Icebreaker-3 Drill Integration and Testing at Two Mars-Analog Sites

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ABSTRACT
A decade of evolutionary development of integrated automated drilling and sample handling at analog sites and in test chambers has made it possible to go 1m through hard rocks and ice layers on Mars. The latest Icebreaker-3 drill has been field tested in 2014 at the Haughton Crater Mars-analog site in the Arctic and in 2015 with a Mars lander mockup in Rio Tinto, Spain, (with sample transfer arm and with a prototype life-detection instrument). Tests in Rio Tinto in 2015 successfully demonstrated that the drill sample (cuttings) was handed-off from the drill to the sample transfer arm and thence to the on-deck instrument inlet where it was taken in and analyzed ("dirt-to-data").

INTRODUCTION

Unlike terrestrial drills, Mars exploration drills must work dry (without drilling muds or lubricants), blind (no prior local or regional seismic or other surveys), and light (very low downward force or weight on bit, and perhaps 100W available from solar power). Given the lightspeed transmission delays to Mars, an exploratory planetary drill cannot be controlled directly from Earth. Drills that penetrate deeper than a few cm are likely to get stuck if operated open-loop (the MSL drill only goes 5cm, and the MER RATs 5mm by comparison), so some form of drill control automation is required.

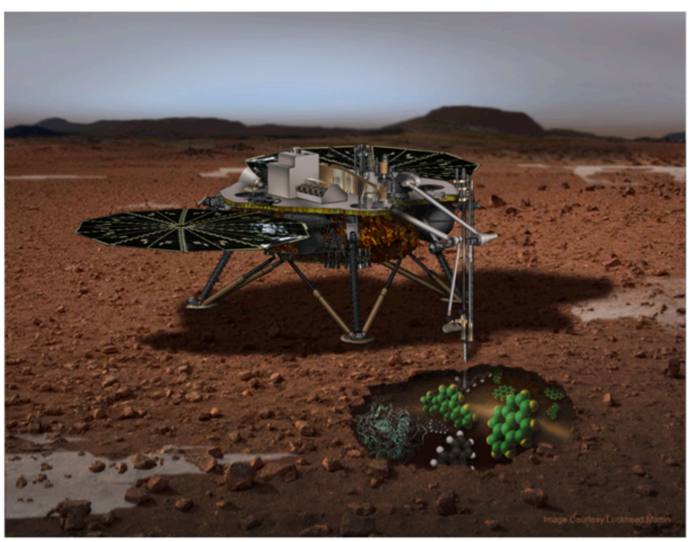

Figure 1. Icebreaker mission concept would return to the northern Mars polar latitudes visited by Phoenix.

The proposed "Icebreaker" mission (Figure 1) would be a return to the Mars polar latitudes first visited by Phoenix in 2007-08 (McKay et al., 2014). Given the hard icy layers and perchlorates found there, Icebreaker is based on the Phoenix/InSight spacecraft bus but would carry an automated 1m rotary-percussive drill, a sample transfer arm, and non-pyrolytic instruments capable of detecting organics in the presence of perchlorates. Looking for organics, biomarkers and signs of past or extant life in the Mars arctic will require sample acquisition there below the desiccated and irradiated surface, and through the hard ice layers that stymied Phoenix. A decade of evolutionary development by NASA of integrated automated drilling and sample handling, at analog sites and in test chambers, has made it possible to go deeper through hard rocks and ice layers. (Glass et al., 2014) The latest Icebreaker-3 drill (Figure 2) was tested with a Phoenix mockup and at the Haughton Crater Mars-analog site in the Arctic (with sample transfer arm) and in a Mars chamber, with successful sample acquisition under automated control.

MARS-PROTOTYPE DRILL EVOLUTION

In August 2013, the Icebreaker-2/Life In The Atacama (LITA) drill, designed originally in 2010 for use at the Atacama Desert Chilean Mars-analog site, was tested at the Haughton Crater Mars-analog site (Glass et al., 2014). Unlike previous tested prototypes since 2004, the 10kg/1m depth LITA did not demonstrate a capability of penetrating hard rock or ice-consolidated material. Earlier Mars-drill prototypes could penetrate these materials, but were/are too massive to fly on a Phoenix-sized Mars lander spacecraft (see Table 1).

