# Rotary Percussive Sample Acquisition Tool (SAT): Hardware Development and Testing

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## Abstract

In support of a potential Mars Sample Return mission, an Integrated Mars Sample Acquisition and Handling (IMSAH) architecture has been proposed to provide a means for Rover-based end-to-end sample capture and caching. A key enabling feature of the architecture is the use of a low mass Sample Acquisition Tool (SAT) that is capable of drilling and capturing rock cores directly within a sample tube in order to maintain sample integrity and prevent contamination across the sample chain. As such, this paper will describe the development and testing of a low mass rotary percussive SAT that has been shown to provide a means for core generation, fracture, and capture.

## Introduction

As part of a potential Mars Sample Return campaign NASA and the European Space Agency are mutually working on a Mars 2018 Joint Rover Mission to potentially send a rover to Mars in order to perform in-situ investigations as well as collection of Martian samples for a return to Earth upon a subsequent mission. As such, it is foreseen that a key NASA payload contribution is the development of a Sample Acquisition and Caching subsystem capable of acquiring Martian rock cores and soil samples that could be cached within a return canister. Once the samples have been successfully cached within the return canister, the canister would be placed on the Martian surface. A follow-on mission element would then utilize a fetch rover to pick up the return canister and place it within a Mars Ascent Vehicle which would be capable of inserting the canister into a passive orbit around Mars. A third and final element of the campaign would then rendezvous with the return canister and return it to Earth [1], [2], [3].


**Figure 1. Integrated sample acquisition and caching prototype subsystem.**

In support of the development of the Sample Acquisition and Caching subsystem, the Integrated Mars Sample Acquisition and Handling (IMSAH) architecture was developed in order to advance the key

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elements necessary for end-to-end sample generation and containerization. The IMSAH architecture has been presented in depth in previous publications [4], [5], [6], [7], and is characterized by three major sub-elements as shown in Figure 1:

1. Tool Deployment Device (TDD)

2. Sample Acquisition Tool (SAT)

3. Sample Handling Encapsulation and Containerization (SHEC).

The corresponding operational process of the specified hardware as it pertains to the IMSAH architecture is depicted in Figures 2 and 3 and defined by the following operational needs [4] [7]:

- Sample transfer between the coring tool (SAT) and the caching mechanism (SHEC) is to occur by means of bit change-out

- Acquire samples into individual sample tubes in order to preserve sample integrity and minimize the risk associated with handling cores of unknown geometry.

- Utilize a rotary percussion mechanism for the Sample Acquisition Tool in order to reduce subsystem mass and maximize efficiency. The use of a rotary percussive coring tool allows for successful coring at a reduced weight on bit (i.e., lower arm preload), minimizes bit walk due to spindle rotation, and allows for robust hole start when compared with rotary only alternatives.

- The coring tool deployment, alignment, preload, and feed would be performed using a five degree-of-freedom (DOF) robotic arm. By using the specified deployment arm the system has enough DOFs to provide tool alignment and accommodate modest rover slip.

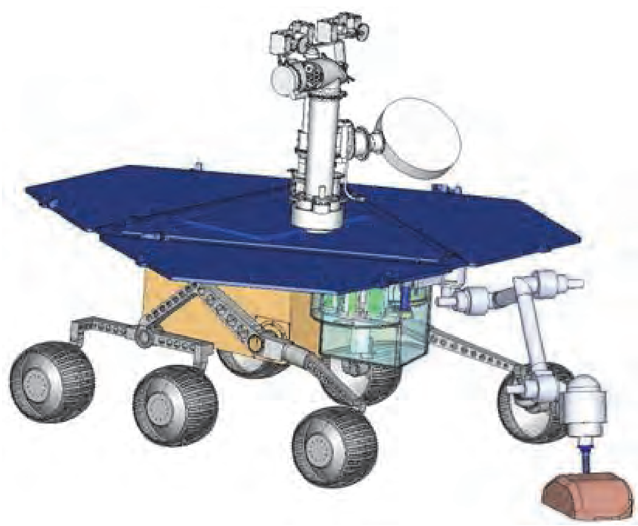

**Figure 2. IMSAH coring tool deployment**

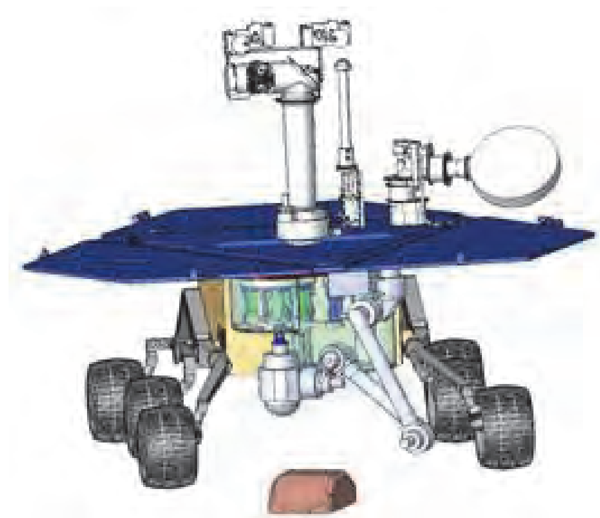

**Figure 3. Bit change-out and sample transfer configuration**

Of the three IMSAH sub-elements, this paper will focus on the development of the rotary percussive Sample Acquisition Tool (SAT) with an emphasis on the tool's mechanism designs, testing challenges, and lessons learned.

