~100 Watts power and ~100 Newton Weight on Bit. The required energy to drill to 1 meter depth was ~ 100 Whr.

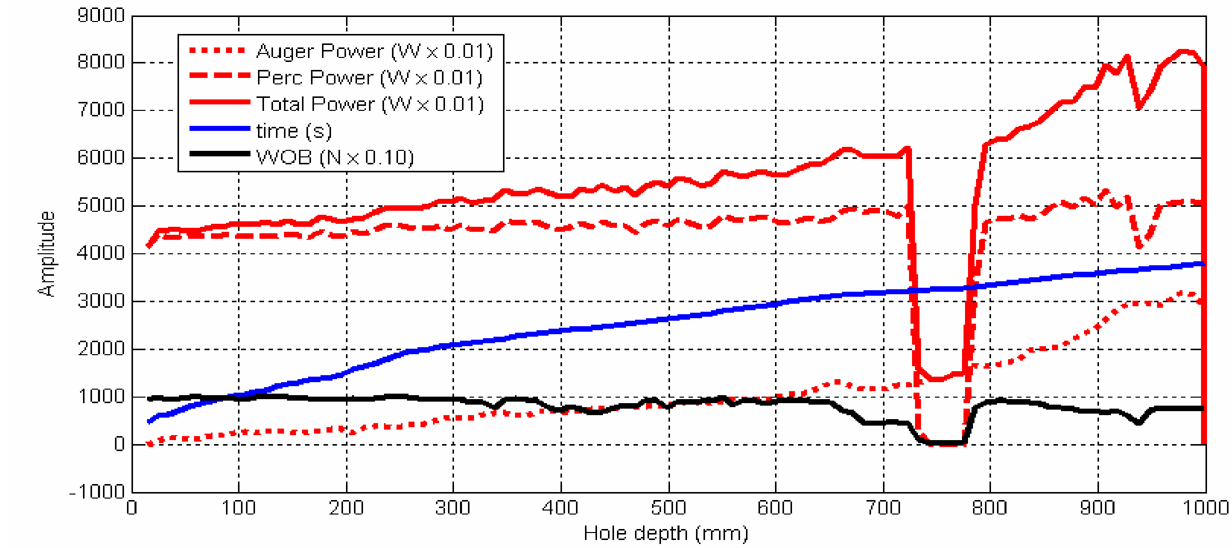

Figure 3. IceBreaker drilling data in ice at -20°C during tests in a vacuum chamber (6.4 torr pressure). The WOB refers to the Weight on Bit. Amplitude on the Y-axis has to be multiplied by the correction factor indicated after each parameter in the legend. For example, to get the WOB value, the Y-axis value of ~1000 has to be multiplied by 0.10 to get 100 Newton.

Figure 4 shows the environmental and thermal data. A number of thermocouples were embedded inside the sample at different distances from the center of the cylinder to monitor the temperature of the icy-soil. These temperatures (Temp 2, 3, 4, and 5) were always at approximately -20 °C. The air temperature was at 22 °C (the atmosphere inside the chamber was not cooled because cooling of 3.5 m x 1m x 1m volume would take a lot of LN_2 and time). The chamber pressure was 6.4 torr vacuum, while relative humidity was less than 10%. **Figure 4** shows that the bit temperature was approximately 5 °C above the formation temperature at the drilling power of ~60 Watt. Hence the drilled formation was always frozen during the drilling process.

