Lightweight Low Force Rotary Percussive Coring Tool for Planetary Applications

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Abstract

A prototype low-force rotary-percussive rock coring tool for use in acquiring samples for geological surveys in future planetary missions was developed. The coring tool could eventually enable a lightweight robotic system to operate from a relatively small (less than 200 kg) mobile or fixed platform to acquire and cache Mars or other planetary rock samples for eventual return to Earth for analysis. To gain insight needed to design an integrated coring tool, the coring ability of commercially available coring bits was evaluated for effectiveness of varying key parameters: weight-on-bit, rotation speed, percussive rate and force. Trade studies were performed for different methods of breaking a core at its base and for retaining the core in a sleeve to facilitate sample transfer. This led to a custom coring tool design which incorporated coring, core breakage, core retention, and core extraction functions. The coring tool was tested on several types of rock and demonstrated the overall feasibility of this approach for robotic rock sample acquisition.

Introduction

Current science for Mars and lunar exploration demands that small diameter rock cores be acquired for geologic evaluation. Tools to acquire these cores must be lightweight, draw minimal power, and induce low loads on their robotic platforms. Unfortunately, no tools have yet been produced that meet these requirements and produce a viable core. Tools developed to date are often complex, require large power and mass budgets, demand down forces beyond the capabilities of anticipated landers and rovers, and either take an inordinate amount of time to generate a core or introduce excessive energy into the core sample, pulverizing it.

A rotary-percussive mechanism for rock drilling offers promise in addressing these requirements. Delivering hammer blows to a drill bit allows rock to be chiseled away as opposed to being worn down by friction alone. This can significantly reduce the amount of down-force, or weight-on-bit (WOB), required as well as offer savings in power consumption.

In addition to raw coring ability, there are other challenges in coring tool design that must be addressed for successful sample acquisition. A means of breaking off generated cores from the parent rock must be included. The design must also provide a practical and reliable means for extracting and handling the generated cores. These are not trivial problems. Common rocks of interest, particularly sedimentary types, are easily fractured during the core generation process. This can cause mechanisms to bind or jam, foiling sample retrieval efforts. In addition, for maximum geological significance, science demands maintaining the order in which fractured rock core pieces are acquired. Finally, the ability to replace worn drill bits is an important consideration for the coring tool design because some rocks of interest, such as basalt and sandstone, are particularly abrasive. A mechanism that allows for bit change-out must be designed to work in concert with the rotary-percussive and core handling mechanisms.

This paper details the development of a rotary-percussive coring tool design that addresses core generation, break-off, containment, and retrieval.

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Corer Tool Background

The Low-force Sample Acquisition System (LSAS)

Previous design efforts were leveraged during the development of the rotary-percussive coring tool. In 2006, the Space Division of MDA Information Systems, Inc. (formerly Alliance Spacesystems) produced a rotary percussive drill designed for space use under a NASA-funded Mars Instrument Development Program (MIDP) project – the Low-force Sample Acquisition System (LSAS) in Figure 1. The flight-like drill prototype that was the end result of the project successfully drilled and acquired 1-cm³ sample fines from a variety of rocks and soils, including the hardest anticipated Martian rock (basalt) and frozen soil. This ability was demonstrated in ambient conditions and in a thermal/vacuum chamber replicating Mars pressure and extreme temperatures. The rotary percussive approach was demonstrated to be simple, robust, and highly efficient in power and mass.

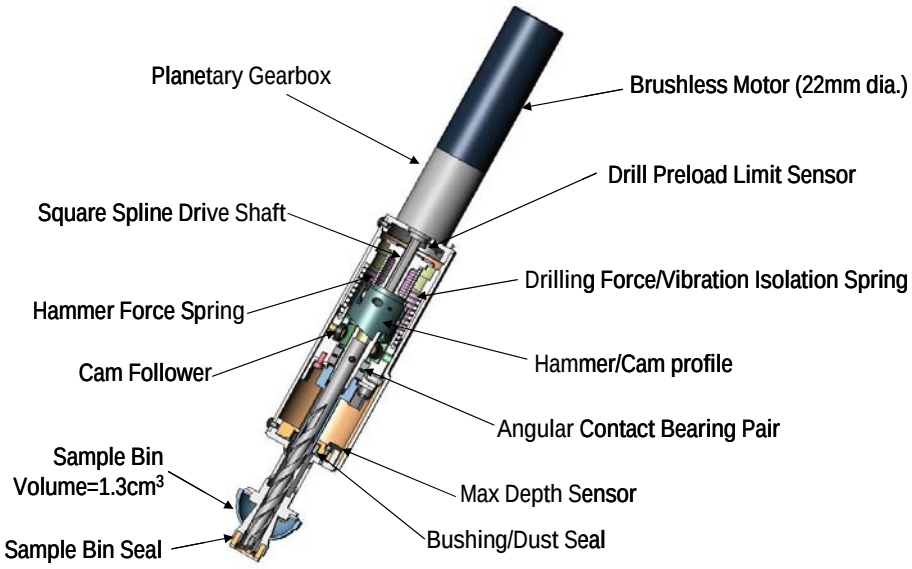

Figure 1. Original Low-Force Sample Acquisition System (LSAS)

The successful performance of the LSAS drilling system, along with the difficulties encountered by existing coring devices, led MDA Information Systems to consider applying LSAS and its rotary percussive action to the coring problem. The LSAS prototype was simply adapted to accommodate a commercial coring bit (see Figure 2), and no attempt was made to optimize the drill for the new coring operating conditions. The results were surprisingly positive. When drilling in limestone, 1-cm-diameter cores were readily produced up to 1 cm long in as little as 20 minutes while mounted on a rover-mounted robotic arm. The drill readily began coring without a pilot hole, probably because of the low applied force and compliance of the robotic arm/rover platform.