Table 1. Drill prototypes tested at Haughton Crater, 2004-14. (Glass et al., 2015)

Drill	Program	Type	Depth Max	Deployed Mass (kg)	Haughton Crater Field Tests
DAME	MIDP, MTP	Rotary	7m	55	2004-6, 2008
CRUX	HEOMD and ASTID	Rotary-Percussive	4m	43	2009, 2010
Icebreaker (IceBite)	ASTID and ASTEP	Rotary-Percussive	3m	32	2011, 2012
LITA/Icebreaker-2	ASTEP	Rotary-Percussive	2m	10	2013
Icebreaker-3	ASTEP and MMAMA	Rotary-Percussive	2m	12	2014

While the earlier LITA drill worked well in the Atacama Desert (Zacny et al., 2013) and in laboratory tests, it did not perform satisfactorily in Haughton Crater's impact-breccia permafrost. An example is shown from 2013 tests in Figure 3. A stiffer drillstring material was needed to improve rotary-percussive operation, when there was significant torsional drag on the drillstring. Post-test analysis of the LITA drill performance issues in ice-cemented ground and ice lenses indicated that a stiffer shaft design with more drill-head rotary power (applied auger torque) would be needed to break those layers and overcome parasitic auger drag on the sides of the drill string. The ability to reverse-rotate would be also needed in order to extricate the drill by backing out when sensors indicated that a jam or sticking was imminent. And a temperature sensor in the drill bit was useful to monitor when the frictional heating of cuttings was approaching the triple point (and hence sample alteration, and Phoenix-like clumping of materials). Figure 4 shows a LITA/Icebreaker-2 drill, and the design changes made in the spring of 2014 to create the Icebreaker-3 configuration.

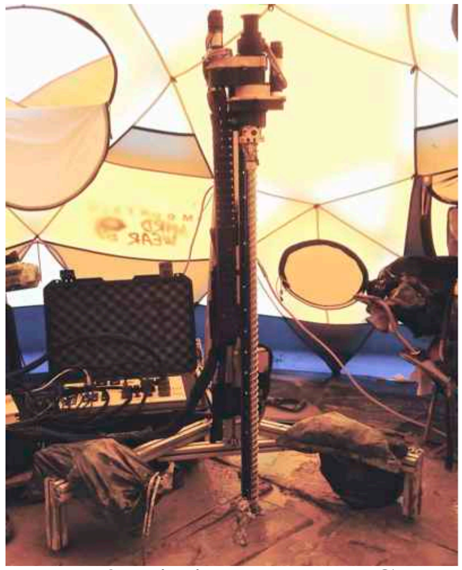

Figure 2. Icebreaker-3 drill in Haughton Crater tests in 2014.

The Icebreaker-3 (IB-3) rotary-percussive drill, completed in June 2014, was (like LITA) 3-5x less massive than earlier Mars drill prototypes. Power consumption was comparable to LITA, at 30-40 W, 200W max during 5-10 min drilling sequences. It was tested in August 2014 at the Haughton Crater analog site in the Canadian Arctic, running automated drilling sequences. In contrast to the LITA drill, IB-3 drilled 5m, in six boreholes, and with sufficient power (torque) and shaft stiffness to break and penetrate hard rock and ice-consolidated material. IB-3 drilled 2m in ice or ice-consolidated material. Unlike prior prototypes, IB-3 drilled rapidly and experienced almost no fault conditions. (Glass et al., 2015)

