

Subsurface Ice and Brine Sampling Using an Ultrasonic/Sonic Gopher for Life Detection and Characterization in the McMurdo Dry Valleys

Y. Bar-Cohen[1], S. Sherrit[1], Z. Chang[1], L. Wessel[1], X. Bao[1], P. T. Doran[2], C. H. Fritsen[3], F. Kenig[2], C. P. McKay[4], A. Murray[3], and T. Peterson[5]

[1] JPL/Caltech, 4800 Oak Grove Dr, M-S 82-105, Pasadena, CA 91109 USA email: yosi@jpl.nasa.gov,
[2] University of Illinois at Chicago, Earth and Environmental Sciences, 845 West Taylor Street (MC186), Chicago, IL 60607 USA email: pdoran@uic.edu or fkenig@uic.edu,
[3] Desert Research Institute, Division of Earth and Ecosystem Sciences, 2215 Raggio Parkway, Reno, NV 89512 USA email: cfritsen@dri.edu or alison@dri.edu,
[4] NASA Ames Research Center, Division of Space Science, Moffett Field, CA 94035 USA, email: cmckay@mail.arc.nasa.gov
[5] Cybersonics, Inc., 5368 Kuhl Rd., Erie, PA 16510, 814-899-4220, tom.peterson@nuvosurgical.com

ABSTRACT

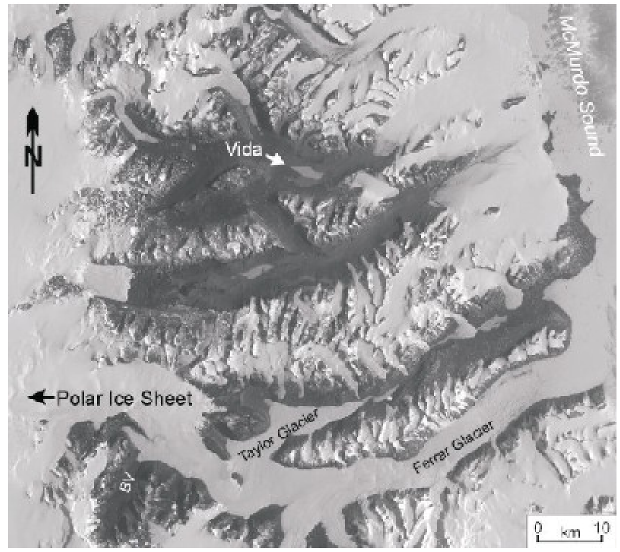
There is growing evidence for ice and fluids near the surface of Mars with potential discharge of brines, which may preserve a record of past life on the planet. Proven techniques to sample Mars subsurface will be critical for future NASA astrobiology missions that will search for such records. The required technology studies are underway in the McMurdo Dry valleys, Antarctica, which is serving as a Mars analog. The ice layer on Lake Vida in the dry valleys is estimated to be 20-meter thick where below 16-m depth there is a mix of ice and brine, which has never been sampled directly due to logistical constraints. A novel light weight, low power ultrasonic/sonic driller/corer (USDC) mechanism was developed that overcomes the need for high axial loads required by drilling via conventional techniques. The USDC was modified to produce an Ultrasonic/Sonic Gopher that is being developed to core down to the 20-m depth for in situ analysis and sample collection. Coring ice at -20^{o}C as in Lake Vida suggests that it is a greater challenge and current efforts are focused on the problems of ice core cutting, ice chip handling and potential ice melt (and refreezing) during drilling. An analytical model and a prototype are being developed with an effort to optimize the design while addressing the thermal issues, drilling rate, power, mass and the electromechanical behavior.

Keywords: USDC, Life detection, Ultrasonic/sonic Gopher, Planetary sampling, Ice drilling

1. INTRODUCTION

NASA exploration missions increasingly are required to perform sampling, in-situ analysis and possibly the return of samples to Earth for further tests. Evidence for ice and fluids near the surface of Mars in both the distant and recent past is growing with each new mission to this planet [Malin and Edgett, 2000; and Mitrofanov et al., 2003]. One explanation for fluids forming spring-like features on Mars is the discharge of subsurface brines [Doran and Forman, 2000; Malin and Edgett, 2000]. Brines offer potential refugia for extant Martian life and near surface ice could preserve a record of past life on the planet. Proven techniques to get underground to sample these environments, and get below the disruptive influence of the surface oxidant and radiation regime, will be critical for future astrobiology missions to Mars. The authors are developing this technology under a NASA's Astrobiology for Science and Technology for Exploring Planets (ASTEP) task. This task has the goal to develop and test a novel ultrasonic/sonic corer in a Mars analog environment, the McMurdo Dry valleys, Antarctica, and to detect and describe life in a previously unstudied extreme ecosystem, Lake Vida (Figure 1), an ice-sealed lake [Doran et al., 2003].