SBIR 2006 Phase 1

Following the encouraging results with the modified LSAS drill, a Phase 1 SBIR effort commenced in 2006 that took this heritage device and expanded its potential to include coring against a variety of rock materials anticipated to be encountered on Mars. An industry and literature search was conducted to identify best practices in rotary percussive coring, and commercial off-the-shelf (COTS) bits were located for test. An extensive test program was performed to evaluate these bits with accompanying performance parameters such as rotational speed, WOB, hammer frequency, and hammer force. Through the use of a breadboard fixture (see Figure 3), coring bit designs and coring parameters were evaluated to identify optimum combinations. The breadboard fixture, with separate motors for driving rotary and hammering action, allowed drilling parameters to be independently varied during testing.

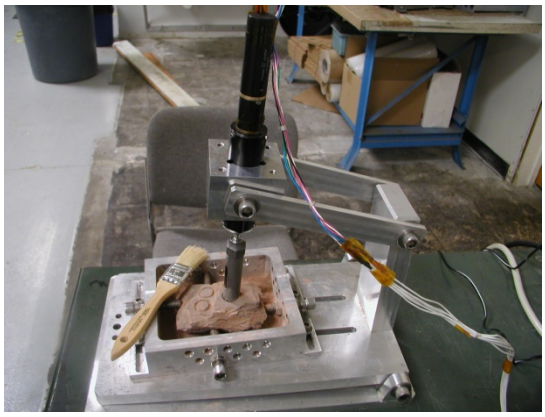

Figure 2. Modified LSAS in Test Fixture with Commercial Coring Bit

Phase 1 results indicated that the primary goal of producing a 1-cm-diameter, 10-cm-long core[1] from a variety of rocks, including hard basalt was achievable, though not without complications. The commercial coring bits exhibited rapid dulling, particularly with basalt and sandstone. This suggested the importance of a bit change-out mechanism and/or the need for further bit refinement. Also, the bit and associated performance parameters required to core basalt are evidently too aggressive for softer materials, particularly layered rock structures, resulting in broken or even pulverized cores. As a result, a conceptual corer was designed that included a bit change mechanism concept and a means of modifying the percussive force. Finally, it was found that relatively large amounts of power, approximately 90 watts, were needed to generate the cores. Although a specific power target was not established at the time of Phase 1 testing, it was clear this was in excess of current rover capacity. Mission requirements were to later baseline 65 watts as the targeted value, an intimidating goal in view of the Phase 1 data.

SBIR 2006 Phase 2

The Phase 2 effort evolved the conceptual design developed in Phase 1 by evaluating each function (coring, break-off, retention, and transfer), building prototypes, and ultimately generating an integrated prototype coring mechanism incorporating each detail function. In addition to the 65-watt power consumption target, mission requirements later defined in the project included a 5-kg mass budget for the integrated corer, coring performance yielding 5-6 cm long corer samples within a Martian day, and a corer WOB no greater than 50 N. This paper focuses on the Phase 2 design efforts to achieve such a corer.

Development of the Corer

The Phase 2 work plan was divided into four primary sections: (1) development of a custom coring bit, (2) core handling mechanisms development, (3) prototype corer development, and (4) corer testing.

(1) Custom Coring Bit Development

The majority of the coring bit data from Phase 1 were produced from tests with the COTS coring bit that showed the most promise for core generation, a 1-inch (25-mm) diameter coring bit from Milwaukee, P/N 48-20-5005. These coring bits are designed for the drilling of holes, not for the generation of intact rock cores. Nonetheless, the Milwaukee bits successfully yielded cores in testing, though the cores were occasionally fractured. Also, the generated cores were 1.5 cm in diameter, substantially larger than the targeted 1 cm.

The objective of the coring bit development was to thus produce a custom coring bit capable of consistently generating intact 1 cm diameter cores. A targeted core length was defined at 6 cm based on the latest mission requirements from the science community. The coring bit development was performed in parallel with the core handling mechanisms development so that the coring bit could be designed to

[1] Original mission requirements dictated a 1 cm x 10 cm long core, and later eased to 5-6 cm long.

accommodate the anticipated coring handling implementation. This necessitated designing a coring bit with a relatively large cutting annulus to yield the space required by the core handling mechanisms.

