The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT); a One-Meter Drill for the Lunar Resource Prospector Mission

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Abstract

A desire to prospect for resources on the Moon, namely water, has led to the development of The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) drilling system. TRIDENT is a 16-kg rotary percussive drill and deployment system that was designed to be deployed from a roving platform and drill to a depth of 1 meter. Designs and testing supported by the Resource Prospector (RP) mission have enabled the TRIDENT system to reach a NASA TRL of 6. Through the development of this system, many lessons were learned. These include lessons learned for cable/pulley and capstan mechanisms, custom slip-ring designs, instrumentation of temperature sensors for measuring subsurface temperatures, sample transfer mechanisms, brazing tungsten carbide to titanium, and the replacement of the drill's cable harness with flexible printed circuits. This summary highlights some of the major lessons learned along with recommended designs and tests to improve the design of the TRIDENT.

Introduction

In 2014, Honeybee Robotics was selected to help the NASA Resource Prospector (RP) mission [1] meet its goals of advancing the technology readiness level (TRL) of the Resource Prospector system by increasing the TRL of the drilling subsystem. The primary goal of the RP mission is to explore the Lunar South Pole Aitken Basin in search of water ice and other volatiles. Instruments on board the RP rover are designed to help locate and quantify the concentration of volatiles (with emphasis on water). This mission is to provide ground truth data in support of previous water detection missions (i.e. LCROSS [2] and other surveying spacecraft). The Lunar environment that the RP mission will experience include hard vacuum, cryogenic temperatures (down to 40K), radiation, and low gravity ($1/6^{th}$ g).

Hurley et. al. [3] state that the desiccated layer on the Moon is on the order of 10's of cm. This would suggest that to find ice on the Moon would require penetrating the surface beyond a few centimeters. The mission requirement, derived from the current remote sensing data, is to have the ability to drill to a depth of 1 meter below the Lunar surface. However, penetrating the surface is only one of the functions of the drilling system. Other functions include sample delivery to a surface directed Near Infrared Volatile Spectrometer Subsystem (NIRVSS), delivering sample to an onboard Oxygen & Volatile Extraction Node (OVEN) and Lunar Advanced Volatile Analysis (LAVA) subsystem, and to measure the subsurface temperature and strength of the regolith.

This paper describes the development of The Regolith and Ice Drill for Exploration of New Terrain (TRIDENT) subsystem for the Resource Prospector mission (Figure 1). Over the course of this development there have been a few important lessons learned on the drill mechanism design and on using this particular mechanism for sensing. These lessons include:

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- ❑ Lessons learned with using a Capstan Mechanism as a driving mechanism for linear feed and deployment stages.
- ❑ Proper isolation of temperature sensors to improve the measurement response of sensors embedded in the mechanism.
- ❑ Simplified Slip-ring design to help reduce production time and cost.
- ❑ Materials selection and design of a passive brush system to assist with sample transfer of regolith.
- ❑ Manufacturing approach for brazing Tungsten Carbide (WC) to Titanium (Ti).
- ❑ Replacement of the drill's cable harnesses with three unique Flexible Printed Circuits (FPC) to reduce system mass and increase reliability.

Capstan Mechanism

A capstan mechanism uses a driven spool and a cable pulley system with two independent cables. In the case of the TRIDENT linear feed mechanism, one of the cables routes to the top side of a carriage on a guide rail system and the other cable routes to the bottom side of this carriage. This allows the capstan mechanism to apply force to the carriage in both directions. For instance, when the spool rotates clockwise, the cable attached to the bottom of the carriage will be in tension and pull on the carriage. In this case, the bottom cable gets wound on the spool while the top cable is being unwound. When the spool rotates in the counter-clockwise direction, the opposite is true. In this case, the cable attached to the top of the carriage is in tension and this cable becomes wound on the spool while the bottom cable is unwound.

Figure 1. TRIDENT Drill and Deployment System.

In space flight applications, such as a drill, where a relatively long linear feed stage is required, the capstan feed approach offers some key benefits over other drive mechanisms such as screws and belt drives. The primary benefit is significant mass savings.

When compared to screw mechanisms, the cable pulley type mechanism is also much more robust to dusty environments; can more easily accommodate coefficient of thermal expansion mismatches between the rail and the driving mechanism (i.e. screw or cable); and because the mechanism is not as stiff, the capstan mechanism attenuates more of the vibrations from the percussive drill that are traveling back towards the rover. When compared to belt systems, the capstan offers better material options for cryogenic and vacuum environments and because there are two cables fixed at both ends (one to the carriage and one to the spool), cable slippage is not a possible failure.

The TRIDENT Engineering Test Unit (ETU) is a third generation one-meter class drill that utilizes the capstan for driving linear feed and/or deployment stages. Previous drill designs (IceBreaker [4] and LITA Drill [5]) used a stainless-steel wire rope cable to drive the carriages. These mechanisms worked quite well for both of these drilling systems. On the LITA Drill, there were some fatigue issues with the initial cable selection as the bend radius of the pulleys in the drive system were too small for the cable. However, switching to a more flexible wire arrangement (7 x 19 cable) eliminated any further failures due to fatigue. For the TRIDENT ETU, however, a new challenge existed: selecting a drive cable that could survive not only the vacuum environment, but also the cryogenic environment that can get as low as 40K. After a preliminary study, Technora – a para-aramid fiber cable produced by Teijin Aramid - was selected as the drive cable. This material offered great tensile strength properties and a broad operating temperature range. A PTFE coating on this cable is used to provide some protection against UV degradation.

On paper, the Technora 600 cable appeared to be an excellent choice to replace the stainless-steel wire rope: a 2-mm-diameter cable was rated to 2667 N (600 lbf) of static tension compared to the 2001 N (450 lbf) rating of the wire rope, and both had comparable allowable bend radii. In testing, however, there were some subtle issues that made this type of cable a relatively poor choice for the capstan mechanism. A "finger trap" loop splice at the ends of the cable (Figure 1) created slight diametrical growth and increased fatigue susceptibility within the last 10 cm of the cable. This region is still nearly as flexible as the rest of the cable and was originally designed to pass over the end pulleys to minimize the length of the deployment structures (z-axes). However, this resulted in an early-life cable failure at the end of the spliced area. Instead, this region of each cable should be treated as a "dead zone" (length at the end of a cable that cannot be passed over a pulley), and in fact this length is much larger for Technora than that created by crimped terminations used for wire rope. Fraying and diametrical growth are also observed in all cable areas subjected to fatigue or abrasion: the spool, the pulleys, and the tensioner mechanisms in particular (Figure 2).