**Sample Acquisition Tool Description & Requirements**

The proposed IMSAH architecutre allows for a less complex tool to be developed than what has previously been investigated or developed as it allows for the use of the TDD for both tool deployment, alignment, preload, and feed. These previous tools required stability tines due to the use of an integral 1-DOF linear feed mechanism which in turn results in the need for greater drilling preload and therefore greater demands on the tool deployment system. Furthermore, the use of the TDD as the linear feed allows for the employment of a sprung linear compliance stage between the turret and the coring tool to provide for both dynamic isolation of linear motion as well as extended linear range of motion during operation under light arm preloads.

In order to satisfy the IMSAH operational needs, as described in the previous section, the SAT was designed to provide for autonomous core generation, core fracture/retention, and bit change-out. The resulting functions necessary to perform these operations have been identified and listed as requirements as follows:

1. Acquire rock cores with approximately 1 cm in diameter by 5 cm in length.

2. Acquire at least 20 rock cores for return.

3. Acquire samples from Kaolinite, Santa Barbara Limestone, Siltstone, Saddleback Basalt, and Volcanic Breccia.

4. Be able to eject a bit that is inadvertently stuck in a rock

5. Be robust to anomalous cores that may be broken in the bit and/or at the bit opening.

6. Account for catastrophic slip conditions where it is presumed the rover experiences a significant shift in position while the SAT tool is in the ground.

7. Cores need to be of appropriate quality and suitable for caching

It is important to note that during the development effort the determination of the tool's performance as it pertains to core quality was a qualitatve assessment that binned the generated cores into three categories as described below and represented in Figure 4:

- Good – full length cores or in a few segments

- Acceptable – mostly segments, discs, and/or pucks

- Bad – Powder and/or small chunks, stratigraphy not maintained

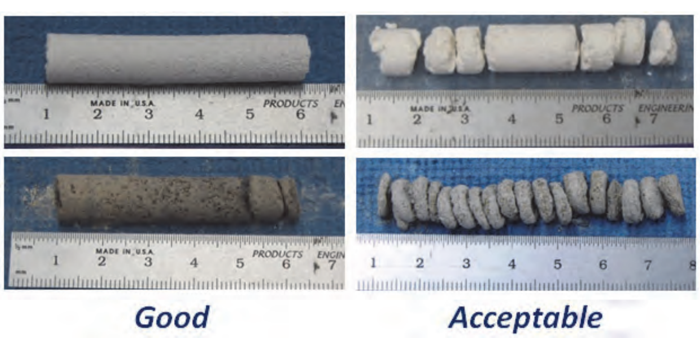


**Figure 4. Assessment of core quality based on qualitative parameters.**

The subsequent sections will provide detailed information associated with the development and testing of the tool as well as resultant lessons learned. The sections are arranged to give a general overview of the SAT followed by greater detail of the four SAT subassemblies/mechanisms.

**Sample Acquisition Tool (SAT) Design & Testing**

SAT Assembly Overview

Figure 5 provides a general overview of the completed sampling tool. The developed SAT is a rotary percussive coring tool comprised of four mechanical subassemblies – the Spindle Percussion Assembly (SPA), the Core Breakoff Assembly (CBO), the Magnetic Chuck Assembly (MCA), and the Core Bit Assembly (CBA). The mechanisms are driven by a total of three dc brushless motors mated to gear heads which provide the necessary actuation to complete the critical functions for core generation, fracture, and capture.


**Figure 5. Rotary Percussive Sample Acquisition Tool (SAT)**


**Figure 6. Core Quality Results**

In order to validate the tool's unit level functionality a series of verification and validation tests have been performed using a rock test suite that encompasses a variety of rock types that are analogous to Martian rocks (as specified in the requirements) and have been used in the past to qualify Martian surface sampling hardware. The results of the testing have shown the tool can successfully generate, fracture, and capture rock cores within a sample tube for all of the rocks within the test suite while maintaining an appropriate level of core quality, see Figure 6.