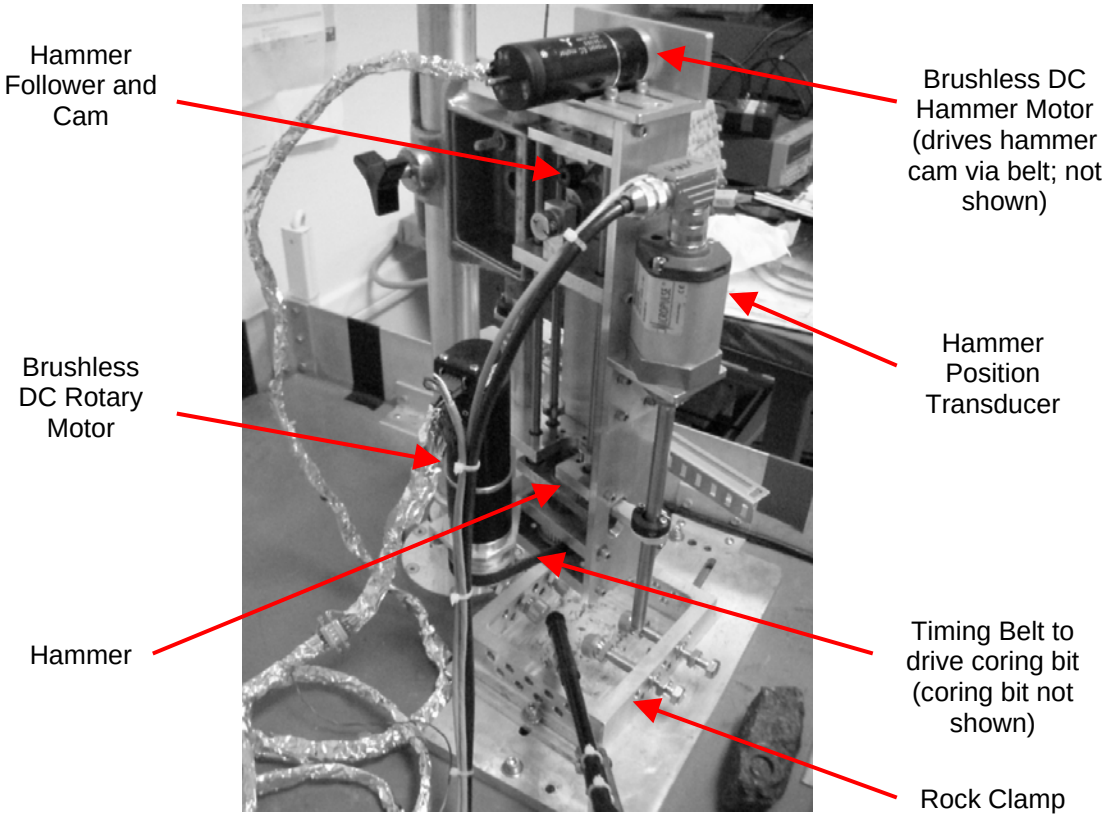

Figure 3. Drilling Breadboard Fixture Used for Coring Bit Evaluations.

A bit design expert was consulted to assist in the analysis of earlier coring results obtained with COTS bits and to develop a custom coring bit design specifically for this application. After two iterations, a successful bit design was obtained to core targeted rock materials.

The first custom coring bit, Revision A, used a single sloping cutting tooth profile as shown in Figure 4. The cutting teeth were fabricated from grade C2 carbide. This coring bit cored basalt successfully, though chipping of the carbide was observed. Unfortunately, the bit had stability issues in softer materials. The bit tended to wander, breaking the softer cores into numerous pieces. On a positive note, the flutes designed into the tool body were effective in carrying away rock fines. In previous testing with non-fluted COTS coring bits, a shop vacuum was used to clear away the fines, and debris clearance was anticipated to be much more of a challenge than was actually encountered.

Revision B, the next coring bit design iteration, addressed the stability issues found in the previous version. This design used a crown-shaped symmetrical tooth profile. A different grade of carbide, GC-012F by General Carbide, was used in an attempt to improve the cutting teeth life and reduce chipping. This coring bit design solved the stability issues in soft rock and still cored basalt well, though the teeth still chipped when coring basalt and even iron spot brick. Nonetheless, because this coring bit design cored well and the chipping did not cause a significant difference in coring performance, it was decided to proceed with this basic design and focus remaining project resources on the development of the integrated corer.

Figure 4. Revision "A" (left) and "B" (right) Coring Bits with Basalt Cores

(2) Core Handling Mechanisms

The core handling mechanisms identified in Phase I – core retention, break-off, and ejection – required prototyping and testing to verify their suitability. This reduced the risk of a possibly failing subassembly to negate the total design and effort.

Core breakage from the parent rock material was a major concern from the beginning of Phase 2 since it was not explored during the Phase 1 effort, which focused primarily on coring. A number of concepts for breaking cores were investigated, including scoring the base of the core to weaken the rock. A Milwaukee 48-20-5005 coring bit was modified to provide a means of scoring existing core samples at the base of the core. This method looked promising as the forces required to snap the rock core were found to be minimal. However, the concept was eventually discarded because of the complexity involved with integrating such a device into the corer design.

Next, a collet concept was conceived to break the rock core samples. Two different design approaches were considered and explored, shown in Figure 5. The first was a conventional axial collet much like the type of collet found in a machine shop. This was tested on rock samples in a variety of rock breakage modes: tension, bending, and compression. The other collet concept used nestled eccentric tubes that generated a shearing force on the rock core when the tubes were rotated with respect to each other. Mechanisms were designed and built to test these concepts, and both methods were found to be effective. Both approaches required approximately the same amount of input torque to snap rock samples. In the end, the eccentric collet concept was selected as the core breakage method of choice because it was observed that the concept would be easier to implement into an integrated corer design, and that it would be simpler and more tolerant of stray rock particles.

During testing with the collet mechanisms, input torques and displacements were measured and recorded to characterize the forces and strains required to break the rock cores reliably. These results then helped define the design parameters for the integrated corer.

(3) Prototype Corer Development

Development of a fully integrated corer prototype was performed following the successful demonstration of the individual core handling mechanisms. As mentioned earlier, it was decided that the integrated corer should be designed to utilize the eccentric collet concept based on the results of the testing with the core

handling mechanisms. However, the problem of containing and transferring the core sample remained unaddressed. A containment sleeve was attractive with the realization that many cores would not be intact, and maintaining the order of the pieces of a disrupted core is a requirement. However, designing provisions for a sleeve into the integrated corer without interfering with the breakage mechanism and providing a clear exit path out of the corer for the sleeve was a challenge. Analysis of the dimensions of the rock cores generated during the core breakage testing revealed that only a very small clearance typically existed between the outside diameter of the rock cores and the inside diameter of the coring bits. The clearance was so minimal that it became clear that ejection of the containment sleeve out the front of a coring bit would be impractical because it would necessitate a containment sleeve of nearly zero wall thickness.