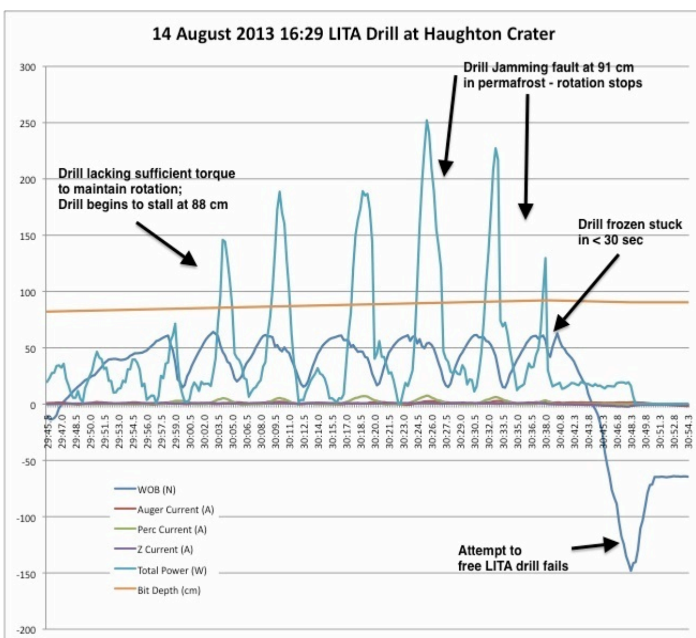

Figure 3. The Life In The Atacama (LITA) drill design lacked the power to penetrate ice-consolidated materials at Haughton Crater in 2013 testing.

In June 2015 the IB-3 drill was then deployed to the Rio Tinto, Spain analog site together with a robotic arm (for sample transfer), a full-scale lander deck and the operational Signs of Life Detector (SOLID) prototype instrument. The purpose of these tests was to demonstrate interoperability and system integration. Tests successfully demonstrated that the IB-3's sample (cuttings) were handed-off from the drill to the sample transfer arm and thence to the SOLID instrument inlet where it was taken in and analyzed ("dirt-to-data"). However, mechanical failures and software control issues caused frequent drilling aborts and faults and IB-3 could not penetrate rocks or consolidated layers, and was only able to drill 2.4m total in five holes.

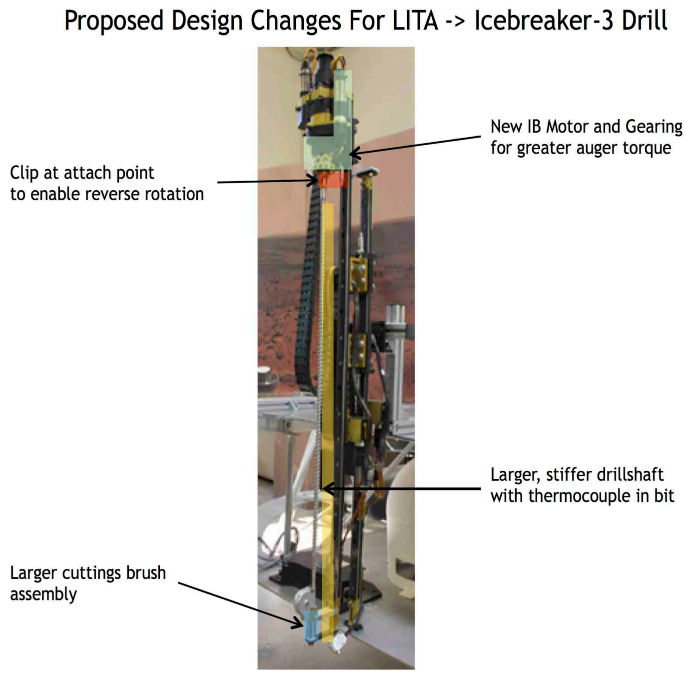

Figure 4. LITA design changes made in 2014 for the Icebreaker-3 drill configuration.

AUTOMATION AND CONTROL

A spacecraft intended to drill on Mars must be capable of hands-off operation for hours at a time without human oversight or control, as by the time Earth learns of a drilling problem, the drill will be at least several minutes further along and possibly stuck. An automated, adaptive drilling controller can change forces and speeds in response to changing downhole conditions, and remediate and continue onward from the most likely faults, making it both less likely to fail and more likely to make drilling progress.