SAT General Hardware Development Lessons Learned

Early on in the tool's development it became apparent, as with most R&D efforts, that schedule and resources were going to be severely limited. As such, it was assessed that the tool design should be somewhat modular, and implement mechanisms and corresponding subassembly interfaces such that each mechanism could be tested and operated independently of the others. Doing so provided for several advantages:

- Mechanisms could be developed relatively independently of the others as long as interfaces were maintained and negotiated.
- Mechanisms could be tested at a subassembly level allowing for early performance/capability investigations prior to tool integration.
- Resultant modularity allows for relatively easy assembly/disassembly of tool during anomalous behavior investigations and allows for the isolation of possible suspect mechanism behavior.

## Spindle Percussion Assembly (SPA) Design & Development

<u>SPA Overview</u>
Figures 7 and 8 provide an overview of the Spindle Percussion Assembly (SPA) within the SAT. The SPA is a linked spindle/percussion mechanism that provides the rotational DOF necessary to drive the Core Bit Assembly through the spindle drivetrain. In turn, the rotational DOF is translated to axial motion through the use of a cam and lever which drives a striker mass and provides the necessary impact energy to facilitate rock fracture. Since the tool development was intended to be a single point design, a linked spindle percussion mechanism was chosen early in the development life cycle because it allowed for a reduction in the number of required actuators and a lower tool mass.

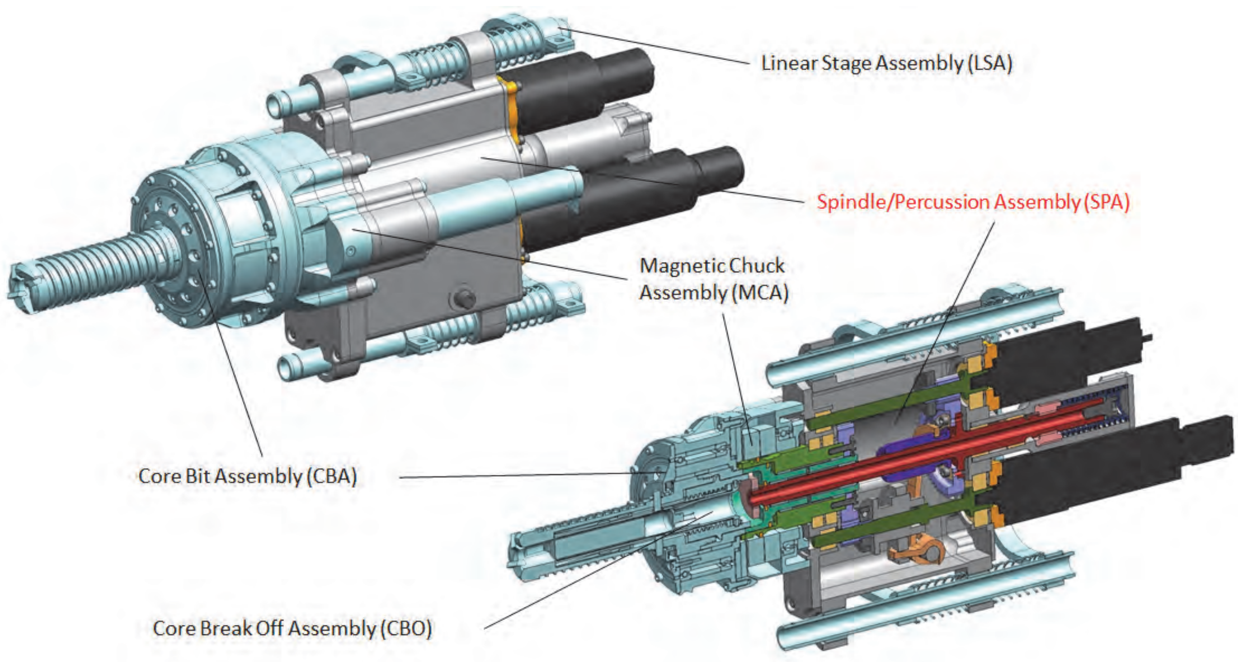


**Figure 7. General overview of SPA within the SAT**

In order to verify the SPA's ability to generate the necessary impact energy, a standalone test was devised using high-speed video to monitor the striker velocity upon contact with the anvil for a given spindle speed (see Figure 9). Due to the linked spindle/percussion mechanism, the impact energy is presented as a function of spindle speed.

The initial SPA design implemented a striker mass of approximately 51 g based on preliminary percussion development tests. However, due to a design error in the lever stroke length the resultant impact energy was approximately 20% less than the intended design point resulting in the need to increase the striker mass to approximately 61 g. However, during additional testing it also became apparent that the losses downstream of where impact energy was being measured were greater than initially expected. As resources were not available to fully investigate the system losses, a final striker mass of 121 g (approximately 2x the 61 g striker mass and the largest striker than could be implemented within the assembly constraints) was selected in order to ensure that an appropriate level of margin could be maintained during drill operations in the harder rocks of the proposed test suite.