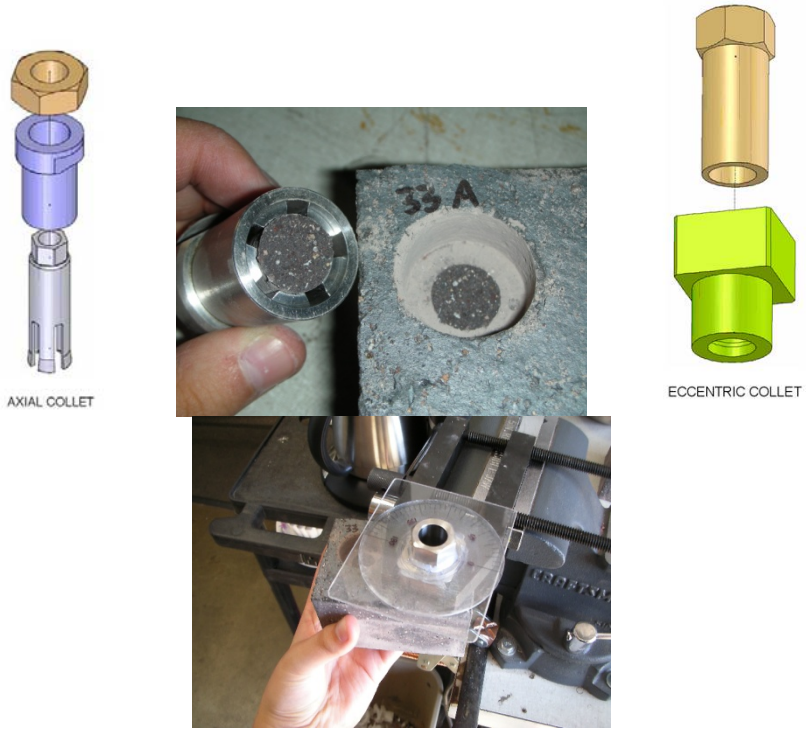

Figure 5. Core Breakage Collet Prototypes

Consideration was thus given to an integrated corer design that allowed the ejection of the rock core containment sleeve out the rear of the assembly. This concept was compatible with the eccentric collet breakage design, and seemed the most straightforward in achieving all of the corer objectives of coring, breakage, retention, and ejection. Because there was a clear exit path through the entire corer assembly, an external plunger mechanism to push the sleeve containing the corer could be housed in the sample system on the base platform to “ramrod” the sample out the rear of the corer. This significantly simplified the integrated corer assembly and also incrementally simplified the requirements of the robotic arm to which the corer would be mounted by reducing mass and required electrical connections.

Other design considerations were addressed prior to finalizing the overall concept of the integrated corer design. A decision was made to use a single motor to drive a spring-loaded rotary-percussive cam mechanism, much like the original LSAS drill. Although it was desirable to have the flexibility of independent control over the hammer and rotary functions in the manner of the drilling breadboard fixture, the single-motor rotary-percussive mechanism offered simplicity and low mass. An additional motor was incorporated in the design to accomplish core break-off. While it appeared possible to leverage the rotary-percussive motor to achieve this function and save mass, it was much more straightforward to add a second motor. See Figures 6 and 7 for CAD views of the prototype design.