NASA Ames has developed software to monitor and control the Icebreaker family of rotary-percussive prototype drills. As shown in the block diagram in Figure 5, the software includes low level controls for maintaining specified performance parameters, diagnostic software for monitoring and estimating the state of the system, and contingent execution software for directing the system through a daily drilling plan while reacting to and recovering from off-nominal situations (Glass et al., 2014, Bergman et al., 2016).

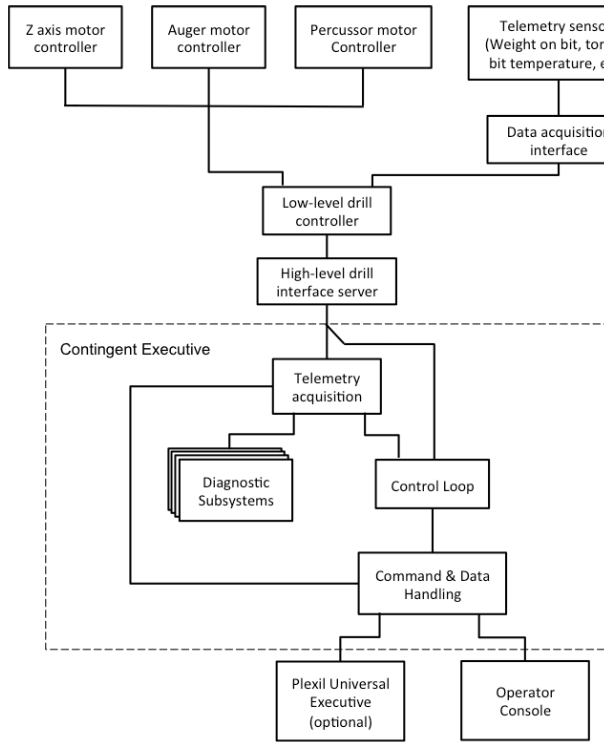

Figure 5. Drill automation architecture.

The Icebreaker drill control software was ported from the CRUX rotary-percussive drill software, which in turn follows the structure that was used by the DAME drill (Glass et al., 2008), but was a ground-up rewrite aimed at allowing the code to run on flight hardware. The middleware-based DAME code used a subset of CORBA and was well-suited to prototyping, but it ran on an ad-hoc network of laptop computers running a combination of Linux and Microsoft Windows -- so a different approach was necessary in order to fit within the memory and CPU limitations of contemporary flight computers (e.g., RAD750 running VxWorks).

FIELD TESTING OF ICEBREAKER-3

Objectives for the Icebreaker-3 (IB-3) drill tests in 2014-15 were: (a) to confirm nominal operations and the efficacy of the design changes under lab conditions, (b) to test drilling operations and behavior under the same permafrost conditions at Haughton Crater and confirm satisfactory performance there with the IB-3, (c) confirm the interoperability of the IB-3 with a sample transfer robotic arm (into instrument inlets (Dave et al., 2013)), (d) test the IB-3 in a Mars chamber to confirm performance and to study the grain size of the icy cuttings produced (Bergman et al., 2015), and (e) test the IB-3 deployed from a full-scale Icebreaker lander deck, with sample transfer arm and the SOLID instrument, at the Rio Tinto Mars-analog site. Figure 2 shows the IB-3 drill at Haughton Crater in August 2014.

For Rio Tinto testing of the IB-3 in June-July 2015, an Icebreaker lander deck mockup platform built at NASA-Ames was set up in the field with the drill, a sample transfer arm, and a prototype Signs of Life Detector (SOLID) instrument with an inlet for automated delivery of sample. Fig. 6

shows IB-3 deployed over the deck alongside the integrated sample transfer arm. The functional SOLID instrument prototype is the black box mounted on the deck in Figure 6 behind the arm and drill.

Figure 6. IB-3 tested with SOLID instrument (black case) and sample transfer arm at Rio Tinto, Spain, in July 2015.