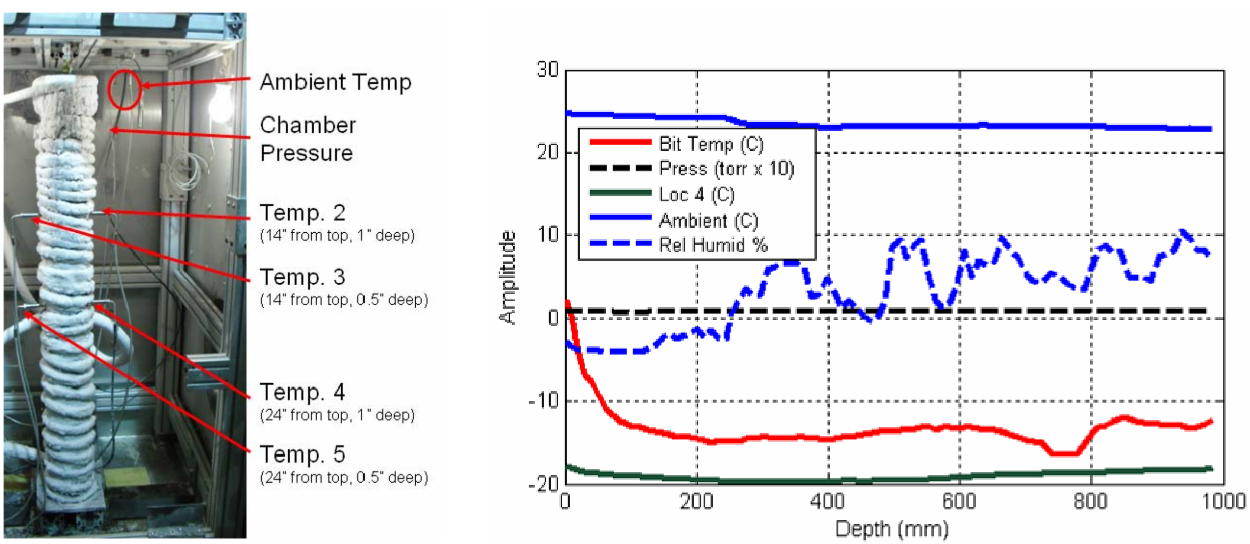

Figure 4. IceBreaker Thermal data in ice at -20 °C. Temperatures at locations 2, 3, 4, and 5 were the same hence only one is plotted (temp 4). The formation temperature was at -20 °C while the bit temperature was below -10 °C.

Figure 5 shows the drilling telemetry to a maximum depth of 100 cm in ice with 2% perchlorate. As before the Y-axis values have to be multiplied by the scaling factor (0.1 or 0.01) in the legend to obtain the actual values. Auger power refers to the rotary power, Perc. Power refers to the power generated by the percussive mechanism, while WOB stands for Weight on Bit.

During the 100 cm test, the total power was below 80 Watts, the WOB was < 100 Newton, and the drilling time was ~2 hours (i.e. 1 hour longer than in pure ice). Thus, the energy was ~ 120 Whr (average power was 60 Watt).

Figure 6 shows the environmental and thermal data during tests in ice with 2% perchlorate. The data is very similar to the tests conducted in pure ice.