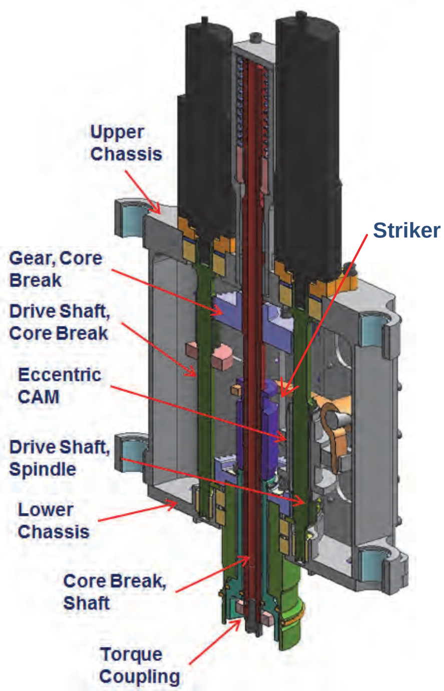


Figure 8. General schematic of SPA

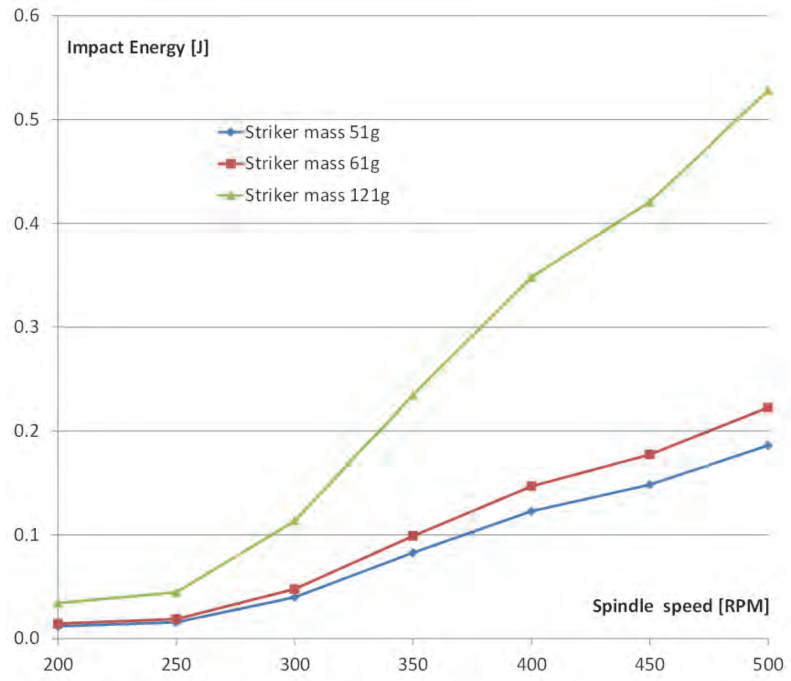


Figure 9. Impact energy at a range of spindle speeds for a variety of striker masses.

<u>SPA Lessons Learned</u>

Several design choices were selected early in the development life cycle because they allowed for either a reduction in the number of actuators or resulted in a lower tool mass. In addition, a fair amount of effort was spent on trying to provide an optimized system in terms of generated impact energy vs. performance. However, in retrospect several noticeable drawbacks cropped up by pursuing these routes:

- Linked mechanisms provide for reduced flexibility in terms of which “knobs” can be turned when investigating tool performance and capability. If the required mechanism capability is clearly defined (i.e., flight like requirements are already known) this may be less of an issue. However, during early development efforts this is not necessarily the case and can actually limit one’s ability to investigate anomalous behavior due to either ill-defined requirements or test parameters.

- Due to the overall complexity of the mechanism, trying to provide an optimized system is very challenging especially due to the number of variables that can affect performance. During early development efforts greater emphasis should be placed on ensuring a high degree of capability rather than optimization as the tool will be utilized extensively to derive “flight” capability requirements. The optimization could then more successfully be implemented during the flight development effort. This is especially true for sampling mechanisms.

**Magnetic Chuck Assembly (MCA) Design & Testing**

MCA Overview

Figures 10 and 11 provide an overview of the Magnetic Chuck Assembly (MCA). The main design driver for the MCA was associated with the desire to allow for a passive breakaway of the Core Bit Assembly under a rover slip condition during drilling. The implementation of a passive release also required that a low-profile separation interface be maintained to prevent an off-nominal loading condition in the event of a hardware hangup or snag occuring during interface separation As such, the MCA design utilizes two permanent magnets (one fixed and one with a rotational degree of freedom) to create a magnetic interface that can be turned on (engaged) or turned off (disengaged) while maintaining a very low-profile separation interface.