FIGURE 1: Landsat image of the dry valleys region showing location of Lake Vida. The image is centered at 77.5°S 162°E.



Existing drilling techniques are limited by the need for large axial forces and holding torques, high power consumption and inability to efficiently duty cycle, as well as the use of heavy equipment. To address these limitations the JPL's NDEAA team and engineers from Cybersonics, Inc. jointly developed the ultrasonic/sonic driller/corer (USDC) [Bao et al, 2003; and Bar-Cohen et al 2004]. Following the development of this novel mechanism (see Figure 2) the team has conceived many innovative designs that were disclosed in NASA New Technology Reports and patents [e.g. Bar-Cohen et al, 1999; and Bar-Cohen et al, 2001]. In 2000, the USDC received the R&D Magazine award as one of the 100 most innovative instruments of the year. This drilling/coring mechanism requires low axial force, thereby overcoming one of the major limitations of planetary sampling using conventional drills in low gravity environments. This capability offers users on Earth the advantage of being able to perform tough tasks of drilling and coring in hard rocks and concrete using relatively small force and relatively lightweight hardware. The USDC was demonstrated so far to: 1) drill ice and various rocks including granite, diorite, basalt and limestone, 2) not require bit sharpening, 3) operate at low and high temperatures, and 4) operate at low average power using duty cycling. The capabilities that are currently being investigated include probing the ground to select sampling sites, collecting various forms of samples (including cores and powdered cuttings), sampling long cores of hard basalt using low power and hosting sensors for measuring various properties. A series of modifications of the USDC basic configuration were implemented in the form of an Ultrasonic/sonic Rock Abrasion Tool (URAT), the Lab-on-a-drill, and the Ultrasonic/Sonic Gopher for deep drilling (see Figure 3). The U/S Gopher is the focus of this paper and it is being developed as a coring mechanism to reach the depth of 20-m in Lake Vida while acquiring samples for life detection analysis. The developed device is expected to be lightweight for operation from a rover to perform deep coring and sample acquisition for ices and brines (and associated sediments) that may exist on Mars and/or in pockets in the shallow ice cover of Europa.

FIGURE 2: A photographic view of the USDC coring in Sandstone with minimum axial force (left), and a schematic diagram of its cross-section (right).

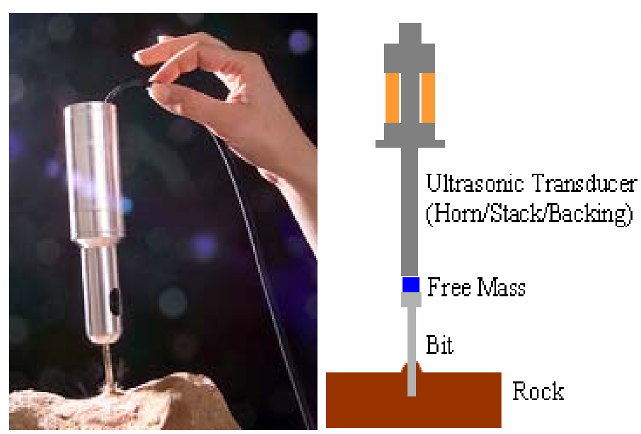


FIGURE 3: A photographic view of a prototype Ultrasonic/Sonic Gopher that drilled limestone and the core that was created.

1.1. Lake Vida in the McMurdo Dry Valleys of East Antarctica [Doran et al., 2003]

To satisfy the task's science objectives, an interdisciplinary approach is currently being pursued to examine the fundamental physical, chemical, and biological properties of Lake Vida that is located in the McMurdo Dry Valleys of East Antarctica. These Valleys have long been studied as extreme environments and potential analogs of purported Martian lakes of the past. Commonly reported dry valley lakes have a 2 to 6 m perennial ice cover and 20 to 60 m water column beneath. These lakes also have a range of salinities from fresh to hypersaline, and all allow sufficient sunlight to pass through the ice for photosynthesis to occur in the water column and benthos.