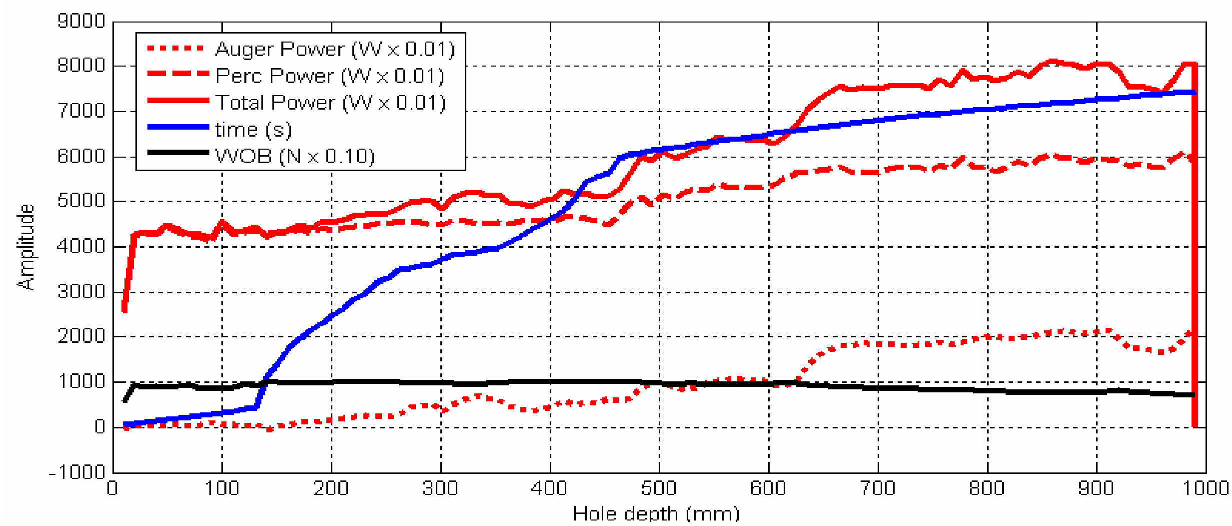

Figure 5. IceBreaker drilling data in ice at -20°C with 2% perchlorate during tests in a vacuum chamber (6.4 torr pressure). The WOB refers to the Weight on Bit. Amplitude on the Y-axis has to be multiplied by the correction factor indicated after each parameter in the legend. For example, to get the WOB value, the Y-axis value of ~1000 has to be multiplied by 0.10 to get 100 Newton.

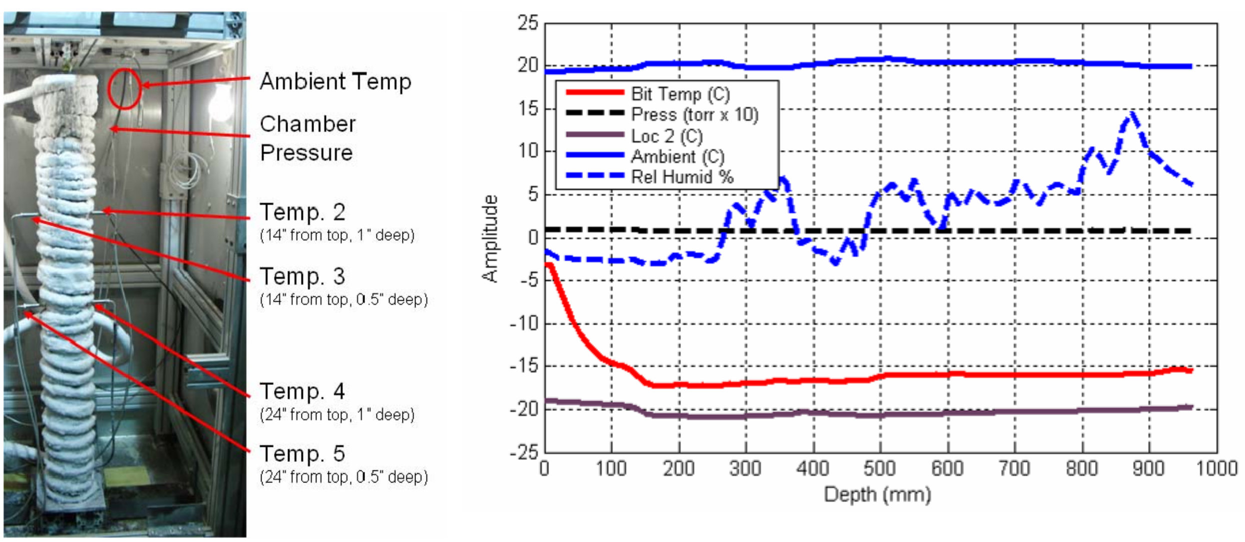

Figure 6. IceBreaker Thermal data in ice at -20 °C with 2% perchlorate. Temperatures at locations 2, 3, 4, and 5 were the same hence only one is plotted (temp 4). The formation temperature was at -20 °C while the bit temperature was below -10 °C.

Testing in the Antarctic Mars Analog

The Antarctic Mars analog drill site was located in the McMurdo Dry Valleys – see **Figure 1**. The tests were performed in dry regolith overlying ice-cemented ground (depth to ice table ca. 15 cm) to a depth of 1 meter (the ground was at - 19°C) and in massive ice at -25°C to a depth of 2.5 meters. The location of the ice-cemented ground test was S 77° 51.891', E 160° 48.029', Elevation: 1709 m. The location of the massive ice test was S 77° 51.950', E 160° 48.418', Elevation: 1724 m.