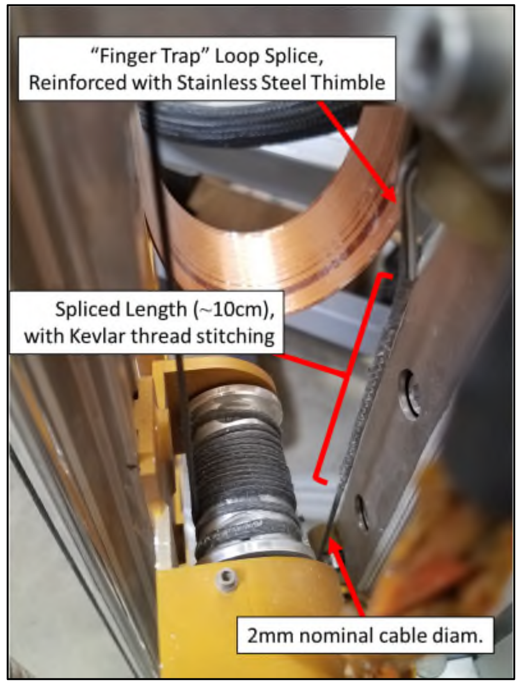


Figure 1. Technora cable termination and spool.

For the cables to wind neatly onto the capstan spool, it works well to use a single row and let the cables route side by side. When using steel cables at low rotational speeds, this is not a problem because of the relative hardness of the wire rope. With the Technora cable (and other fibrous cables) this is far from ideal, however, as the rubbing friction between two cables in contact increases the rate of fraying. The Teijin manufacturer data sheet reports that Technora can abrade up to 219% faster when moving in contact with itself than it does when moving over a metal surface [6]. Once fraying begins, the damage to the cable is amplified as the fibers that fray can get trapped under the wrap on the spool that is adjacent to the frayed portion of the cable. When the cable is being spooled out, these trapped fibers are pulled on with the full force of cable tension. This type of behavior significantly reduces the life of the cable.

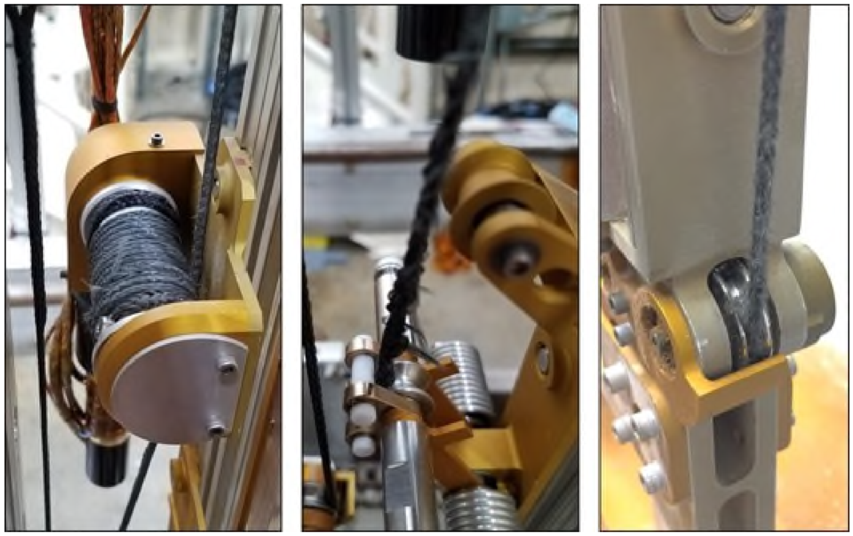


*Figure 2. Fraying observed at various cable bend locations throughout the capstan mechanism (*left – *spool;* center – *tensioner;* right – *pulley).*

In-house testing was conducted to better characterize the expected bending fatigue degradation of the cables. With a minimum mission operational life of eight holes to a depth of one meter each (and an expected “bite” size of 10 cm), the absolute minimum capstan system life is 80 up-and-down Z-stage moves, excluding any factor of safety. A representative load test put different small sections of cable under maximum expected tension (310 N, or 11.6% of the Technora static load rating) and cycled that section up and down over a single 90° pulley bend. When the section tested included part of the loop end termination, cables were found to only survive around 110 cycles and always failed at the end of the splice. When tested in an otherwise featureless middle section, cables could survive more than 250 cycles. No testing was conducted to characterize the wear rate on the spool, but it was believed to have a worse cycle life expectancy than the cable middle segments on the pulleys due to the increased Technora-on-Technora abrasion consideration.

With the failure of the Technora cable, an additional study on rope or cable options was conducted. Again, the most important first consideration is that the cable maintains flexibility in cryogenic environments. Though more tests are required, the cable down selection process thus far has indicated that the titanium wire rope cable is the frontrunner for replacement. The titanium wire rope provides similar fatigue performance characteristics as the stainless-steel wire rope but maintains its ductility properties better at cryogenic temperatures.