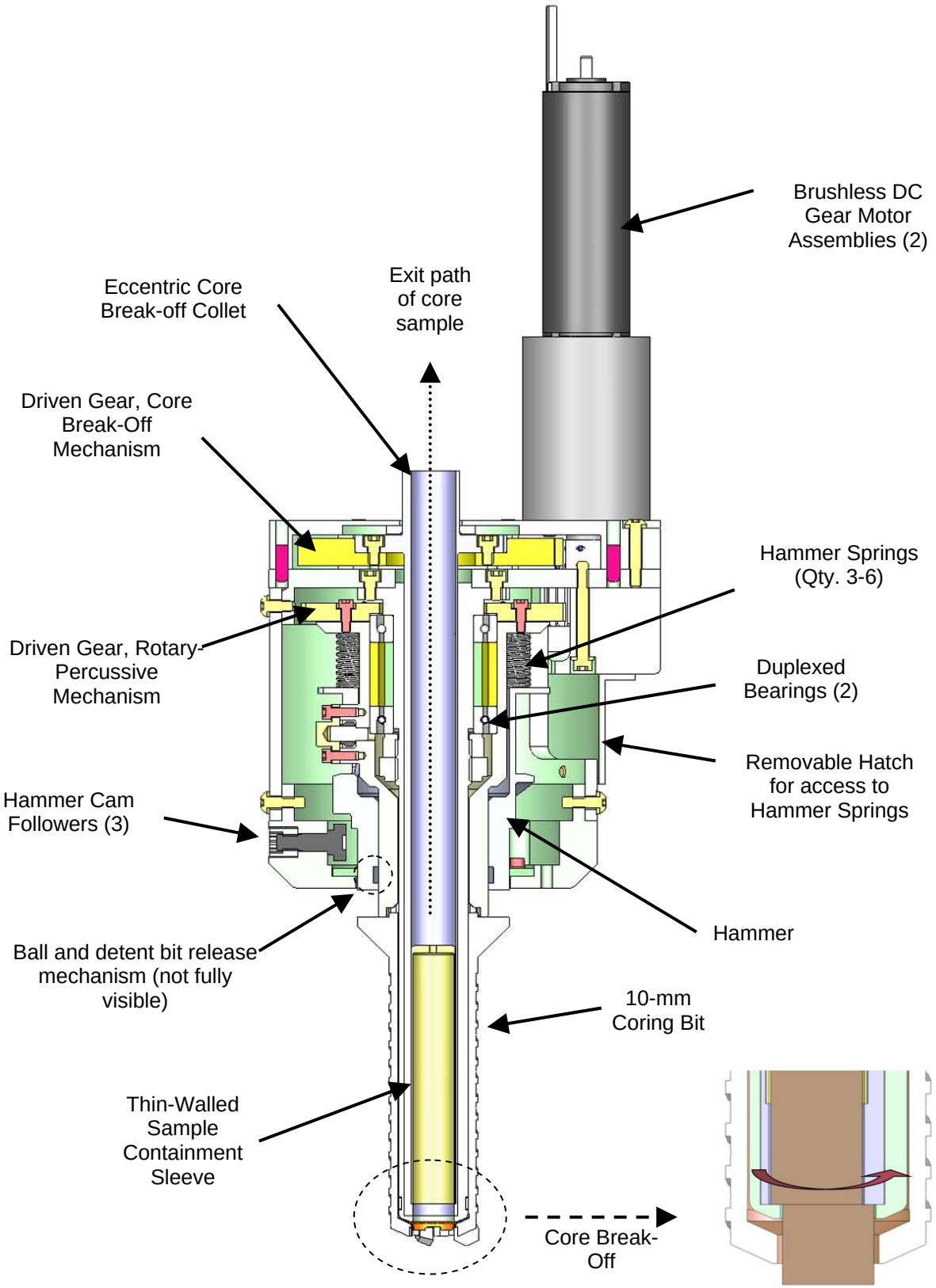

Figure 6. Integrated Corer Prototype Cross-Section

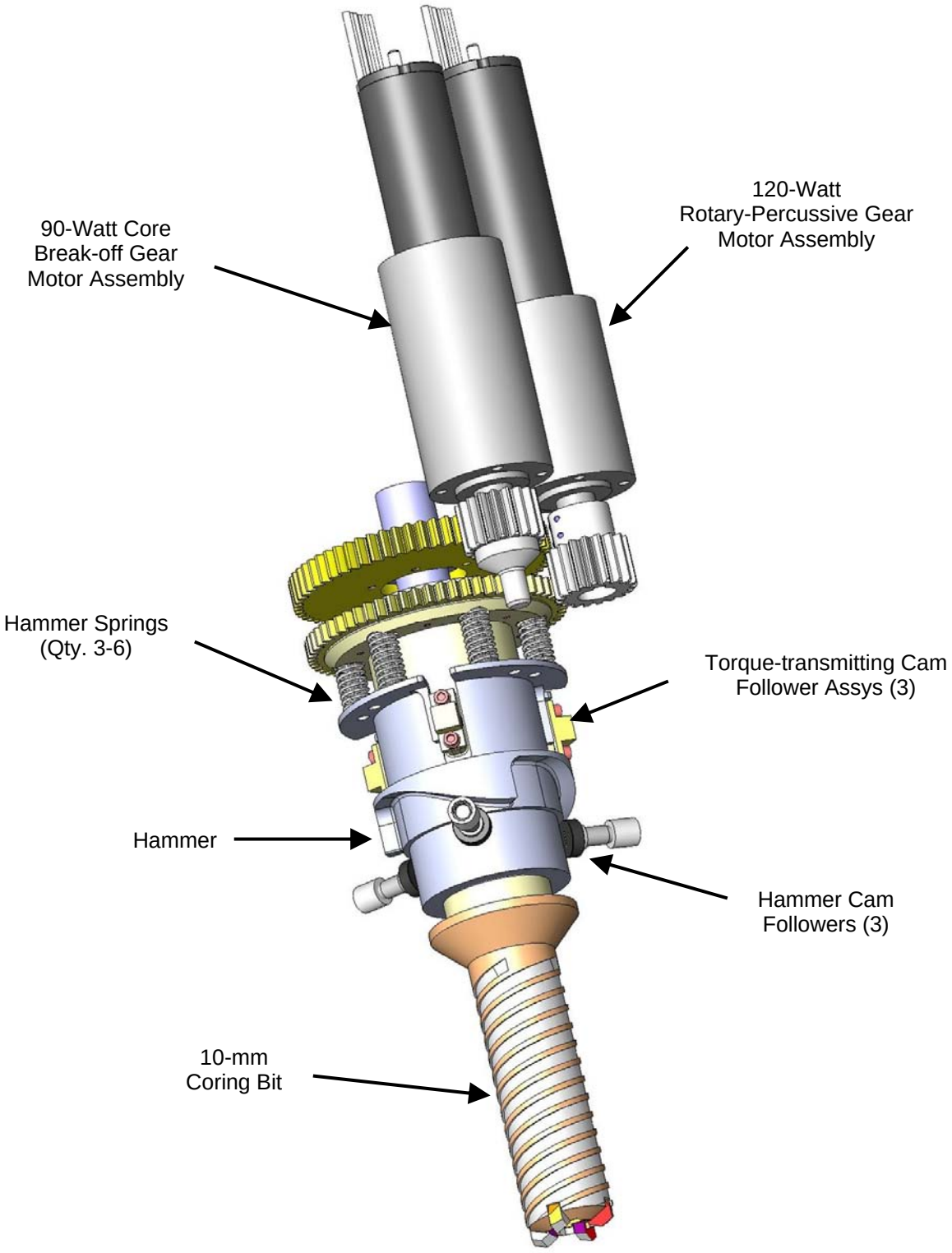

Figure 7. Integrated Corer Prototype (housings omitted)