In each case, the drill was placed on a ~5-10° slope to demonstrate off-vertical operation. The drill followed the "bite" sampling routine (called "peck drilling" in machine shop terminology): samples were collected in 10 cm intervals. After drilling a 10 cm hole, the drill was retraced and lowered back into the hole for the next 10 cm "bite". During this time, cuttings were augered up and out of the hole and either gravity fell into a plastic jar or were brushed off of the auger flutes with a passive brush as the drill was being pulled out (see). After acquiring the samples from each 10 cm interval, the content of the jar was emptied into sterile bags and the jar was attached back onto a sampling system.

Figure 7. Samples collected during drilling at the Mars analog site in the Antarctic.

Drilling operations included executing three commands: SEEK (find the bottom of the hole, or the top of the ground), DRILL (drill the hole), and RETRACT (retract the drill out of the hole). This pattern is currently being used to operate of Rock Abrasion Tool on Mars Exploration Rovers. The drilling software also included a number of subroutines to monitor the drill state, such as the Temperature routine and the Energy routine.

For the Temperature routine, the bit temperature data was fed into the drilling algorithm, and the drilling operation would slow down to keep the bit temperature below certain value.

The Energy routine included monitoring the WOB and penetration rate and turning the percussive actuator on only when encountering harder formation.

Figure 8 and **Figure 9** show the drilling data in ice cemented ground and in massive ice-respectively.

The depth of 1 meter in ice cemented ground was reached in 50 minutes (penetration rate was 1.2 m/hr). During this time, the maximum power was ~ 120 Watts, while the average WOB was <90 Newton. The total drill energy to reach 1 meter and sample ten, 10 cm intervals, was 100 Whr. Hence, the IceBreaker again demonstrated drilling at the 1-1-100-100 level.

Note that the percussive and the total power increased at ~100 mm depth. This was the depth to ice-cemented ground. Between the surface and 10 cm depth, the soil was dry and in turn easy to penetrate. Below the 10 cm depth the drill encountered icy-soil, which was as hard as ~40 MPa rock (Ma et al., 2001; Hongsheng et al., 2002). Hence from 10 cm depth onwards the percussor was automatically turned on to maintain steady penetration rate at low WOB.

Figure 9 shows the drilling telemetry in massive ice to a depth of 2.5 meters. The total power reached 150 Watt at the depth of 2.5 meters due to parasitic losses (auger rubbing against the borehole) and the large distance the ice chips had to be moved to the surface. In this test, it seems that the auger was quite effective to 2 meter depth with clearing of cuttings but just below 2.5 meter, the auger power started to increase almost exponentially. Note that the increase in power was not due to drilling into a harder substrate, since the bit temperature remained low at -20°C during the entire drilling process. In this test, the WOB was < 90 Newton, while the time to reach the 2.5 m depth was less than 2.5 hours. Hence the total energy was ~250 Whr or 100 Whr/meter.

Note that the bit temperature in both tests was always below freezing and this prevented cuttings from sticking. As opposed to the chamber tests, where the atmospheric temperature inside the chamber was at +22°C, the air temperature in the Antarctic was always below freezing. Hence the entire drill system, including the auger, was cold. The drill string acted as a heat pipe, helping to dissipate heat during the drilling operation. Although the auger during the chamber tests also acted as a heat pipe, it was moving heat from the outside and into the formation (since the outside was warmer).