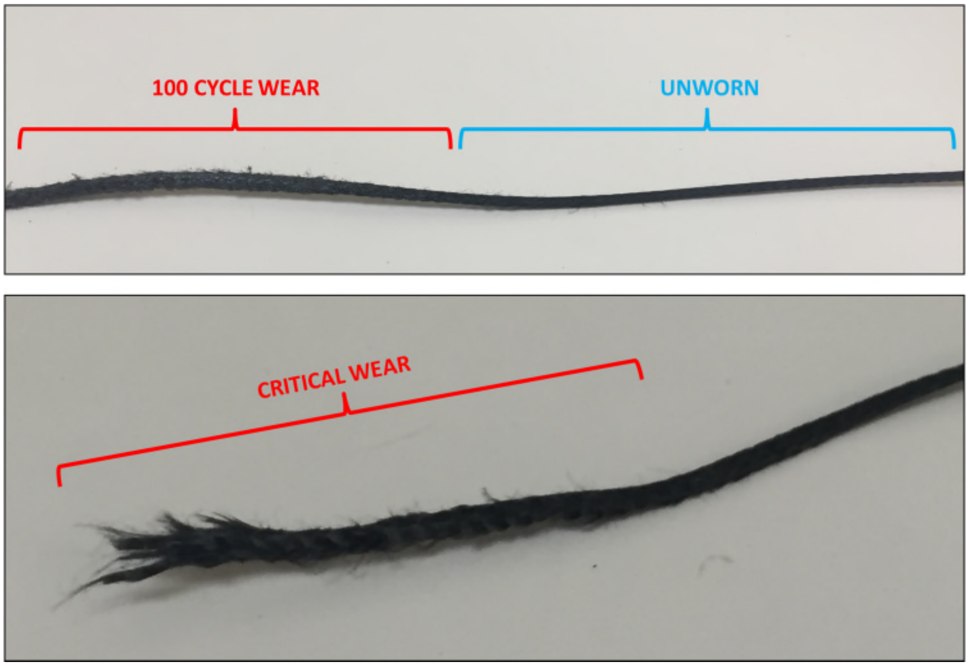


*Figure 3. Cable fatigue characterization test results (*top *– Technora 600 cable with a featureless middle section cycled up and down 100 times over a 90° pulley bend;* bottom *– the same cable after continued testing to failure).*

Using the TRIDENT Drill for Temperature Measurements

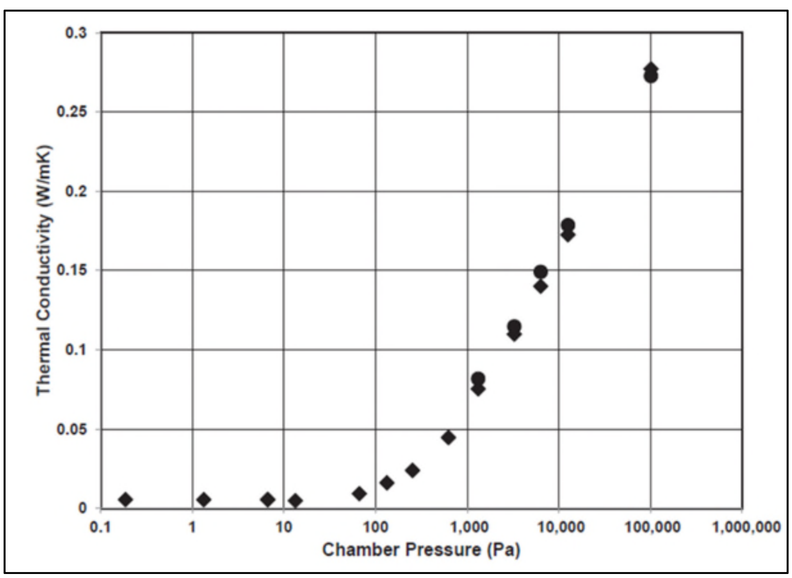


Figure 4. Thermal Conductivity of JSC-1A vs. Atmospheric pressure [7].

Obtaining subsurface regolith measurements on the Moon is difficult because of the low thermal conductivity of the regolith. The thermal conductivity of the lunar regolith (~0.01 W/mK) (Figure 4) is expected to be a few orders of magnitude lower than thermal conductivity of a titanium drill auger (~6.7 W/mK). Of course, variables such as relative water / ice concentrations in the regolith, among other things (particle size, concentration, density) can affect the thermal conductivity of the regolith. Relatively speaking, the baseline concept of drilling operations only allows for a short time duration for temperature measurement, as the drill string is only ever in contact with regolith at depth for a few minutes at a time. This makes the task of measuring the subsurface lunar temperature even more challenging. Two design concepts have been tested that involve embedding a Resistive Temperature Detector (RTD) in the drill string. The first concept had the RTD embedded in the center of the drill bit (near the tungsten carbide cutter - Figure 5, top). The RTD was thermally bonded to the metal structure (in this case 17-4 Stainless

Steel) using a thermally conductive epoxy. The second concept attempted to expose the RTD directly to the lunar regolith and thermally isolate the sensor from the rest of the drill string (Figure 5, bottom).

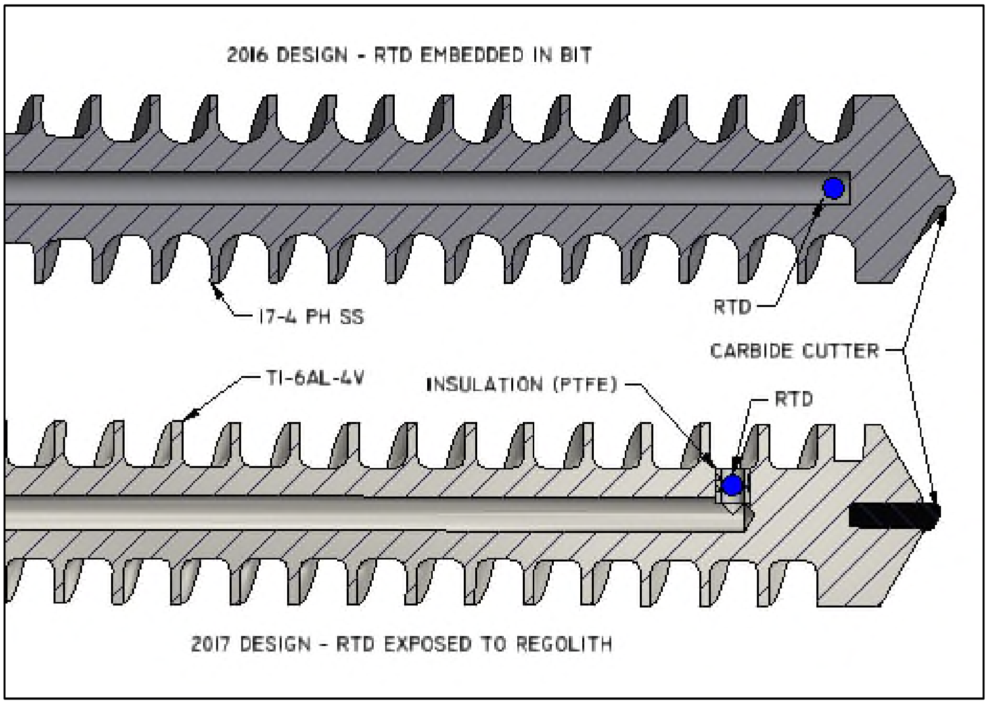


*Figure 5. RTD placement within the TRIDENT drill string (*top *– 2016 design;* bottom *– 2017 design).*