A limited amount of analysis was performed prior to finalizing the integrated corer design. In view of the successful coring achieved with the breadboard fixture, the rotary-percussive motor and gear drive mechanisms were sized on the integrated corer to achieve the maximum hammering energies investigated with the breadboard fixture. Because gaining an understanding of the coring problem was deemed more important than strict mass reduction of the integrated corer prototype, the motors were sized with extra torque margins to ensure that all data points of interest could be obtained during testing. Finally, attention was given to developing efficient hammer cam profiles to minimize the amount of power required by the integrated corer. The hammer cam profile was modeled and simulations run (see Figure 8) in order to optimize the shape of the cam profile and to ensure that correct timing of the hammer strikes was obtained.

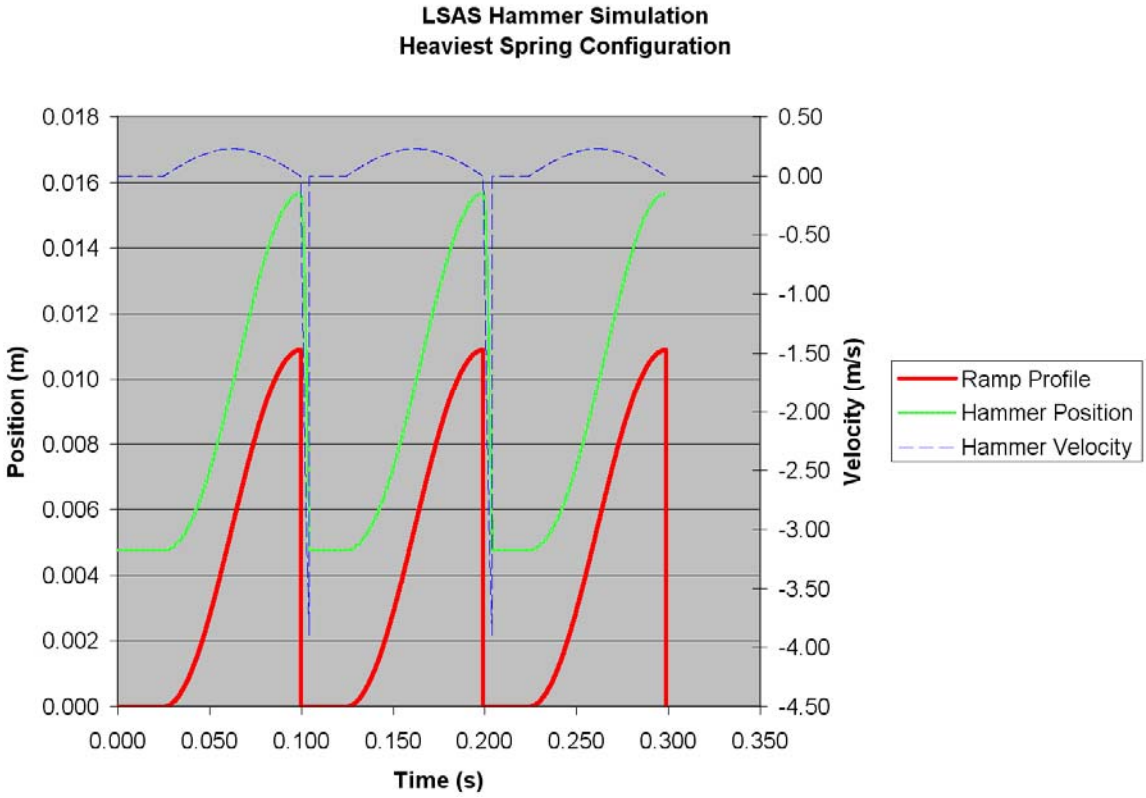

Figure 8. Hammer Cam Profile Analysis

It became clear during the cam profile analysis that a rotary-percussive mechanism can only operate within a narrow speed range and still be effective. If the mechanism rotates too slowly, the hammer loses energy by not being cleanly released by the cam mechanism. If the rotary-percussive mechanism rotates too fast, the hammer can be picked up before contact with the coring bit takes place.

An additional design concern regarded the mounting of the corer to the robotic arm or test fixturing. Early concepts assumed that advancing the unit down the coring axis could be accomplished by coordinated movements of the robotic arm joints. However, work performed on another project showed that low velocity, coordinated moves were very difficult and required positioning accuracy and control beyond the capabilities of current robotic arms. Power requirements were also quite high because all arm joint motors were energized along with the corer. In response, the simple solution of mounting the corer to linear slides with preload springs was implemented. The arm would press the corer against the target rock and preload the springs. The arm motors would be turned off, engaging the joint brakes. Coring would then begin and the corer assembly would be advanced by the preload springs. The preload springs could be re-compressed by shutting off the corer and advancing the robotic arm, then the process repeated until

the desired core length was achieved. See Figure 9 for the completed Integrated Corer Prototype mounted on spring-loaded linear guides.

Figure 9. Integrated Corer Prototype

(4) Corer Testing

The integrated corer prototype was then functionally tested in a laboratory environment with a variety of rock samples. See Table 1 for a summary of the results. The tests were narrow in scope because of the limited funds remaining on the program. However, the testing was adequate to demonstrate the successful performance of the integrated corer against the rock types anticipated to be encountered on Mars. It is hoped that additional more comprehensive testing be performed in the future as funding becomes available.

