SLUSH: SEARCH FOR LIFE USING SUBMERISBLE HEATED DRILL. K. Zacny[1], T. Costa[1], F. Rehnmark[1], J. Mueller[2], T. Cwik[2], W. Zimmerman[2], A. Gray[2], P. Chow[1], [1]Honeybee Robotics, [2]NASA JPL

Introduction: Europa has been a primary target in the search for past or present life because it is still geologically active and has a large ocean underneath an ice shell. Theory and observation indicate that the icy surface shell is approximately 3-30 km thick [1]. Unfortunately, we have very limited experience drilling that deep. The deepest hole in the ground, the Kola Superdeep Borehole, is just over 12 km deep and the deepest hole in ice – the Vostok borehole – is approximately 4 km deep. Based on our terrestrial experience it may appear that deep drilling on another planetary body is not feasible. However, robust technology development focused on penetration approaches tailored specifically to the required space environment should produce a system (or systems) capable of reaching the target depth (e.g. Europa's Ocean) within a few year mission. This assumes no major scientific/technological breakthroughs that would make a probe even more robust and efficient.

Approaches to Deep Drilling: To advance forward, a probe would need to 'destroy' the formation and move the drilled material behind it. This can be achieved via two primary methods: thermal and mechanical [2]. Each of these two methods has unique advantages and disadvantages but neither is sufficient to reach the ocean. Thermal probes (e.g. melt probes, closed cycle hot water drills - CCHWD, lasers) are very robust penetrators that require just heat to melt through and advance deeper below the surface. Thermal probes, however, are slow (especially in cryogenic ice), require significant amount of power (kW to 10s of kW, depending on the probe's diameter and length), and are inefficient, because >90% of the heat is lost into surrounding ice. For that reason they have not been widely adopted in Antarctic or Greenland exploration. To make thermal probes feasible for planetary applications, they would require nuclear reactors with 10s of kW power output capability.

Mechanical drilling systems, on the other hand, are approximately 100x more efficient and significantly faster. For that reason they are primary methods of making holes and capturing ice cores in Greenland and Antarctica. They can also penetrate materials other than ice (e.g. salts). The major drawback of these drills relates to chips removal. Chips need to be removed by either periodically lifting the drill with chips basket out of the hole (conventional method used in terrestrial ice drilling) or lifting the chips above the probe and re-compacting them to their original density (e.g. inch worm approach). This could be feasible and is being developed by Badger Explorer for Oil and Gas. The required pressure to compact ice chips is 30 MPa.

SLUSH Drill: Mechanical systems have very efficient formation breaking approach while thermal systems have very effective chips removal approach. SLUSH drill (Search for Life Using Submersible Heated drill) is a thermo-mechanical probe that combines the best from the two techniques: mechanical drill to break the formation and melting to remove the cuttings (**Figure 1**). However, instead of melting an entire volume of ice, SLUSH melts just a fraction of it to form slush. Slush behaves like liquid but is still partially frozen this enables significant reduction in power draw. Since mechanical approach generates higher penetration rates, SLUSH can also reach the ocean in much shorter time.

SLUSH looks like a torpedo with a drill bit in front and anti-torque blades on the side (proven system in Antarctic wireline drills). It houses scientific instruments for in-situ analysis (e.g. Raman). It is connected to a surface lander by an umbilical for data and power. To reduce power draw from the surface energy supply needed for partial melting, SLUSH incorporates GPHS (General Purpose Heat Source) – bricks with ~250 Watt thermal power. The GPHS drive diameter of the probe to be ~14 cm.

Once SLUSH passes through the cryogenic ice (a few km thick), it can use just a thermal approach to melt through the warmer ice without the need for mechanical cutting. Thermal probes are significantly more efficient in tempered (warm) ice.

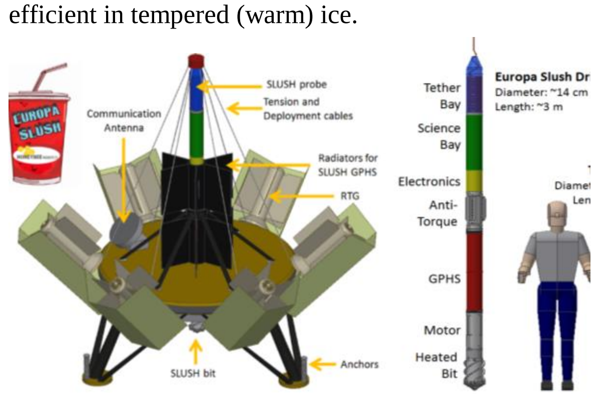


Figure 1. Example of Europa SLUSH mission

SLUSH – Experimental setup: Under NASA SBIR Phase 1, we fabricated two different slush bits (Table 1) and tested them in ice as shown in **Figure 2**.