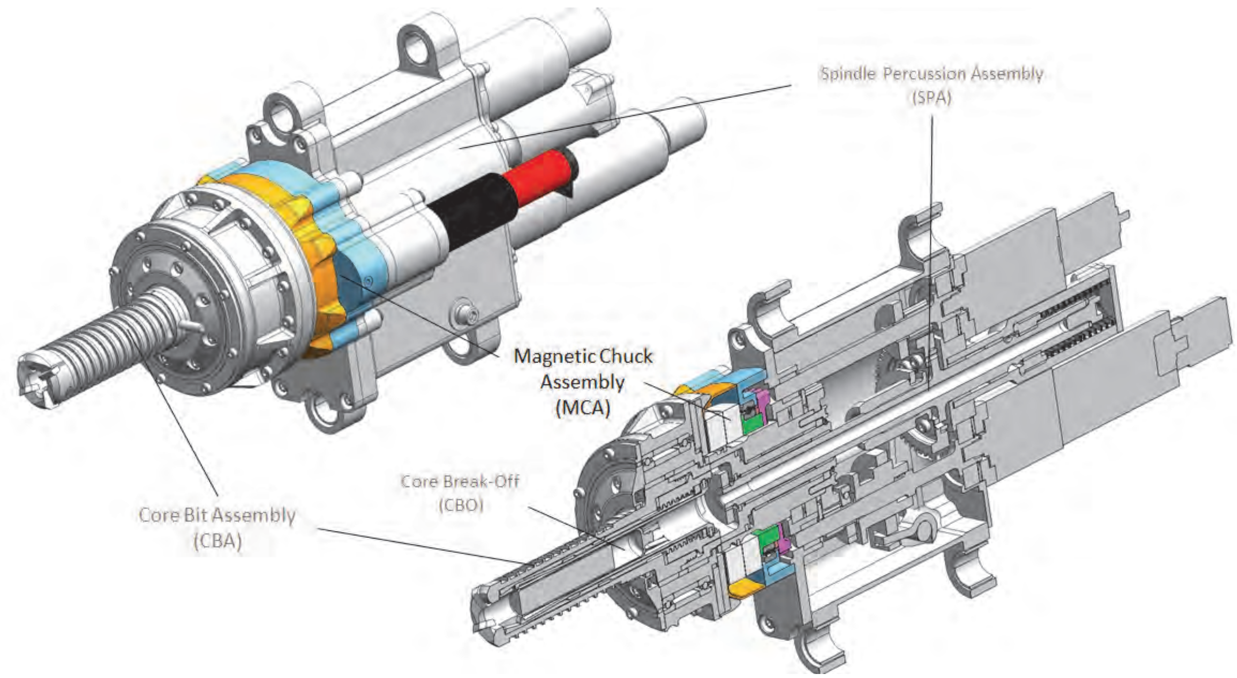


**Figure 10. General overview of MCA within SAT**

Upon testing, the MCA was shown to function as intended and the bit could be passively released under a given separation load of 100 N at the bit tip. In order to utilize the magnetic chuck approach, several compromises were required in terms of material selection. In order to prevent unwanted interactions between the MCA and adjacent mechanisms, several torque coupling interfaces and drive shafts were machined from non-magnetic A286 which could not be hardened as much as desired. In anticipation of the accelerated wear that would occur on these compromised interfaces, additional material was provided to allow for increased torque coupling wear during operation while preserving the tool's functional lifetime. As expected, accelerated wear was noticed during testing at the specified torque coupling interfaces (see Figure 12).

MCA Lessons Learned

In order to employ a new and novel approach for bit retention it became apparent that several common mechanism design issues would need to be considered:

- More often than not some type of compromise (e.g. accelerated wear of low hardness materials at torque interfaces due to material selection contraints) often results that may not present itself until the hardware is well into its verification and validation testing. As such, recognizing this compromise early in the design processes may allow for a better anticipation of the actual hardware performance and possible mitigation paths.

- This also clearly highlights the need to address hardware durability early in the design lifecycle as well as providing a means for graceful degradation.