Coring Performance

Sandstone: This material had been found to be very abrasive and hard on the coring bits in the past, and this experience was repeated during testing with the integrated corer. Run 3H with a virgin coring bit through sandstone started to reach a performance plateau towards the end of the run. The coring bit teeth, while not fractured as during the runs with basalt, exhibited substantially worn cutting edges at the conclusion of the run.

Basalt: All coring bit runs in basalt produced chipping of the teeth, as evident in Figure 10. In two extreme cases - Runs 2I and 3I - the brazed joints on some of the cutting teeth failed as shown in Figure 11, causing the coring bits to lose cutting teeth. In the case of Run 3I, two adjacent cutting teeth were lost, resulting in a large side load to be imparted onto the generated core and causing it to inadvertently snap from the parent rock material. This occurred with the corer set for maximum hammer energy (1.09 J per blow)[2]. Subsequent Run 4I was performed with reduced hammer energy (0.61 J per blow) with much better results. One possible reason for failure was that the highest hammering energy was too aggressive on the coring bit teeth. In addition, the current coring bit design had cutting teeth that overhang the coring bit body by a substantial amount, making the teeth susceptible to failure. A future design change to the coring bit should be considered to minimize this overhang.

Shale: Coring penetration rate was the highest of the three materials tested, and the coring bit was in good condition at the end of the run.

[2] "Hammer energy" used here refers to the approximate change in potential energy the hammer springs experience between two points: (A) when the hammer is fully "up" (cocked) and (B) when it first strikes the coring bit. This is not the same amount of energy that is actually transferred to the coring bit and imparted to the rock, which would require extended detail analysis to predict. However, hammer potential energy was an easily calculated, convenient reference when comparing the different hammering settings.

Table 1. Corer Prototype Test Summary

Test ID	Rock Material	Required Electrical Power, W	Speed Range, rpm	Theoretical Hammer Potential Energy, J	Weight On Bit Range, N	Total Coring Bit Penetration, mm	Average Penetration Rate, mm/min	Core Breakoff Achieved	Core Sample(s) Retrieved in Containment Sleeve
1H	Sandstone	18-32.2	131-199	0.21-0.42	78.6-83.0	9.04	0.0747	No	No attempt to sleeve core samples.
2H	Sandstone	25.9-27.1	193-202	0.61	49.2-59.1	13.72	0.229	No	(1) ϕ 9.61 mm x 2.58 mm thk (1) ϕ 9.78 mm x 2.72 mm thk
3H	Sandstone	28.3-33.8	189-201	0.61	55.2-68.4	24.36	0.0727	No	(1) ϕ 9.60 mm x 3.32 mm thk (1) ϕ 9.79 mm x 2.68 mm thk (1) ϕ 9.85 mm x 4.66 mm thk (1) ϕ 9.78 mm x 3.24 mm thk
1J	Shale	26.2-30.5	191-201	0.61	51.2-68.3	25.93	0.370	No	(1) ϕ 10.30 mm x 9.16 mm thk
1I	Basalt	28.6-30.2	192-199	0.61	56.0-59.3	4.55	0.1467	No	None (too short to break off)
2I	Basalt	38.4-46.8	188-200	1.09	59.7-68.3	9.16	0.1017	No	None (too short to break off)
3I	Basalt	36.2	190	1.09	65.8	--	--	No	None (bit failure caused generated core to prematurely break off)
4I	Basalt	33.6-60.0	189-199	0.61	61.7-101	18.16	0.1316	Yes	(1) ϕ 9.68 mm x 11.55 mm thk

Figure 10. New Bit and Chipped Bit after Basalt Testing

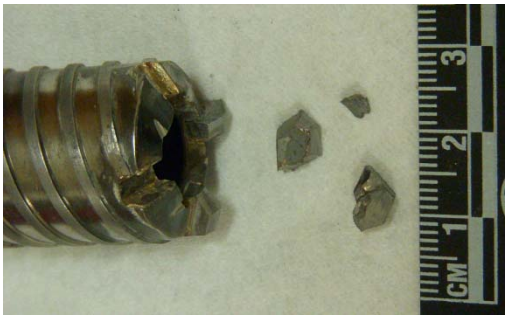

Figure 11. Failed Bit after High Energy Basalt Testing

Overall, as shown in Table 2, the coring penetration rates were lower than observed during the coring bit development testing with the breadboard fixture. This was not surprising because of the inherent hammer/rotation phase drift that prevented a rapidly-repeating strike pattern from developing. The breadboard fixture contained separate rotary and percussion motors which were run open loop and always drifted with respect to each other. This was naturally conducive to preventing a rapidly repeating strike pattern. Indeed, on many rock samples cored by the integrated corer prototype, deep strike marks were seen in the rock that was suggestive of a repeating strike pattern. Performance could have been improved if a design feature had been introduced to shift the hammer/rotary phasing relationship. This could have been in the form of separate drive and hammer motors, a cam device to oscillate the LSAS Corer with respect to the robotic arm, or a number of other mechanical options.

Table 2. Prototype Corer Penetration Rate

	Average Penetration Rate, mm/min	
	Corer Prototype	Breadboard Testing
Sandstone	0.0727-0.229	15.812
Shale	0.370	6.789
Basalt	0.1017-0.1467	2.817

The low input power required to core, even in the most aggressive setups, was a pleasant surprise. Approximately 90 watts were required to core effectively with the breadboard fixture. During all of the representative runs with the corer prototype, power consumption was below 50 watts. Even in the one extreme case where the weight on bit was taken to a very high level (Run 4I), the maximum current draw was still only 2.5 amps (60 watts). To ensure conservatively that data could be collected in any likely test condition, the corer prototype was designed around a 120-watt motor. Further mass reduction could have been possible from motor substitution alone.