There was a noticeable improvement in response time for the second concept, but the assembly of this option is more complex. The increased assembly complexity for the second concept is because the assembly requires bonding a thermal isolator to the base metal using a thermally insulating epoxy and then bonding the RTD to the insulation using a thermally conductive epoxy. The goal here is ultimately to minimize the mass or thermal inertia of the temperature sensor (including the epoxy used to bond and protect the sensor). Though improvements to the design / assembly can still be made, the initial results show great promise. When comparing the two concepts over a similar operational scenario, it is apparent that the rate of change measured with the RTD is much faster in the 2017 tests (~8°C / min) compared to the 2016 tests (~2°C / min) (Figure 6).

In tests performed in 2016 and 2017, the average regolith temperature was < -100°C with the ambient chamber temperature being < -50°C and atmospheric pressure < 10^{-5} Torr. In both cases, the NU-LHT 3M lunar regolith had 5% weight water added to simulate expected values from LCROSS data. Similar drilling profiles were performed for these tests though the Rate of Penetration (ROP) during the 2017 tests were a little faster than in the 2016 tests. This means that the 2016 tests were putting more energy into the regolith per cm of regolith displaced. During both tests shown here, the power required to displace the regolith was comparable and on average only a few Watts. It is unlikely that the additional energy used during the 2016 test would have account for the large differences in measured temperatures between the two tests. The 2017 test actually started with the drill bit approximately 20°C warmer than in the 2016 test, but was more than 15°C colder by the time a 40-cm depth was reached. Another interesting observation is that the 2016 test never measured a temperature colder than the initial starting temperature of approximately -65°C whereas the sensor in the 2017 test ended up measuring temperatures less than -105°C shortly after reaching a 75-cm depth.

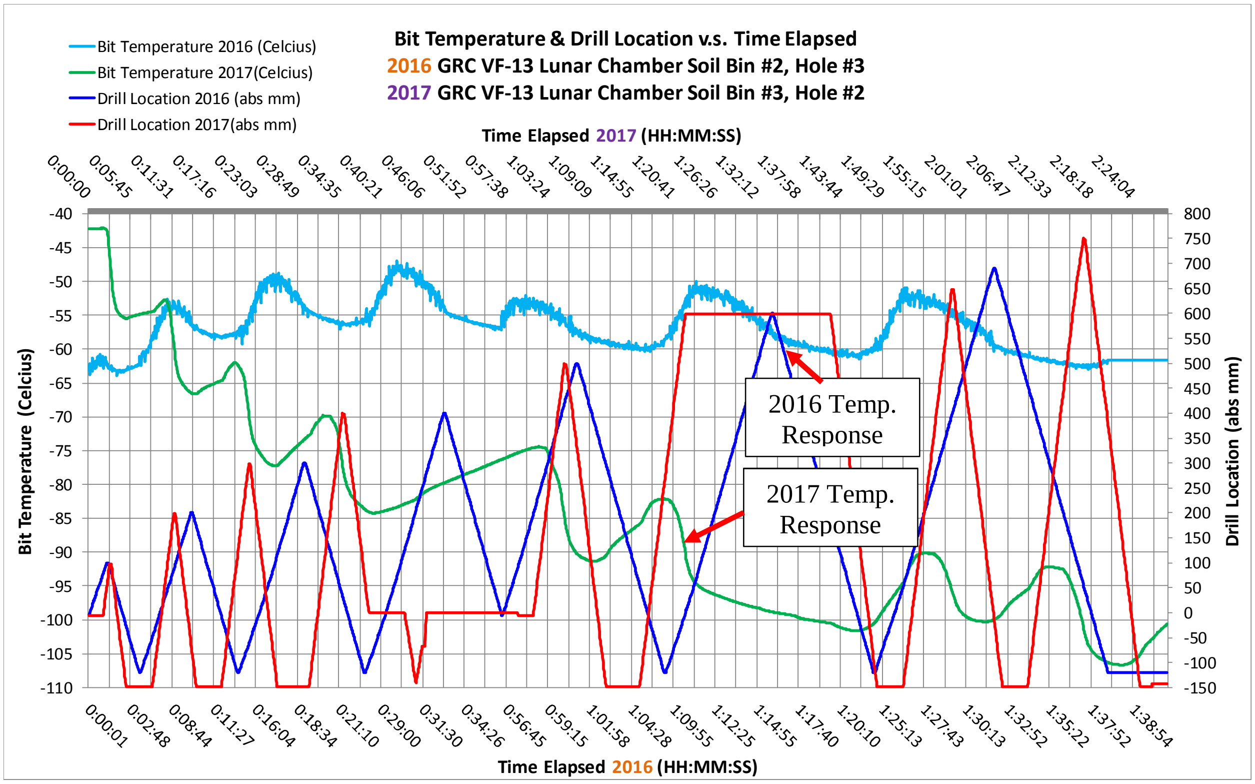


Figure 6. Drill Bit Temperature vs. Depth (2016 & 2017- Original & Modified Design).