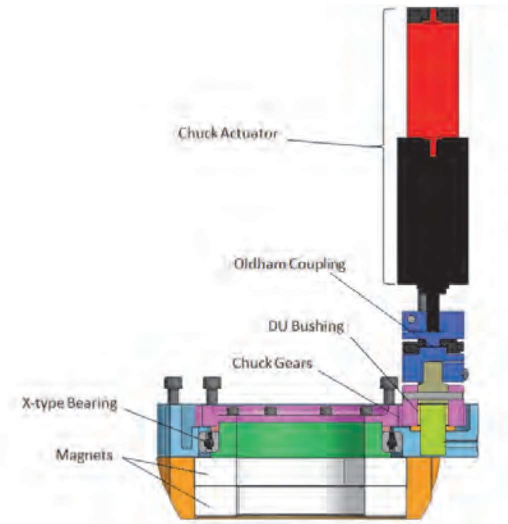


**Figure 11. General schematic of MCA**

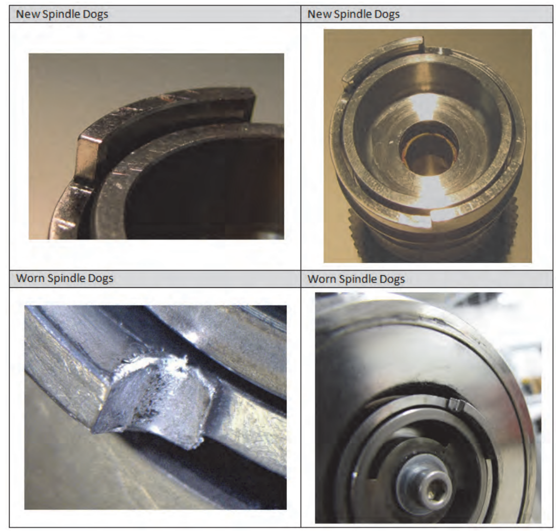


**Figure 12. Accelerated wear at torque couplings**

**Core Bit Assembly (CBA) Design & Testing**

CBA Overview

Figures 13 and 14 provide an overview of the Core Bit Assembly (CBA). The CBA is used to provide the mechanical constraints for the Core Break-Off Mechanism and to accept the impact energy and the rotational input from the Spindle Percussion Assembly. The main component of the CBA is the custom drill bit which is supported by a duplex bearing pair and is free to translate axially within a sleeved bushing to allow maximum transmission of the applied impact energy to the rock. The drill bit is based on a COTS coring bit tooth configuration with two external helical flutes for cuttings removal.

Due to the choice of implementing a magnetic chuck, a large overall chuck interface was required for the CBA. This in turn resulted in a large bit housing which inadvertently reduced the tool's capability to accommodate large surface irregularities in the rock as well drilling full-depth holes at off-normal angles (see Figure 15). Furthermore, the large diameter has downstream impacts to the overall IMSAH architecture volume and mass as the SHEC houses the spare bits.