A few lakes in the dry valleys have been largely unstudied until recently because they were believed to be frozen to their beds. One of these lakes (Lake Vida) is also one of the two largest lakes in the dry valleys (Figure 4). Using a combination of ground-penetrating radar and ice coring techniques the coauthors have established that Lake Vida comprises a NaCl brine with a salinity seven times sea water and temperature constantly below -10^{o}C lies beneath ~20 m of ice that is at least 2,800 radiocarbon years old. Microbial mats occur throughout the ice column and are viable upon thawing. Sediment layers in the ice effectively block incoming solar radiation (Figure 5).

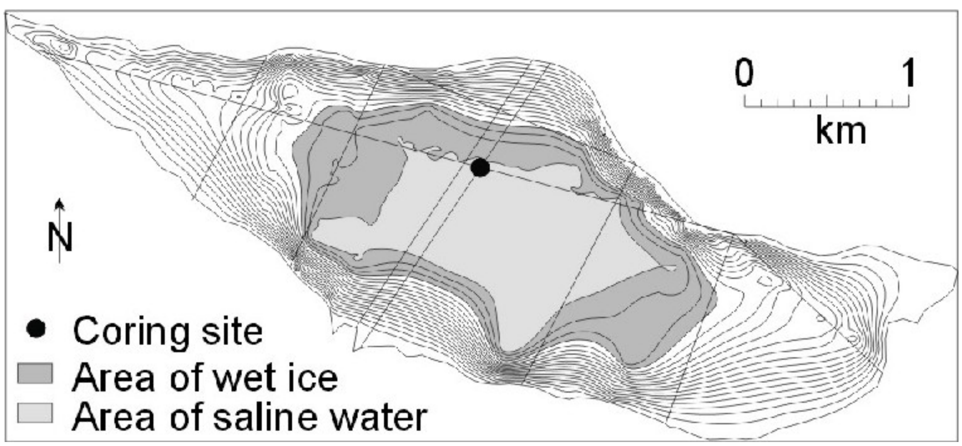


Figure 4: Bathymetric map of Lake Vida based on GPR and ice coring. GPR transect lines are shown. Solid black circle is the coring site.

Profiles of microbial biomass in the ice cores indicate that bacterial and microalgal cells (primarily filamentous cyanobacteria) are associated with sedimentary material within the ice matrices (Figure 5). Assays performed on ice core meltwater demonstrated that the populations of both heterotrophic and autotrophic microbes (at depths ranging from 0 to 12 meters) retained metabolic potential (measured via the incorporation of radio-labeled CO_2, thymidine and leucine) which was realized upon thawing of the ice samples. This suggests that the ice-bound microbial populations are capable of growth if liquid water were to become available within the permanent ice environment [Fritsen and

Priscu, 1997]. During coring, brine pockets were encountered in the ice at 16 m depth, which is the deepest point we have yet sampled. The ~3 m of ice and brine beneath this level, and the main brine body have yet to be sampled and are the targets of this proposal.