There are ongoing analyses being performed to help predict steady state temperatures from the response of the temperature sensors over a relatively short time duration. Vetted models to predict temperatures are required as extrapolation is almost certainly necessary to estimate the actual temperature of the lunar regolith at various depths. Currently the time required for the sensor to reach a steady state temperature measurement is on the order of several hours. Improvements to the sensitivity of the temperature sensor in the form of improved thermal isolation from the drill bit, reduced mass, and reduced thermal resistance between the sensor and the regolith will result in better estimations of the regolith temperature.

Slip-Ring Design

To enable the use of an embedded temperature sensor in the drill bit, it's necessary to use an electrical slip-ring to convey the electrical signal through the rotating auger joint. The drill design preceding TRIDENT was originally designed and built under a different NASA program targeting more terrestrial field testing [4]. In the early stages of the RP program, the drill, then named RP15, underwent random vibration testing to qualification levels. The drill mechanisms all survived and continued to function nominally, except for the slip ring. During the Z axis vibration test (in-axis with the drill bit), the off-the-shelf slip-ring experienced separation between the rotor and the stator at a bonded interface, as shown in Figure 7. Certainly, this commercial-off-the-shelf (COTS) slip-ring was not designed for this environment and definitely not the large response observed at ~110 Hz (Figure 8). Though the COTS slip-ring did survive several hours of testing on the rotary percussive drill system up to this point, the random vibration environment proved to be more than the bonded joint could handle. Given this failure, it was apparent that for the TRIDENT drill design, slip-ring design and/or selection was going to require a more concerted effort.

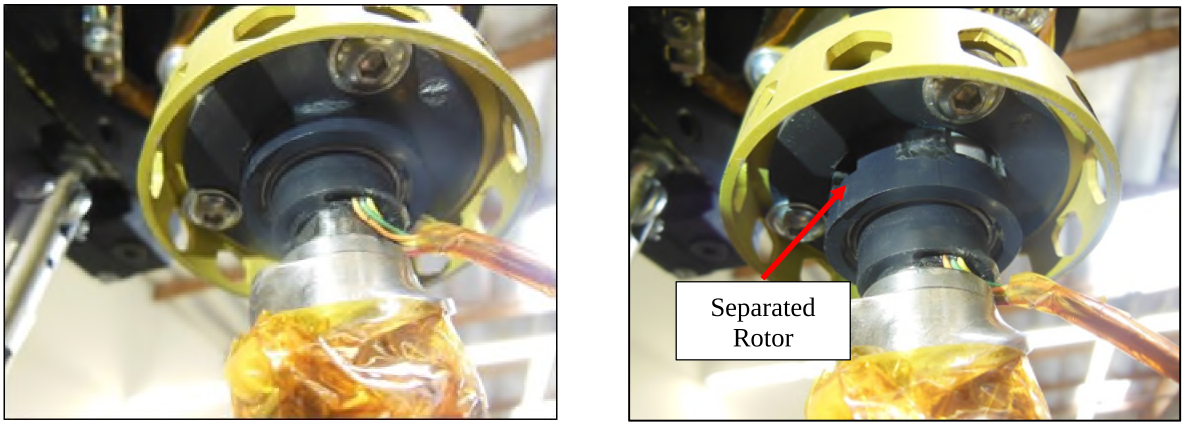


*Figure 7. Slip-ring damage from system random vibration test (*left – *undamaged Slip-ring before test;* right – *damaged Slip-ring after test).*

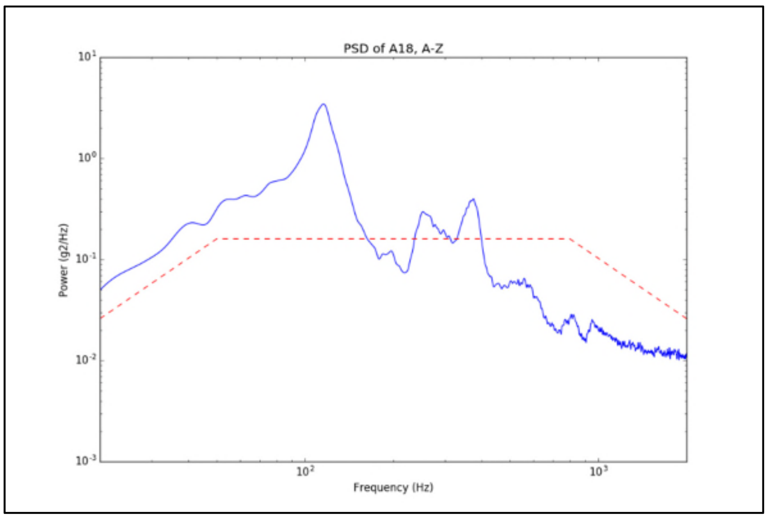
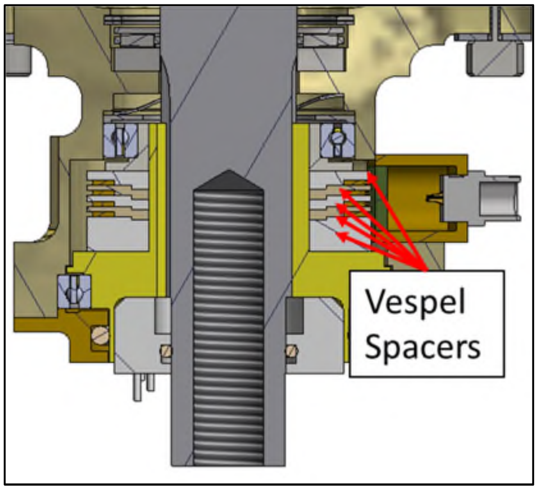


Figure 8. Response of Drill Head Accelerometer during Z-axis Random Vibe.

After researching availability of slip-rings that would meet the form, fit, and function for the TRIDENT drill, it became evident that a custom solution was going to be necessary. To help save on time and costs, the solution for TRIDENT was to design and build the slip-ring using in-house expertise. Fortunately, there existed a heritage design that closely fit the size and signal requirements for TRIDENT. This was a significant benefit to reduce the time required for materials selection, coatings, sizing, etc. However, the heritage process used for space-flight applications to build up the rotor, secure the internal rings in place, and isolate the rings (or channels) from each other is highly involved and quite expensive. The more traditional process was not a financially viable option given the budget available to produce and test the TRIDENT Engineering Test Unit (ETU). Fortunately, this problem had a relatively simple solution which was to use Vespel spacers to isolate and constrain the conductive rings (Figure 9).