RESULTS

The IB-3 drill was successfully field-tested in Arctic impact-breccia permafrost at the Haughton Crater site in August 2014. IB-3 drilled >5m, in six boreholes, and with sufficient power (torque) and shaft stiffness to break and penetrate hard rock or ice-consolidated material. IB-3 drilled >2m in ice or ice-consolidated material, Unlike prior prototypes tested at Haughton (Table 1) IB-3 drilled rapidly and experienced almost no fault conditions. Melt-refreeze and binding faults, seen often during the prior year's tests with the LITA drill and LITA software, were not experienced by the IB-3 drill. One of the few fault conditions experienced at Haughton Crater is shown in Figure 7, a corkscrewing fault recovery upon drill retraction.

In the summer of 2015, the IB-3 drill was integrated with a sample handling arm with scoop, and they (together with the Signs of Life Detector prototype instrument) were mounted on the full-scale InSight/Icebreaker lander mockup in Figure 6, for tests at the Rio Tinto, Spain, Mars-analog site. Drilling was conducted adjacent to a low-Ph acidic stream (seen in the upper left of Fig. 6), characteristic of those where extremophiles have been typically observed at the Rio Tinto site. The drill managed 2.4m drilled total in five boreholes, after its primary auger torque motor unexpectedly failed by shorting on the first full day of drilling (3 July 2015). Unfortunately, the available field replacement spare in Spain was a former LITA drill auger motor that would also develop an intermittent electrical short in its windings (viz. Figure 3 LITA example).

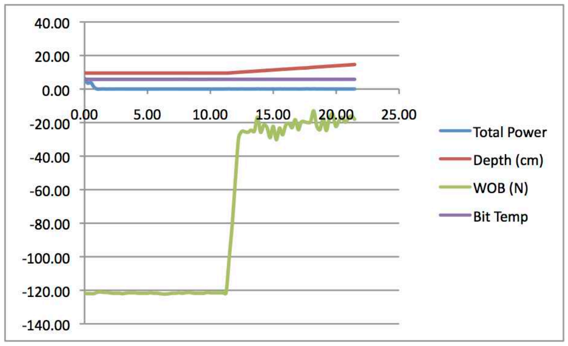

Figure 7. Corkscrewing fault recovery on 2 August 2014 at Haughton Crater by Icebreaker-3 drill.

Figure 8 shows the drill making successful headway with its original IB-3 auger motor: reaching the existing bottom of the borehole around 60cm depth, making progress until a hard rock layer was encountered (around 67-68 cm depth) at which point percussion began. This was then followed by shorting of the auger torque motor (which stopped rotation), and finally a spike in weight on bit as the control software attempted to maintain the penetration rate.

Coming close on the heels of Honeybee's final LITA-project Atacama tests two months earlier in Chile, there had not been time for thorough drill maintenance and a teardown inspection before the shipping date to Rio Tinto. The Maxon motors used in Honeybee's LITA/IB-3 drills have failed in the field in several instances in 2015. Subsequent inspection determined that there was an intermittent connection within both the IB-3 Rio Tinto motor and its older spare, and as a result encoder counts and current signals were lost or corrupted, probably resulting in higher (spurious) operating current values and hence many false-positive faults. The original IB-3 torque motor also failed mechanically (due to a bad bearing or excessive drag between rotor and stator). The rush from Chile to Rio Tinto resulted also in the drill avionics being inadvertently shipped to the field site with the LITA-drill control software version still installed (instead of the IB-3 software). Operated as a LITA drill, with a primary LITA auger motor, the drill in Rio Tinto then struggled to penetrate more than 20-40cm per borehole into the cemented tailings and pyrites at the test site.

After the replacement of the auger torque motor with its older spare, its reduced drilling capability and frequent intermittent shorts in its windings led to binding and hard material faults that were called by the LITA control software, leading to repeated occasions where the drill was automatically stopped motionless on the bottom of the hole. Figure 9 shows a typical example on 6 July 2015, as the now IB-3/LITA hybrid drill configuration encounters harder material around 21 cm depth, increases weight on bit and greatly increases auger power (current) until a binding fault is called and the drill stops motionless at 27cm depth. While a bottom-stop was easily recoverable in the relatively dry and warm Rio Tinto material, had this happened in icy substrates a frozen-stuck condition would have likely occurred (e.g., as in Figure 3 in 2013 in the Arctic).