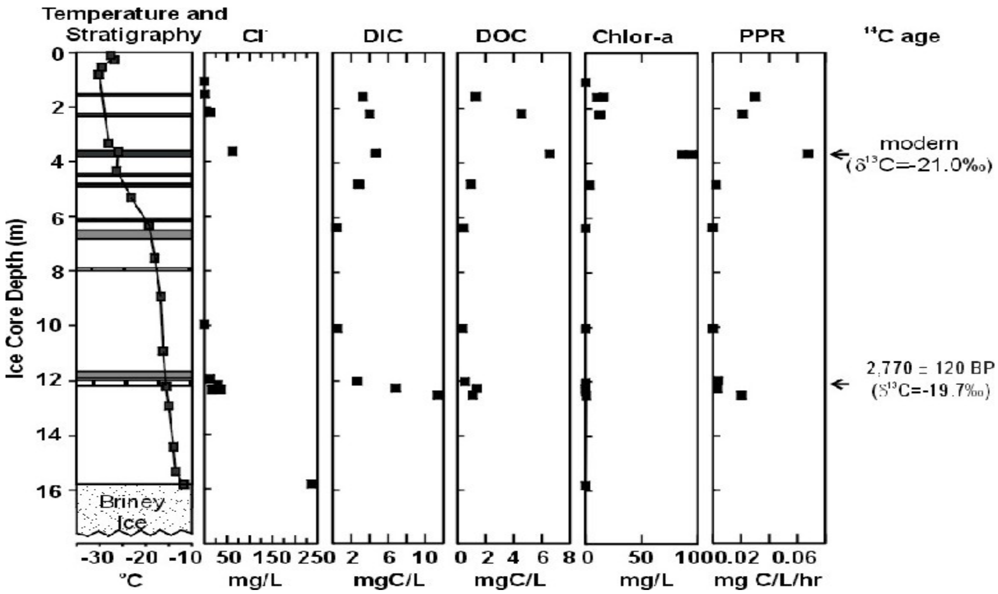


FIGURE 5: Physical and chemical properties of Lake Vida ice core taken in October 1996. Black horizons on the stratigraphy plot represent sediment layers, gray horizons are sandy ice, and vertically banded horizons contain microbial mat. The temperature profile shown was taken at the time of ice extraction.

2. ULTRASONIC/SONIC GOPHER

The U/S Gopher has significant potential of drilling beyond the current limit of existing technology of reaching the brine body that is below the 16-m depth ice in Lake Vida. Early versions of the U/S gopher suggest that coring through -20°C ice may prove a bigger challenge than coring through rock. A large part of the current efforts are focused on the problems of chip handling, core breaking and ice melt during drilling, which can create significant potential for getting the instrument stuck during the mission.

As mentioned earlier, the U/S Gopher is based on the USDC. The USDC is made of three key components: actuator, free-mass and bit (Figure 2). The actuator operates as a hammering mechanism that hits the free-mass, which in turn hits the bit to fracture the rock that is in contact with the bit. The actuator consists of a piezoelectric stack with backing for forward power delivery and a horn for amplification of the induced displacement. The USDC actuator is driven in resonance at 5-20-kHz depending on the design and a stress bolt holds the stack in compression to prevent fracture during operation. Unlike typical ultrasonic drills where the bit is acoustically coupled to the horn, in the USDC the actuator drives a free flying mass (free-mass), which bounces between the horn tip and the drilling or coring bit converting the ultrasonic impacts to hammering at sonic frequencies. The impacts of the free-mass create stress pulses that propagate to the interface of the bit and the rock onto which the USDC is placed in contact. The impacted brittle medium (rock, ice, etc.) is fractured when its ultimate strain is exceeded at the medium/bit interface.

The USDC has been demonstrated to drill rocks that range in hardness from granite and basalt to soft sandstone. This novel drill is capable of high-speed drilling (2 to 20-mm/Watt·hr for a 2.85mm diameter bit) in basalt and Bishop Tuff using low axial preload (<10N) and low average power (<5W). It drilled 25-mm deep, 6-mm diameter holes in basalt in a little over 2-hrs from a 4-kg platform using 10W average and 25W peak power. Also, it has drilled 15-cm deep, 5-mm diameter holes in sandstone in just over an hour using similar power as for the basalt drilling.

The operation of the USDC was analytically modeled to allow effective design [Bao et al, 2003 and Bar-Cohen et al, 2004]. This model consists of five elements including the electrical driver, ultrasonic transducer, free-mass, drill bit, and the rock. In the initial modeling effort, the main elements and the interaction between them were analyzed and modeled separately. A one-dimensional model was developed for each interaction (except the bit-rock interaction). Later, the strain that is induced in the rock was calculated by using a two-dimensional axisymmetric model and the drilling rate was estimated based on the specific energy required to fracture the rock

The versatility and the overall capability of the USDC have been investigated in parallel to the modeling effort and various configurations were conceived. As a platform for sensors, a lab-on-a-drill is being developed to allow probing sampled materials and the surroundings area prior to acquisition in order to optimize the selection of sites with the highest likelihood of containing biological signatures. Methods of acquiring samples in different forms are being studied and the effect of the sampling process is investigated to assure minimum impact on the sample characteristics. Using sensors that are mounted on the bit, including thermocouple and fiberoptic, real time measurements are enabled reducing concern of cross contamination that may result from sample handling.