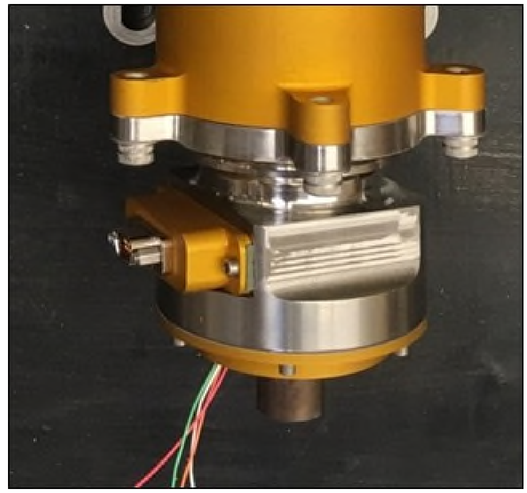
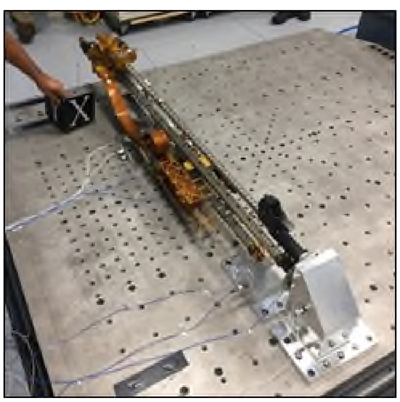


*Figure 9. Slip-ring assembly overview (*left – *assembly cross section showing Vespel spacers;* right – *final assembly).*

Once this solution was realized, the design and fabrication of the hardware was completed. The slip-ring assembly was then assembled and integrated into the TRIDENT ETU. To date, the TRIDENT slip-ring continues to perform as designed (the 2017 temperature response from Figure 6 is evidence of its functionality). This mechanism, along with the rest of the TRIDENT drill, went through the same vibrational test procedure as the RP 15 drill. However, improved designs for launch lock concepts greatly reduced the response at the drill head (Figure 10). It's conceivable that the COTS slip-ring may have survived the significantly reduced loading experienced at the drill head during this test. However, other environmental factors (temperature, atmospheric pressure, etc.) also dictate the necessity of a custom slip-ring for this application.



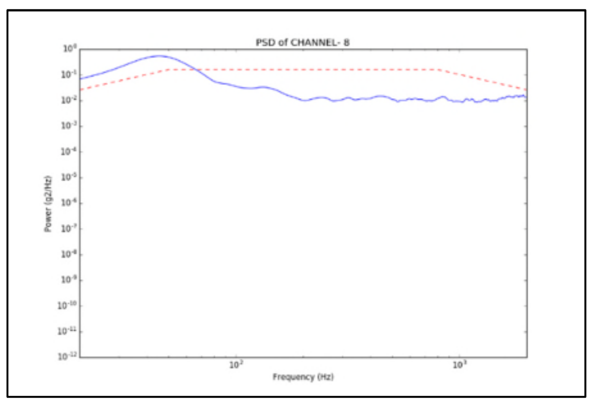


*Figure 10. Improved fixtures / launch lock concepts for the TRIDENT drill in random vibration testing (*left – *drill on vibration table;* right – *significantly reduced response at the drill head).*

Passive Brush for Sample Transfer

One of the key systems in ensuring enough sample is delivered to the OVEN subsystems is a passive brushing system designed to help remove regolith from the drill auger and direct it to a chute leading to the OVEN crucible. The RP environmental requirements have greatly reduced the trade space for materials that can be used in the passive brush. To protect against electrostatic charge build up, the brush material had to be conductive while also remaining flexible at cryogenic temperatures. The effectiveness of the brush at removing regolith from the auger is dependent on a number of factors which include: cohesiveness of regolith, size of brush bristles, length of brush bristles, stiffness of material used for the brush bristles, wear rate of the bristle material, and position of the brush with respect to the auger.

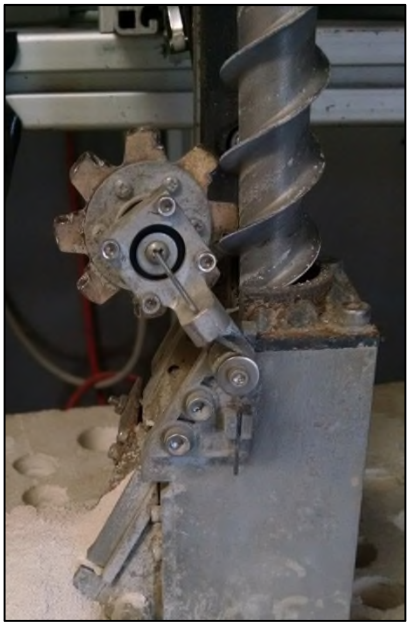


Figure 11. Keyed scraper for IceBreaker (a TRIDENT predecessor drill) [5].

The trade space studied included brass brushes of various bristle and brush diameters, Tampico, Thunderon, and conductive Nylon 66 (Table 1). Regolith used for the testing included JSC 1A and NU-LHT 2M Lunar regolith. Criteria used to evaluate the various brush materials included electrical conductivity; brush life expectancy, and effectiveness of cleaning debris from the drill string. Observations from the testing were:

- ❑ Bronze offered excellent electrical conductivity & was the most effective cleaner, but experienced significant wear after only a single hole which has a significant effect on the ability to clean the drill string for subsequent drilled holes.
- ❑ Thunderon fibers were too small to be an effective cleaner.
- ❑ Tampico cleaned sufficiently well, had sufficient life expectancy, but because it is a natural fiber, it will have more variance in conductivity.
- ❑ Conductive Nylon 66 cleaned sufficiently well, had sufficient life expectancy, and excellent conductivity.

Table 1. Brush materials and physical dimensions.