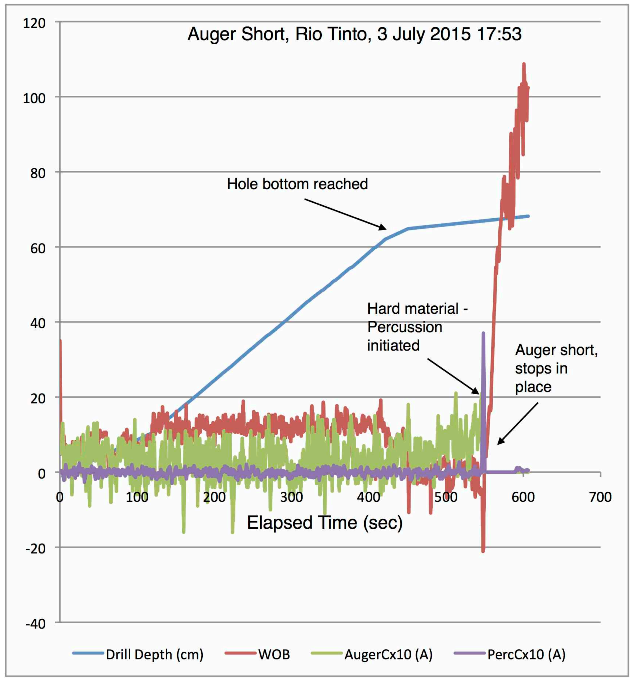

Figure 8. IB-3 initial drilling headway in Rio Tinto, followed by motor failure.

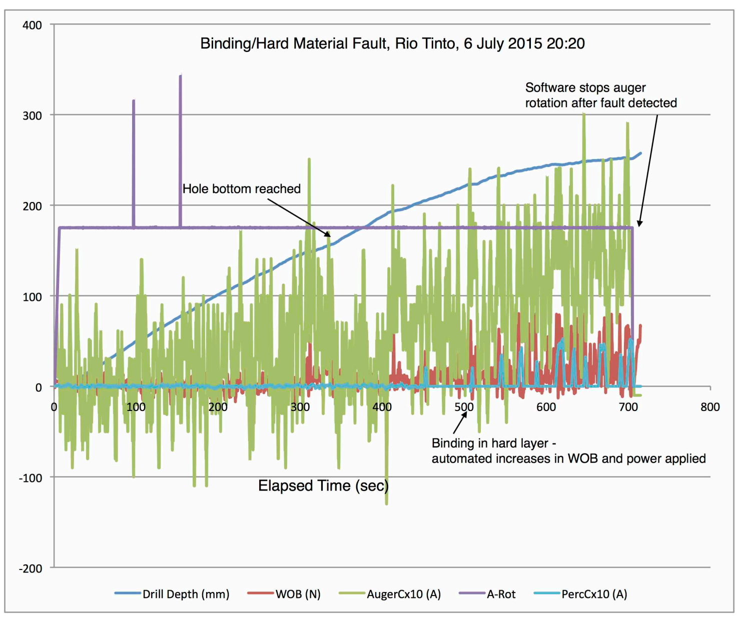

Figure 9. LITA-powered drill and LITA control software together struggled to penetrate hard material layers at the Rio Tinto site in July 2015, similar to 2013 performance at Haughton Crater (Figure 3).

The primary objective of the 2015 Rio Tinto tests, however, was to demonstrate integrated science sampling and analysis, and the reduced drill performance was adequate to do this successfully. Interoperability testing with the drill, sample transfer arm, and SOLID instrument on the lander deck at Rio Tinto demonstrated that sample (drill cuttings) was handed-off from the drill to the sample transfer arm and thence to the SOLID inlet port (so-called "dirt-to-data" from (Dave et al., 2013)) whereupon analysis of the sample was accomplished. The initial dirt-to-data demonstration is in Figure 10, where the bottom of the hole was reached at about 3 cm depth and the drill proceeded until a binding fault at just over 8cm. The cuttings were automatically deposited in the transfer arm's scoop, which in turn moved up and over and dumped them into SOLID's intake funnel. SOLID ran analyses on Rio Tinto samples from the drill down to 20 cm depth. Figure 11 shows the bioassay summary results with the dirt-to-data SOLID results shown in red at the right of the 0-13cm and 13-20cm depth ranges. For the sample acquired through drilling in Figure 10, SOLID detected acidithiobacillus and unspecified actinomycetales.