The USDC mechanism has also demonstrated feasibility for deep drilling where the U/S Gopher is reeled into the borehole to create a core, the core is fractured and removed to the surface and then the process is repeated until the desired depth is reached (see Figure 6). In the earlier phase of this development, two units were developed with 3 and 4.5 cm diameter respectively. Generally, the bit creates a borehole that is larger than the drill bit outer diameter and it also creates a core that is smaller in diameter than the inner diameter of the coring bit. This reduces the chances of bit jamming where the hole integrity is maintained, and it eases in the extraction of the core from the bit. Current analytical models suggest that the USDC performance does not change significantly with changes in ambient gravity.

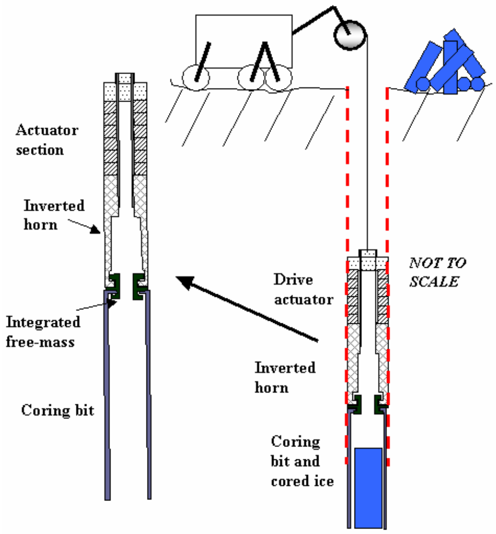


FIGURE 6: Schematic view of the ultrasonic-gopher operating inside the borehole.

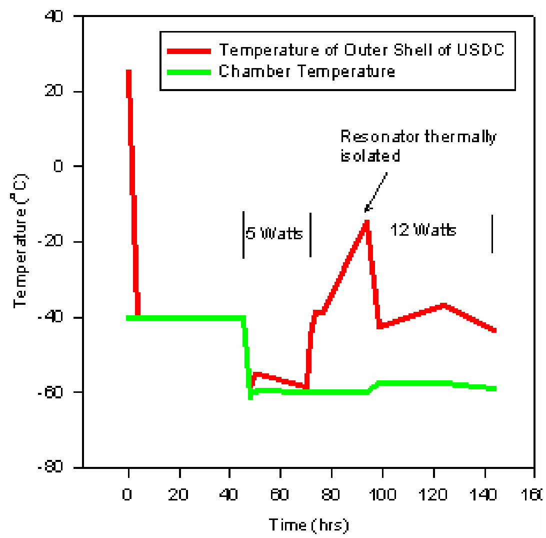


FIGURE 7: Tests of the USDC operation at low temperatures (conducted at the JPL's Extraterrestrial Materials Simulation Laboratory)

2.1 Drilling ice with the USDC.

Preliminary experiments using the USDC to drill ice have shown highly effective drilling and coring capability (Figure 7). Tests were performed as follows:

-40ºC: drilled about 1 cm deep solid ice in about 30 sec.

-140ºC: cored solid ice to about 3 mm deep using a 10 mm diameter. Since no allowance was made to address the issue of maintaining freezing temperatures throughout the unit, in the preliminary tests the cored and melted ice refroze and jammed the bit.

-40ºC and -60ºC: Drilling limestone for up to 160 hours with 24 hours initial exposure to the environment of -40ºC in the chamber.

-40ºC and -140ºC: drilled crushed ice and no problems were encountered. The speed was too fast to be measured with the limited setup that was used.

To avoid temperature increase at the tip of the coring bit and minimize potential ice melting and refreezing, two approaches are being considered. These approaches are (a) use of low thermal conductivity bit (Teflon bits were already been demonstrated successfully) and (b) use duty-cycling to drive the actuator. The use of duty-cycles to drive of the U/S Gopher allows operation with high power ultrasonic percussion to core the ice while maintaining low average power, and lower dissipation of heat.