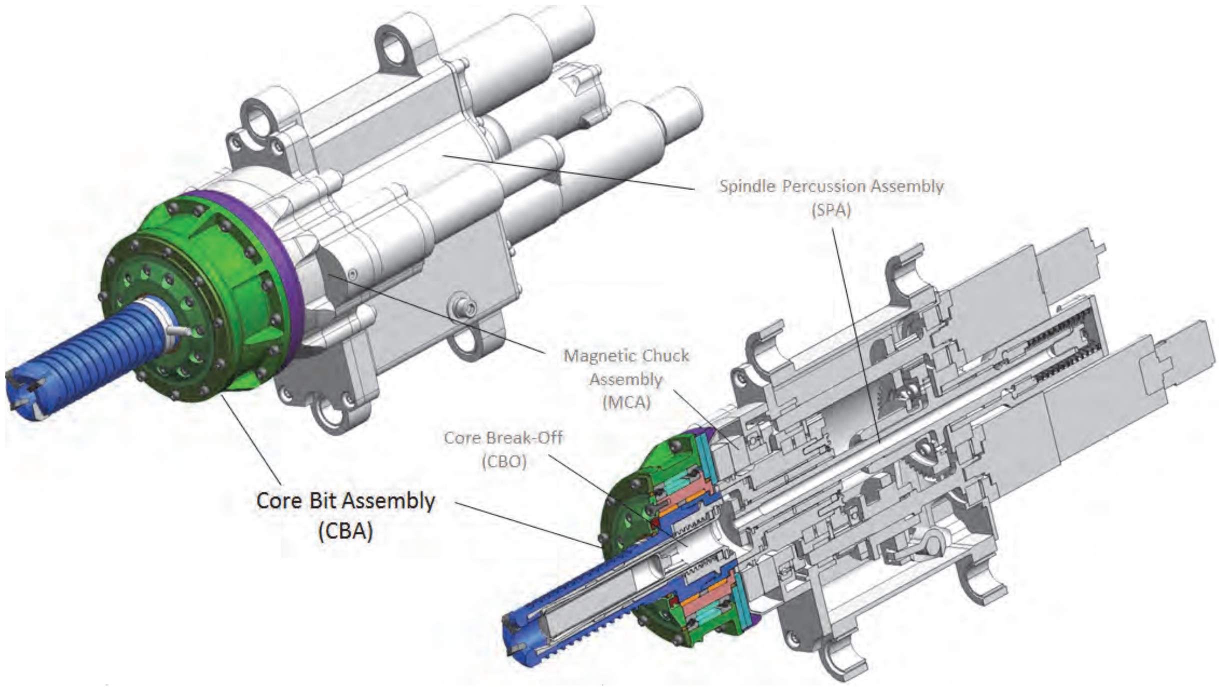


**Figure 13. General overview of CBA within SAT**

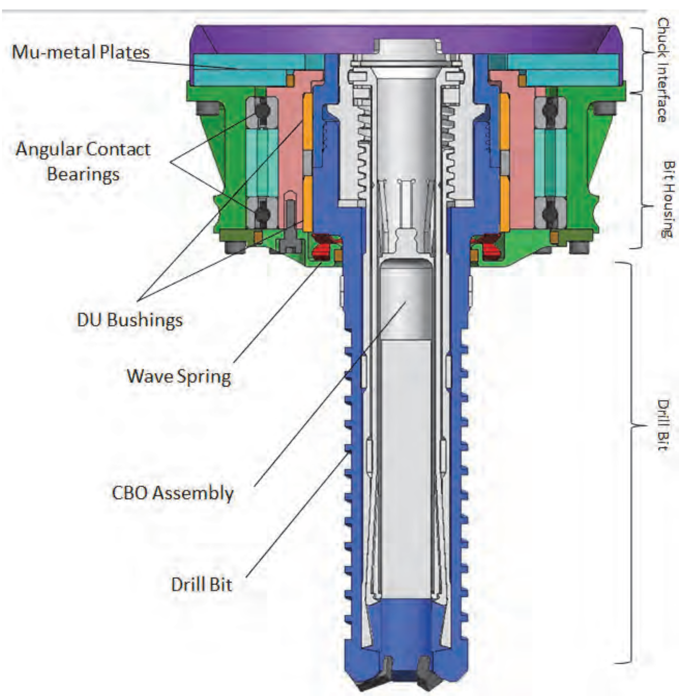


**Figure 14. General schematic of the CBA**


**Figure 15. Tool cannot accommodate large surface irregularities or drilling at off-normal angles due to minimal clearance between bit housing and rock.**

During the tool development it was presumed that the amount of rock that needs to be removed as well as bit tooth wear play a significant factor in the tool's rate of penetration performance. Since the ID of the bit is based on a desired core size of 9.9 mm (0.39 inch), the amount of material that is removed during drilling (and the corresponding bit face surface area) is driven by the coring bits outer diameter. Furthermore, because the coring bit houses the Core Break-Off mechanism understanding the tool's sensitivity to bit diameter would be useful for follow on development efforts. Although resources were not available to fully investigate the sensitivity of the tool to bit diameter, two bounding cases were developed:

1. Min Bit OD – 22.6 mm (0.89 inch)

2. Max Bit OD – 24.4 mm (0.96 inch)

It is clear from the test data shown in Table 1 that there appears to in fact be a significant improvement in rate of penetration even with a minor reduction in the bit face surface area of only 16%. For the purpose of this investigation relatively unworn bits were used during the rate of penetration investigation in order to limit the amount of test variables.

**Table 1. Rate of penetration of coring tool utilizing 121g striker at 500 rpm**

| | Avg Drilling Rate [mm/min] | |
|---|---|---|
| | 22.6 mm (0.96") Bit | 24.4 mm (0.89") Bit |
| Limestone | 26.2 | 59.6 |
| Kaolinite | 49.3 | 162 |
| Siltstone | 6.3 | 27.9 |
| Saddleback Basalt | 2.4 | 7.9 |
| Volcanic Breccia | 1.3 | 2.7 |

<u>CBA Lessons Learned</u>

During the CBA design effort, the modularity of the tool's sub-elements allowed for a relatively independent development from its mating hardware; however, it also resulted in a failure to check the implications of an increase of the mating chuck interface at the tool's assembly level resulting in a significant reduction in capability to drill holes that are off normal from the rock surface.

- As such, remember the big picture – resultant interface growth that is satisfied at the mechanism level, i.e. black box interfaces to black box as intended, might still allow proper mechanism function, but upset higher level functionality

In addition, it was recognized that since this was an early development effort with a low maturity level, a significant portion of the verification and validation effort should focus on understanding the tool's performance and capability sensitivity as it relates to bit diameter.

- Therefore, during early development efforts with hardware that has a low maturity level, significant emphasis should be placed on the desire to understand the hardware's performance sensitivity to varying requirements, especially if the results may be used as inputs on subsequent higher fidelity tools.