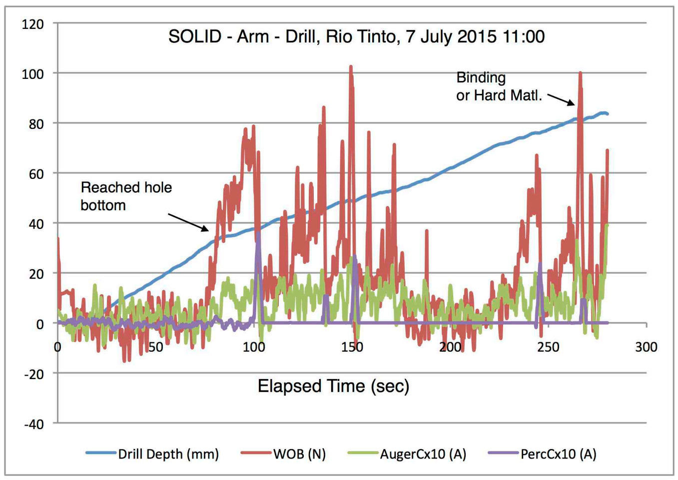

Figure 10. Dirt-to-data: 5 cm of drilling leads to sample (cuttings) that were automatically provided to the SOLID life-detection instrument.

CONCLUSIONS

July 2015 tests in Rio Tinto successfully demonstrated the functionality of the sample (cuttings) handed-off from the drill to the sample transfer arm and thence to the SOLID instrument inlet where it was taken in and analyzed ("dirt-to-data") with life detected. In 2014 Arctic field tests, the very lightweight, low-power, low weight-on-bit, Icebreaker-3 drill (with its design improvements over LITA) was capable of penetrating hard rock and ice-consolidated material that had resisted the earlier LITA drill. However, reversion back to a LITA-like drill in the 2015 Rio Tinto testing led to more drilling performance problems, due to faulty motors. For future drill tests, as are planned in a return to the Rio Tinto site in 2017, a more robust redesign of the LITA/IB-3 drill is recommended in order to reach greater drilling depths at that site and for testing at other Mars-analog sites in icy substrates. An alternative future supplier of space-rated motors may be advisable, as well as the use of a configuration checklist to ensure that basic maintenance checks and software reconfiguration are completed prior to sending a drill to the field. Improved software diagnostic and control software design is recommended to fully-safe the drill in faulted states, with no full stops on the bottom.

Drill samples assays

SAMPLES	DNA [ug/ml]	DNA R (260-280)	PROTEINS (ug/g)	SUGARS (ug/g)	Biomass PLFA Cells/g	Phyllogenetic groups LDChip	Phyllogenetic groups PLFA
0-13	8,5	1,8	124,632	13,578	1.05E+07	Gammaproteobacteria: Acidithiobacillus spp + Actinomycet	Proteobact. Actinomycet Firmicutes Eukaryotes
13-20	2,4	2	40,571	3,93	---	Gamma +Firmicutes	---
20-30	2,1	2,4	0	0	---	Gammaproteobacteria	---
30-40	2	2,27	37,140	0	5.45E+05	Gammaproteobacteria	Proteobact Firmicutes
40-50	2,8	1,5	21,7	0	5.11E+05	Gammaproteobacteria	Proteobact Firmicutes
50-57	4,1	2,31	92,037	34,237	---	Gammaproteobacteria	
Solid 50-57			83,459	12,201	---	Gammaproteobacteria	

Red: Assay in SOLID

Figure 11. Bioassay results from 2015 tests at the Rio Tinto site. Red text indicates dirt-to-data results by SOLID from drill-provided automated sample transfer. (Parro 2015)

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