Material	Bristle Diameter mm (in)	Outside Diameter mm (in)	Brush Thickness mm (in)
Bronze	0.152 (0.006)	63.5 (2.5)	9.53 (0.375)
Bronze	0.356 (0.014)	63.5 (2.5)	9.53 (0.375)
Bronze	0.356 (0.014)	76.2 (3.0)	15.88 (0.625)
Tampico	0.203 (0.008)	63.5 (2.5)	9.53 (0.375)
Tampico	0.203 (0.008)	76.2 (3.0)	9.53 (0.375)
Thunderon	0.051 (0.002)	63.5 (2.5)	9.53 (0.375)
Conductive Nylon 66	0.203 (0.008)	76.2 (3.0)	9.53 (0.375)

Though test results thus far have been instructive in selecting the appropriate brush parameters, there is still much that can be improved. Other items to investigate are: alternative brush materials (other than what has already been tested - i.e. titanium) and alternative brush mounting configurations. The end goal driving the selection is ultimately based on the volume of material that the brush helps deliver to the instruments and the consistency of the volume delivered.

Traditional brushes were not the only thing considered to remove material from the auger flutes. A spring-loaded and rotating scraper design was also considered (Figure 11). This design was used on a preceding drill design and was largely more effective at removing more cohesive cuttings than traditional brushes. A prototype design was built and tested for the RP drill (Figure 12). One challenge in this case was designing the rotating scraper to interact with both fine pitch and coarse pitch flutes on the auger. For the TRIDENT drill, this variable pitch combination is necessary to help retain cuttings / regolith near the bit (fine pitch) for delivery to other instruments and more efficiently transfer cuttings / regolith through the remaining auger length (coarse pitch). Though the concept would work well while operating in either section of the auger (fine or coarse pitch), the transition point between the fine and coarse pitch flutes was a failure point for this mechanism. The primary reason causing the failure is that the coarse pitch flute requires the scraper to rotate twice as fast as the fine pitch flute because the pitch of the coarse flute is twice that of the fine pitch flute. This discrepancy could not be easily reconciled for this sample transfer approach.

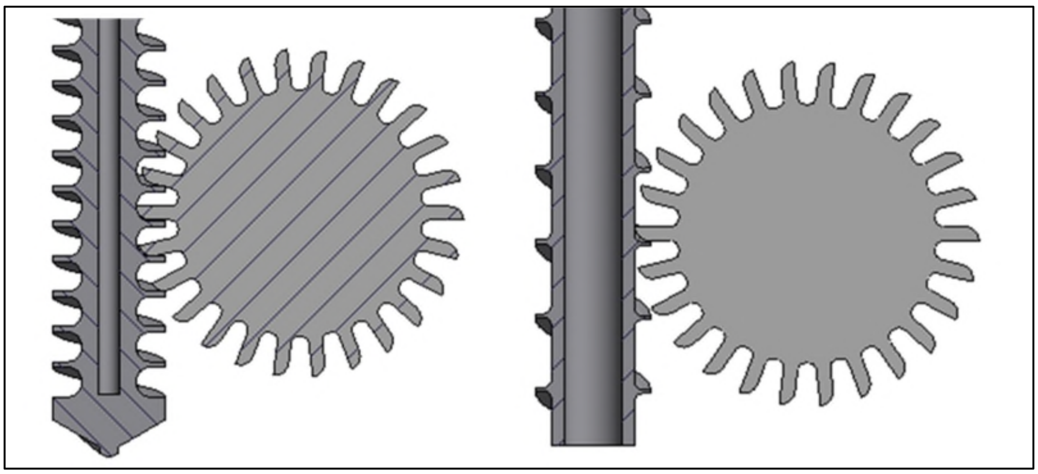


*Figure 12. Single Rotating Scraper design (*left *– scraper interacting with fine pitch flutes;* right *– scraper interacting with coarse pitch flutes).*

Although the brush has an obvious direct impact in the performance of the sample cleaning system, the mechanism supporting the brush is equally important. For both the 2016 and 2017 tests, the same conductive nylon brush design was used. However, there were significant performance differences. In 2016, a single brush lasted the entire test phase with minimal wear. In 2017, it was apparent that the brush stopped rotating as significant wear on only one part of the brush was observed after only a few tests (after which the brush had to be replaced). Two factors likely led to this change: one was an offset on the axis of the brush in the 2017 test to bias the brush towards one side of the auger; the other factor was a design modification in the 2017 design to help better protect the brush bearings by adding a seal between the brush housing cavity and the bearings for each bearing (Figure 13).

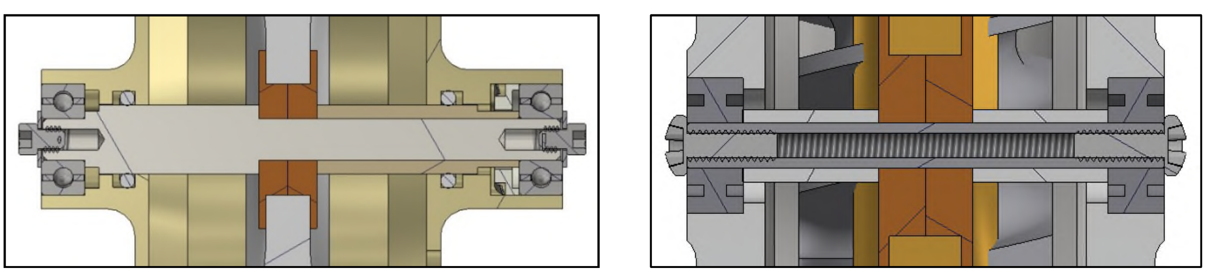


Figure 13. TRIDENT brush mechanism cross-sections (left - 2017 TRIDENT brush mechanism; right – 2016 RP15 brush mechanism).

Adding the axial offset in the brush was originally intended to help improve removal of cuttings / regolith from the drill string. However, this offset led to periodic pinching of bristles between the auger and auger tube which would ultimately pull out or shear bristles in the brush. If this happens enough in one section of the brush, there is no longer enough bristle engagement with the auger to cause the brush to rotate. Of course, this also reduces the ability of the brush to clean the auger.