2.2 Analytical modeling of the U/S Gopher

Each of the three components of the USDC needs to be carefully examined to determine the required modifications to produce optimal performance of the U/S Gopher. The parameters that are currently being investigated include weight of the free-mass, dimension and geometry of the horn and the coring bit, the number and the size of the piezoelectric rings. For this purpose, the model that was developed earlier for the USDC [Bao et al, 2003] is currently being modified and used for the analysis of the U/S Gopher. The ultrasonic actuator is assumed to vibrate at a frequency range of about 5-8 KHz depending on the design. The free-mass is excited by the actuator to bounce back and forth between the horn and the coring bit at frequencies varying from tens of Hz to 1 KHz. In the process the free-mass gains energy from the actuator and transfers it to the coring bit. The interactions between the free-mass, the actuator, and the coring bit are very complicated and it is investigated using Finite Element Analysis (FEA). With information derived from the FEA, a computer program is developed to simulate the operation of the Gopher and its components. The program traces the translation movements of the transducer and the free-mass as well as the vibration of the horn as functions of time. It predicts the time and location of the free-mass/horn or free-mass/bit collision. It also calculates the changes of the variables as time evolves. The movements and vibration due to the impact are recorded along with the impact momentum and time. The program then proceeds to determine the next impact. The energy supplied by the electric source and delivered to the transducer is integrated and recorded concurrently. The statistics reported by the program include electric input power, mechanical output power delivered to the coring stem, average and distribution of the free-mass speed, etc. The level of the impact momentum and its frequency is used as a criterion to determine the performance of a gopher. Various configurations of the horn and the bit are being studied and the predicted modal behavior is compared with the experimental data. Example of the predicted modal characteristics and the experimental data is show in Table 1.

TABLE 1: Example of the predicted modal characteristics and the experimental data for the U/S Gopher actuator.

Data type	No. of PZT rings	Thk of PZT (mm)	Length of horn (mm)	Length of backing (mm)	Resonance (Hz)	Anti-reso. (Hz)	Coupling	Max. Disp. (mm)	Max. Vel. (mm/sec)
Analytical	32	3.2	150	33	5963	7245	0.5679684	0.1433	5369.0
Experiment					6180	7000	0.4696416		
Analytical	16	3.2	150	33	8279	9440	0.4804672	0.07886	4102.2
Experiment					8215	8950	0.3968648		
Analytical	16	6.4	150	33	5964	7246	0.567933	0.0718	2690.6
Experiment					5835	6550	0.4543178		
Analytical	8	6.4	150	33	8281	9442	0.4804196	0.03938	2049.0
Experiment					8085	8850	0.4067055		

Generally, the USDC generates heat as a result of thermal losses from the actuator and friction. This heat raises the concern that surrounding ice may melt and refreeze leading to drill jamming. This potential jamming may introduce a long list of complications, including uncontrolled thawing of any microbial matter encountered, or re-freezing of ice onto the drill bit or drill body. To deal with this concern, the development of a thermal model was initiated to study heat flow in the ice surrounding the U/S Gopher. This thermal model, created in MathCAD, was able to approximate the temperature at a given area in the ice as a function of radial position, depth, and time. It incorporates approximate values for heat output at each section of the U/S Gopher as a percentage of input power, 50 Watts. A drilling rate of 4 cm per minute was assumed. Ice temperature at the proposed Antarctic drilling site is reported at -20°C at the surface, increasing at 0.5°C per meter as depth increases. With these and other input values, the model showed that significant melting would occur in the region surrounding the piezoelectrics after less than ten minutes of drilling (see Figure 8). However, after drilling twenty minutes, enough time to fill the coring bit with 80-

cm core sample, the temperature at the bit/ice interface had not yet reached -10°C. Therefore, melting and re-freezing of ice onto the bit should not be a concern and can be further prevented with an efficient method of ice chip removal. Melting around the piezoelectrics, though the model indicates it would occur, could be minimized or prevented with an appropriate housing design, including a cooling system, and dissipating heat over a larger surface area.

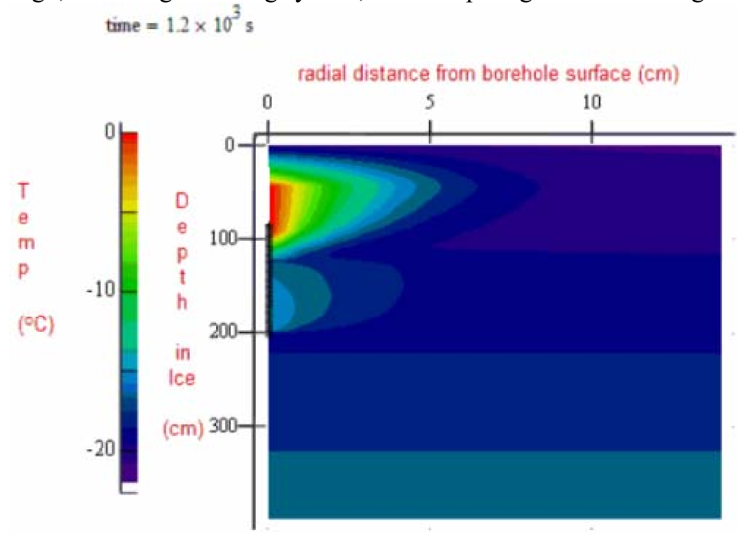


FIGURE 8: Thermal model results at 20 minutes indicating further melting near the piezoelectric stack but no melting at the bit/ice interface.