Slush bit designs were based on bits used in previous projects; they have been modified to allow for heaters. Each of these bits has different cutter configuration, heating chamber layout, as well as heater configuration. Unlike a melt probe that requires high power density at the tip, SLUSH does not have this requirement. The heat can be spread along the entire length of the bit to melt cuttings as they flow along the length of the bit.

Table 1. SLUSH drill bit options

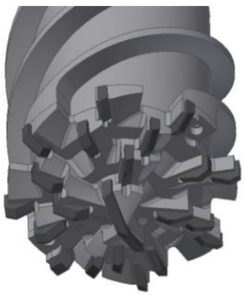
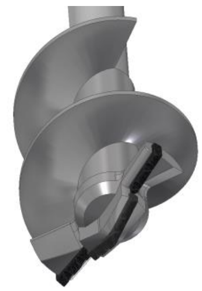
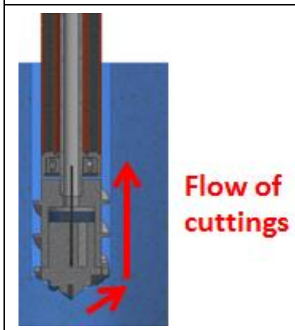
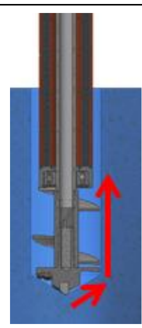
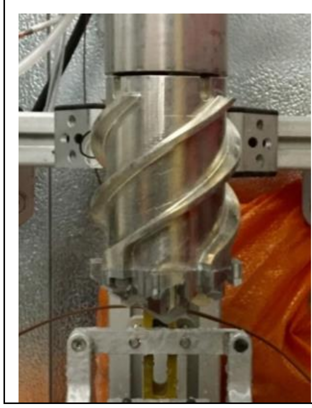
AMNH	Watson
	
	
Large bit body for high heater power density.	Large flutes for easy transport of cuttings.
	

Figure 2 shows experimental setup inside the freezer. It consists of a rotary-percussive drill (a 4 axis system that allows rotation, percussion and feed control) and the SLUSH bit (the cutting bit, non-rotating probe body model, and bit/probe heaters). Heater wires were routed along the inside of the SLUSH bit and through the COTS slipring at the drill/bit interface. The ice bin was created by freezing tap water in the freezer. An embedded thermocouple provides actual ice temperature (-20 C).

We used a GoPro camera to record video pictures and videos of all the tests.

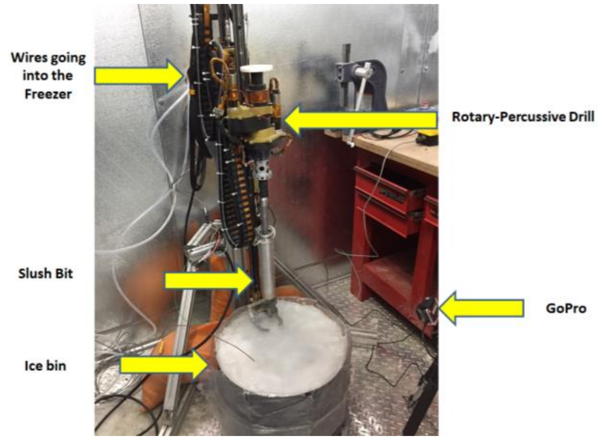


Figure 2. Experimental setup on the inside of the freezer.

SLUSH-Test Results: To allow apples to apples comparison, we performed side by side tests using AMNH and Watson bit as meltprobes, slush, and mechanical drills.

Figure 3 shows that melting (as expected) is significantly more energy inefficient than slushing, and slushing is more energy inefficient than mechanical drills. In general, the energy required to melt, slush, and drill is in the ratio of 100:10:1. It should be noted though that the mechanical system did not account for the energy required to move the chips to the top of the probe, and to compact it to its original density.

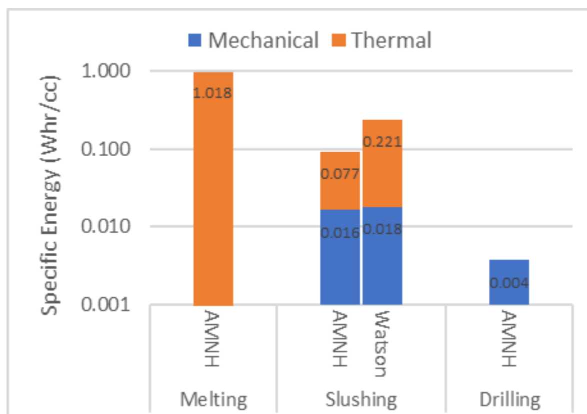


Figure 3. Mechanical vs Slushing vs Melting

Acknowledgments: This work was funded by NASA SBIR project and NASA JPL.

References: [1] Pappalardo et al. (2009) Europa. Tucson, AZ: University of Arizona Press, [2] Zacny et al., (2018), IEEE Aerospace Conf