Using seals to better protect the bearings also had a negative impact on the brush. For the 2016 configuration, the design was more simplistic and only relied on bearing shields to protect the bearings. Though this wasn't ideal, given the proximity of the bearings to regolith dust, these bearings had never failed – low speeds, cycles, and loads minimized the chances of failure in the bearings. The seals added in the 2017 design were entirely precautionary, but the increased drag from the seals made brush rotation more difficult and contributed to a reduction in the life of the brush

Design improvements around the brush and brush support are both necessary to help improve sample transfer efficiency. One design that can be leveraged to support the brush may be the design built to support the Atacama Rover Astrobiology Drilling Studies (ARADS) project [8]. This particular design (Figure 14) utilizes a rotating scraper (the ARADS drill has a constant auger pitch) that is supported on a cantilevered arm. The scraper could be replaced with a brush and the mechanism can be simplified due to the more compliant nature of a brush compared to the more rigid scraper (i.e. spring loaded arm is not required).

Figure 14. Alternative Support to use for brush (scraper shown here).

Brazing Tungsten Carbide (WC) to Titanium

To help reduce the overall system mass for the TRIDENT ETU, a titanium drill string was used instead of a stainless-steel drill string (as was used on RP15). This change introduced a new challenge of bonding the tungsten carbide (WC) cutter to the titanium drill string. Given the properties of titanium, a vacuum brazing approach is required. Also non-traditional brazing materials must be utilized. Because this is not a common process, there are not many vendors that have the capabilities or knowledge to perform this properly. In this case, a third-party vendor (Titanium-Brazing) was used to perform this work.

Figure 15. Assembled drill bits with deposited brazing paste in graphite support.

A standard titanium-based filler metal TiBraze200 (AWS BTi-5) reinforced by 20% of niobium particles was used for brazing. Melting temperature of the filler metal TiBraze200 is 863°C, melting temperature of niobium is 2477°C. Therefore, niobium powder is not melted together with the matrix TiBraze200 but is reinforcing it to improve strength of brazed joints. Also, the un-melted niobium powder increases viscosity of the melt to fill out uncontrolled, non-capillary gaps that may appear after assembling carbide tips with titanium drill bodies.

Brazing paste was deposited inside the slot in the drill body, then the carbide tip was inserted into the slot and compressed. A simple graphite fixture was manufactured to support assembled parts and fix them in the vertical position during heating and cooling in the vacuum furnace. Assembled drill bits with the deposited brazing paste are shown in Figure 15. The graphite support with parts to be brazed were positioned in the vacuum furnace. An alumina ceramic plate loaded by the "dead weight" ~250 g (0.5 lb) was placed on top of carbide tips in order to compress them after melting the brazing filler metal.

Overall, the brazing process was successful at bonding the WC cutters to the Titanium auger. No voids were found in the brazed joints, but there were rolls of excessive filler metal on the surface of the titanium bodies. The rolls were formed because brazing paste had to be deposited outside of the gap to provide enough filler metal. Also, a few of the WC bits were bonded noticeably off-center as they shifted during the brazing process. Recommendations to improve this process would be to add holes or grooves to the WC insert to provide more volume for the filler metal to reside between the insert and the Titanium auger. Also, an improved fixture design is necessary to help keep the insert on center with the auger axis during the brazing process.

Flexible Printed Circuit Cable Harness

TRIDENT ETU's cable harnessing system consists of three unique flexible printed circuits (FPCs). The first circuit carries motor power signals, the second circuit carries motor feedback signals, and the third carries heater and RTD signals. Each circuit is around 65 in (1.65 m) in length, 2 in (5 cm) in width and less than 0.015 in (1.3 mm) in thickness. The three circuits are stacked and joined together via twelve thru-hole right angled MIL-DT-83513 Micro-D connectors, which in turn translates to 148 discrete wires with a current carrying capacity of 3 ampere on each pin.

The FPC assembly approach offers numerous advantages over a discrete wire harness assembly. The motor power and motor feedback FPCs each have its own integrated crossed-hatched copper shields to protect the drill and other subsystems from Electromagnetic Interference (EMI) and reduce signal cross-talk. The mass of the cable harnesses was also reduced by 85% (from 7 lb to 0.5 lb (3 kg to 0.2 kg)) in comparison to the RP15 Drill (Figure 16 and Figure 17).

The FPC assembly has proven to be extremely robust since the base dielectric and coverlay material of are all made from Polyimide (e.g. Kapton). Not only does this perform well in cryogenic application, it also provides excellent electrical insulation and low outgassing profile in the vacuum environment.

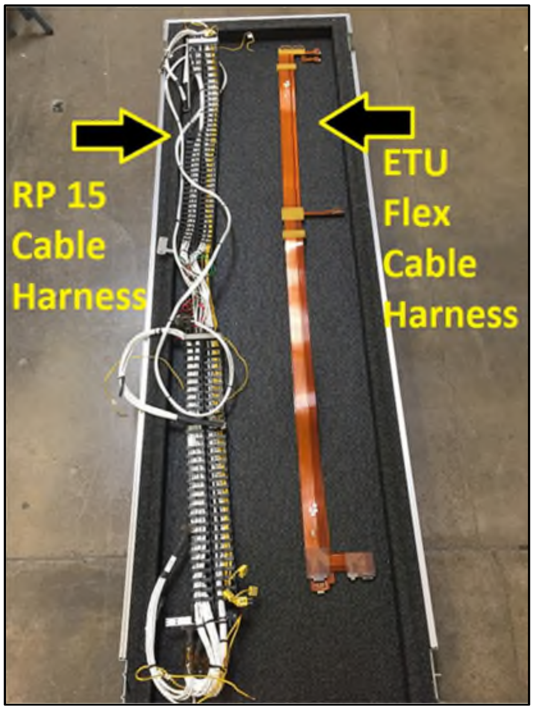


Figure 16. Side by side comparison of RP15 cable harness with TRIDENT ETU flex cable harness.

Figure 17. Reduced bulkiness and mass from RP15 (left) to TRIDENT (right).

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