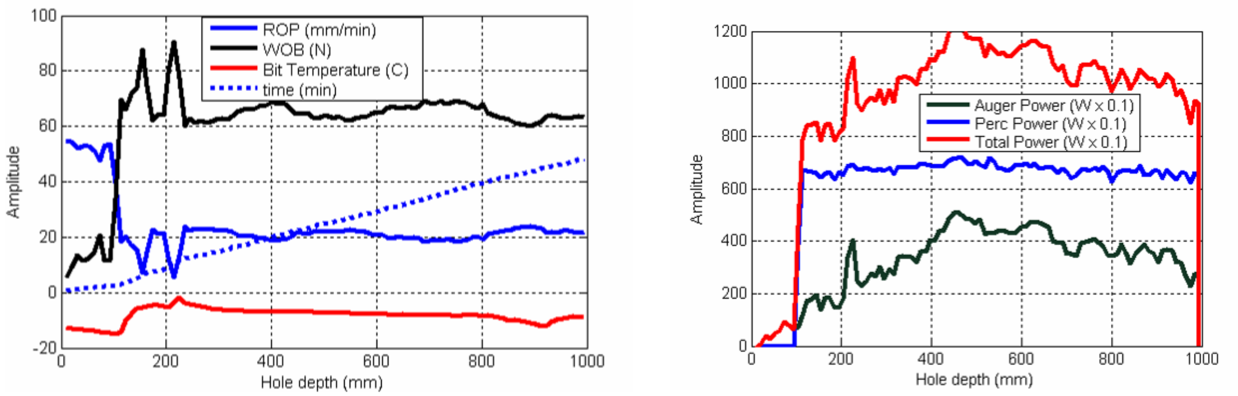

Figure 8. IceBreaker drill telemetry during tests in the ice-cemented ground in the Antarctica's Mars analog site.

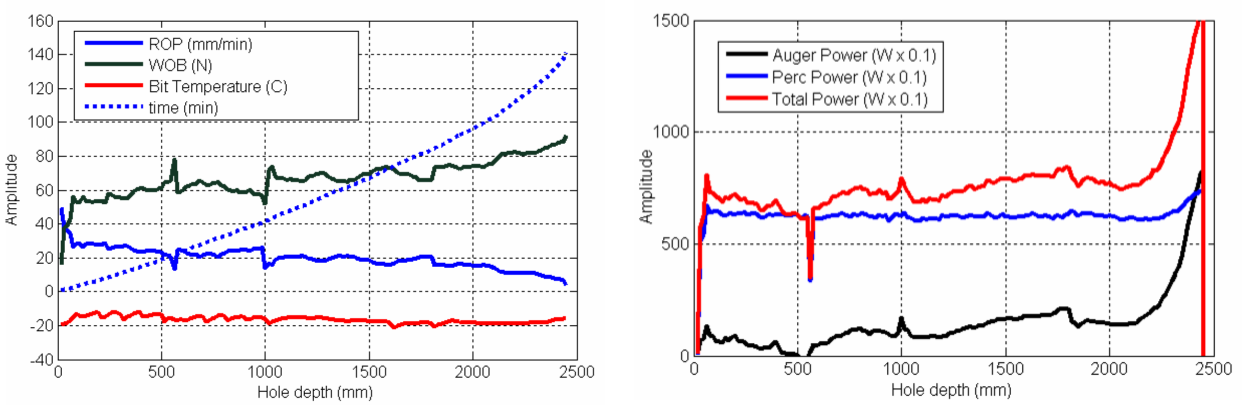

Figure 9 IceBreaker tests in massive ice in the Antarctica's Mars analog site. The test data shows Weight on Bit (WOB), Time, Rate of Penetration, Temperature of a drill bit, Auger Power (rotary-power), Percussive Power, and Total Power.

IV Conclusions

The IceBreaker drill described in this paper has been developed from a very low TRL to TRL of 5/6. The system was tested in a vacuum chamber under Mars-like conditions of low temperature, pressure, and soil simulants, as well as at an analog site in the Antarctic.

The system demonstrated drilling at 1-1-100-100 level; that is the drill penetrated 1 meter in 1 hour with 100 Watts and 100 Newton Weight on Bit. The required drilling energy was ~ 100 Whr. At the same time, the temperature of the drill bit measured by an embedded thermocouple did not exceed 8°C above the formation temperature.

The drill was operated semi-autonomously with only three high level commands and autonomous subroutines such as the Temperature and the Energy routines. The high level commands included: SEEK, DRILL, and RETRACT. Drill health monitoring was performed autonomously using drilling telemetry and bit temperature data. The Icebreaker Drill successfully drilled and recovered samples from up to 1 meter depth in heterogeneous regolith containing ice-cemented sediments and hard volcanic rocks, and up to 2.5 meters in massive glacial ice, even in the presence of a low eutectic salts such as perchlorate. These results demonstrate that drilling and sampling the ice-rich regolith in the Martian Arctic and mid-latitudes is technologically feasible, therefore paving the way for future life detection missions on Mars. The IceBreaker drill is currently being designed for future Mars missions, in the Discovery class.

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