**Core Break-Off (CBO) Mechanism Design & Testing**

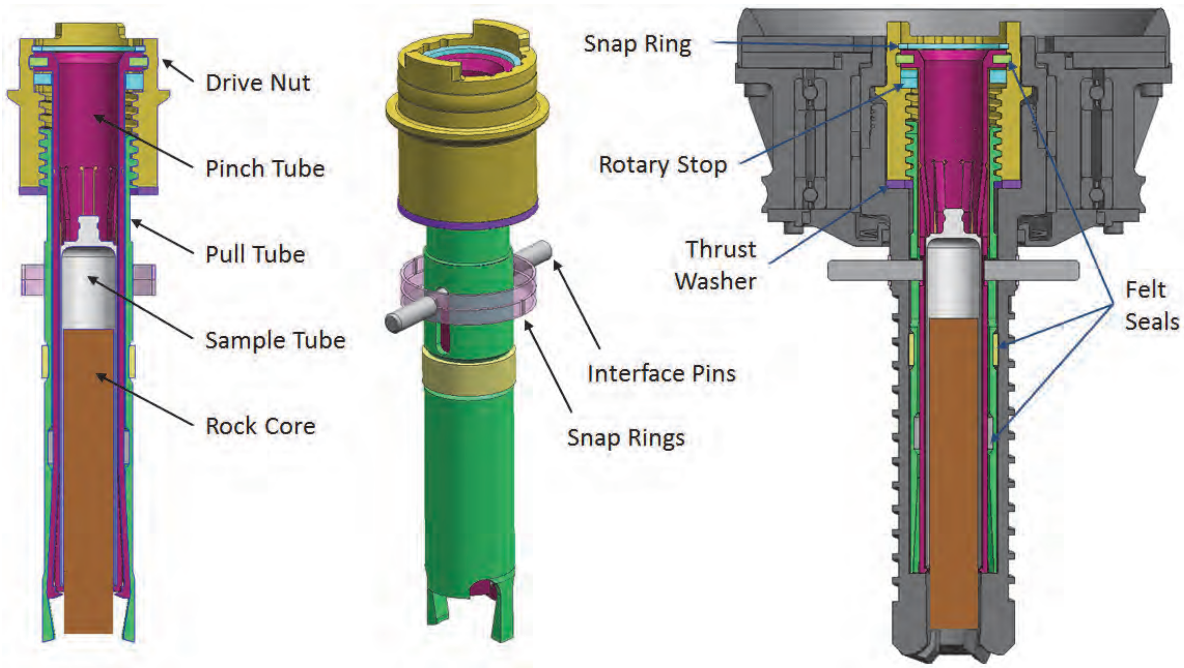


**Figure 16. General schematic of CBO**

<u>CBO Overview</u>

Figure 17 provides an overview of the Core Break-Off (CBO) Mechanism. The core break-off device is a pinching/cleaving mechanism that uses two opposing $45^{o}$ wedges that are symmetrically split about the cleaving plane. The mechanism is actuated through the CBO drivetrain located within the SPA and is designed to fracture cores that range in diameter from 9 mm to 10 mm.

As alluded to above, the need to fracture the generated core close to the parent rock required the CBO to be nested within the ID of the drill bit. As such, during nominal drilling operations the CBO is disengaged from the CBO drivetrain in order to allow for unobstructed operation of the Core Bit Assembly. Once the desired core is generated, the CBO drivetrain interfaces to the CBO mechanism thru a novel axially compliant lead screw that translates axially to interface with the CBO torque interface as well as provide the rotational input to fracture the core. During testing, the CBO was able to fracture all generated cores as intended.

However, a significant problem did present itself during testing. In addition to providing a means for core fracture and capture, the CBO also provides a method for retaining the sample tube within the pinch tube by way of flexure retention fingers. During testing, these retention features began to fail at high stress concentration regions located at the base of the flexures. This failure method was initially missed during the design phase as the flexures were only analyzed under a low static load which showed significant margin. However, this load case did not appropriately account for the repeated cyclical loading generated by the SPA and the resultant failure of the flexure by fatigue.

<u>CBO Lessons Learned</u>

As previously mentioned, due to the vibratory environment generated by the percussive mechanism several retention features ended up failing to retain the sample tube. Therefore:

- In a vibratory environment, stress concentration regions should be analyzed for fatigue failure even if the resultant cyclical load is small and static results show high margin.

## Conclusion

In support of the development of the Integrated Mars Sample Acquisition and Handling (IMSAH) architecture, a low-mass Sample Acquisition Tool (SAT) has been developed. As with most R&D efforts, the project's schedule and resources were limited so a modular approach to the tool's development was implemented such that individual subassemblies/mechanisms could be independently developed and tested from the others prior to integration. In addition, these same schedule constraints resulted in early design choices that limited the tool's flexibility to investigate some anomalous behavior due to several linked mechanisms as well as a premature attempt at performance optimization. As such, during early development efforts with low maturity levels, it became readily apparent that greater emphasis should be placed on the desire to understand the hardware's performance sensitivity to varying requirements. In doing so, more useful feedback can be provided to allow for better informed decisions on subsequent higher fidelity developments efforts. With that said, the developed SAT has demonstrated the necessary capability to autonomously generate, fracture, and capture rocks cores as necessitated by the proposed sampling architecture.

## Acknowledgements

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