3. PROTOTYPE ICE DRILLING U/S GOPHER

The developed prototype ice Drilling U/S Gopher is currently being optimized to maximize the speed of drilling while preventing possible jamming due to ice refreezing. Each of the components of the unit has been examined individually to determine the most effective design.

3.1 Piezoelectric Actuator

As mentioned earlier, the actuator consists of a piezoelectric stack with backing for forward power delivery and a horn for the amplification of the induced displacement. The key areas of improvement are the horn design and the type of piezoelectric stack that is used. Preliminary efforts are currently underway investigating the use of various configurations of horns including the use of the stepped down (conventional), solid shape and the dog bone. The dog bone offers the equivalent of using the fist in boxing match or the heavy head in a hammer. The solid and dog-bone shape actuators next to the Gopher coring bits are shown in Figure 9. Preliminary analysis indicates advantages of the use of the dog-bone design of the horn but more work is currently being done to determine the viability of the use of this design.

3.2 Free-mass

Even though the free-mass has a relatively simple configuration of a ring or disk, various options of designing the free-mass are being sought in an effort to maximize the performance. The key variables that are being investigated are the dimensions and weight (via material selection) of the free-mass and the contact area.

3.3 Drill/coring Bit

The bit is generally designed in a tube shape that allows drilling in the desired diameter while maintaining the low cutting surface area to assure the use of minimal energy for the drilling. The optimization of the coring bit design is another critical area that can significantly affect the drilling rate. A combination of tough lightweight materials and thin wall allow fast drilling via the use of lower power while assuring robustness of the bit. Experiments have shown that the shape of the teeth in the cutting edge can significantly improve the drilling rate and lower the required power.

The use of teeth produces larger ice cuttings and minimizes the surface area of the fractured ice. Various configurations of teeth are being considered where the height and gap between the teeth are the key parameters.

FIGURE 9: A view of the solid and dog-bone shape actuators next to the U/S Gopher coring bits.

4. U/S GOPHER DEVELOPMENT AND FIELD DEPLOYMENT

We are currently designing and fabrication an Ultrasonic/Sonic Gopher prototype that is 50 cm long, 5 cm diameter. At a later time, the U/S Gopher will be equipped with a minimum of a thermocouple, conductivity sensor, and pressure gauge to monitor the environment to which the drill is exposed. A photographic view of the U/S Gopher prototype and cored limestone are shown in Figures 2 and 10, whereas a cross section view of the Ultrasonic/Sonic Gopher drill-head and a simulated operation from a rover are shown in Figure 6. The drill-head can be battery operated and delivered to the bottom of the borehole by a suspension cable. The U/S Gopher will be reeled down the borehole in a cycle of creating a core, breaking it and delivering it to the surface. Drilling will be conducted down to a depth of about 20 m. Methods of cutting the core including hot wires, wire saws and hot scoops are currently being investigated. The cutter will also serve as the core holder. Once a core is created a suspension cable will be used to raise the core to the surface and a push rod will be used to extract the core from the bit. The use of low power and low axial load will allow operating from light mobility platforms overcoming the power and bracing limitations of alternative mechanisms.

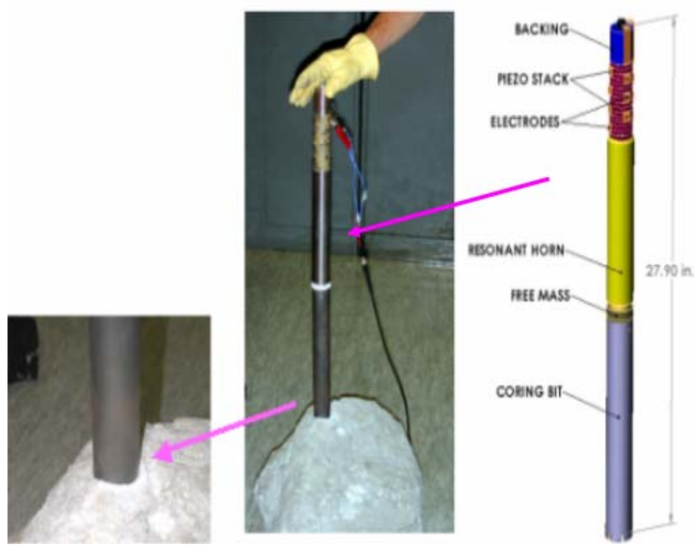


FIGURE 10: Overall view and photograph of the drill head.

5. CONCLUSIONS

Lake Vida provides the unique opportunity to investigate lake ecosystems on the edge of existence to determine what conditions may lead to the eventually complete freezing of a lake and the subsequent development/evolution of microbial communities and geochemical signatures. The combined hyper-saline, aphotic, atmospherically isolated and cold conditions in Lake Vida make it potentially among the most extreme aquatic environments on Earth. These conditions are likely to have been present during the last stages of purported lakes on Mars near the end of its water-rich past. Under a NASA ASTEP program, we are developing an Ultrasonic/Sonic Gopher that will drill though cold dirt and ice with a low power and light weight instrument to retrieve samples for life detection.

We envision the U/S Gopher being a rover "accessory" that can be added to missions that require access to ice, sediment, or fluid samples within 20- to 30-m of planetary surfaces such as Mars and Europa. As stated above, getting samples from these depths on Mars will be critical to many future astrobiological missions focused on the search for extant and extinct life.

ACKNOWLEDGMENTS

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REFERENCES

Bao X., Y. Bar-Cohen, Z. Chang, B. P. Dolgin, S. Sherrit, D. S. Pal, S. Du, and T. Peterson, IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control (UFFC), Vol. 50, No. 9, (Sept. 2003), pp. 1147-1160.

Bar-Cohen Y., S. Sherrit, B. Dolgin, S. Askin, T. M. Peterson, W. Bell, J. Kroh, D. Pal, R. Krahe, and S. Du, "Ultrasonic/Sonic Mechanism of Deep Drilling (USMOD)," NTR, submitted on June 12, 2001, Docket No. 30291, July 17, 2001, U.S. Provisional Patent Application No. 60/341,443 filed on December 20, 2001.

Bar-Cohen Y., S. Sherrit, B. Dolgin, T. Peterson, D. Pal and J. Kroh, "Ultrasonic/Sonic Driller/Corer (USDC) With Integrated Sensors," NTR, August 30, 1999, Item No. 0448b, Docket No. 20856, November 17, 1999. NASA Tech Briefs, Vol. 25, No. 1, Jan. 2001, pp. 38-39. Patent was submitted on (May 1, 2001), Registration No. PCT/US01/14289 and US 10/258007

Bar-Cohen Y., S. Sherrit, X. Bao, and Z. Chang, the JPL's NDEAA Ultrasonic/Sonic Driller/Corer Homepage, http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/usdc.htm (2004).

Doran, P.T., and Forman, S.L., 2000, "Ideas about the surface runoff features on Mars," Science, v. 290, p. 713-714.

Doran, P.T., Fritsen, C.H., McKay, C.P., Priscu, J.C., and Adams, E.E., 2003, "Formation of the 19 m ice cover and associated brine in Lake Vida, Antarctica," Proceedings of the National Academy of Science, v. 100, p. 26-31.

Fritsen C.H., and Priscu, J.C., 1997, "Photophysiology of cyanobacteria in the permanent ice covers on Antarctic lakes," American Society of Limnology and Oceanography, Annual Meeting, Santa Fe, NM, February 1997,

Malin, M.C., and Edgett, K.S., 2000, "Evidence for recent groundwater seepage and surface runoff on Mars," Science, v. 288, p. 2330-2335.

Mitrofanov IG, MT Zuber, ML Litvak, WV Boynton, DE Smith, D Drake, D Hamara, AS Kozyrev, AB Sanin, C Shinohara, RS Saunders, and V, T., "CO_2 snow depth and subsurface water-ice abundance in the northern hemisphere of Mars," Science, v. 300, (2003) p. 2081-2084.