One of the primary differences in power consumption between the breadboard fixture and the integrated corer prototype was initially thought to be caused by the lower WOB used with the most recent testing. However, the high WOB settings investigated during Run 4I suggested this was not the case. It is suspected that the keys to the high efficiency of the current corer were the use of ball bearing cam followers for lifting the hammer mechanism (the original LSAS Corer Prototype used bushings), a hammer mechanism that did not slow down the rotation speed of the coring bit at every strike, a freely moving hammer mechanism, and careful tailoring of the hammer cam profile. In contrast, the hammer on the breadboard fixture did not rotate with the coring bit, causing loss of bit speed each time the hammer struck the shank of the bit. The hammer on the breadboard fixture also had excessive frictional losses.

Differences in the dynamics of the core bit fluting were noticeable during testing with the corer. In some cases the fluting appeared to be very effective removing debris, with rock fines being ejected with such velocity that they actually became airborne. In other cases, the rock fines tended to gather around the coring bit. One variable not previously explored is vibration of the overall test setup, helping to cause the dispersal of the fines. Indeed, when a rather large rock sample was used, the fines did not disperse in a similar manner to a nearly identical test setup that used a smaller rock that had fractured during the test. It was suggested that vibration of the small rock fragments helped with the fines dispersal. It appeared that more realistic testing (e.g. testing in the field on large in-situ rocks) might have yielded results that are more applicable.

Core Handling

With the exception of the one basalt sample (see Figure 12), all of the coring runs yielded core samples that were either too short to be snapped by the eccentric collet breakage feature, or the rock samples were already fractured. In the latter case, despite the core already being broken, the eccentric collet still retained the captured pieces in the order they were produced. In all four cases of obtaining captured rock pieces via the eccentric collet, the pieces were retained and successfully inserted into the thin-walled containment sleeve.

In all cases of successful rock sample retrieval, loose rock was found to remain with the parent rock. In some cases, a substantial amount of rock core was unaccounted for when comparing the length of the retrieved samples versus the leftover rock. It was evident that some of the cored rock is pulverized during the core generation process. It would have been useful to understand why this was happening to maximize the yield of retrieved rock cores and to avoid potential problems with debris jamming. The addition of a passive sample retention feature to the open end of the containment sleeve could have been a possibility.

Because of schedule and budget constraints, the core breakage mechanism was tested only against a sample of basalt, the most challenging material of interest for this application. Though this test demonstrated the success of the breakage function against the strongest sample type, it would have been more rigorous to perform testing against all types of anticipated rocks and measure the actual strain displacements needed to break the cores reliably. Having a statistically significant amount of breakage data could have enabled the development of a smaller, more compact design. A conservatively large amount of eccentricity was designed in the collet breakage mechanism to ensure success. However, this makes the corer larger and more massive, and the coring bit annulus subsequently larger, thus requiring more power during coring.

Figure 12. Containment Sleeve at Rear of Integrated Corer (left), Sleeve with Basalt Core (right).

Conclusions and Recommendations

Most, though not all, of the goals for the integrated corer were met and the results are encouraging. The 65-watt power requirement, previously thought to be insurmountable because of the high power consumption seen with the breadboard fixture, is clearly achievable. The low WOB target of 50 N was exceeded during test, but this was primarily caused by an oversight in the setting of the preload springs. Based on the relative ineffectiveness of higher WOB values briefly explored during testing, it is believed that sufficient coring performance is achievable with a lower WOB provided other measures are taken to improve coring performance.

Improved coring performance is likely achievable with design changes to alter the hammer/rotary phasing relationship in the integrated corer, since the coring bits cored much more efficiently on the breadboard fixture than in the integrated corer. The coring bits were the same in both cases, but the natural drift between hammering and rotary action on the breadboard is a major differentiator. Indeed, witness marks

on rock samples cored by the integrated corer reflect the rapidly-repeating strike pattern. A variable strike pattern will erode the rock more efficiently.

The performance and life of the coring bits can definitely be improved. A bit design with an asymmetrical tooth spacing arrangement would also help to avoid a rapidly-repeating strike pattern. Other cutting teeth geometry and material variations could be investigated to help address the robustness issue since the basic bit configuration is defined.

The containment sleeve concept was demonstrated to be effective along with the rear exit path of the contained sample. The eccentric core break-off/retaining feature likewise worked successfully. However, more statistically significant testing must be done to determine how well these mechanisms perform over time with varied rock materials.

A mass goal of less than 5 kg was established when requirements were re-baselined early in the program. The final configuration was significantly under this goal, the corer weighing 2.5 kg without mounting features. This leaves considerable room for future improvements which could include increased margins (though the motors in particular are currently oversized), and additional functionality such as motorized tool change, additional spare bits or bits for other functions, etc. The low mass also potentially reduces strength and stiffness requirements for the robotic arm or other mount device, resulting in further mass savings. Depending on the actual mission application, the motors could be readily reoriented at a 90° angle or even doubled back upon the assembly to reduce length.

Though commercial components were used, the design has a direct path to flight with vacuum and temperature compatible materials and lubricant. The current prototype is capable of environmental testing in a laboratory environment.

Early component and subassembly testing certainly reduced risk. Individual testing of the core handling mechanisms allowed definition of the design parameters needed to complete the integrated corer design while giving confidence that the integrated corer would function successfully.

Additional telemetry and improved data are required for fully understanding the rotary-percussive problem. As mentioned earlier, the analysis done while designing the hammer cam profile on the integrated corer yielded insight to the critical timing nature of the rotary-percussive mechanism. A rotary-percussive mechanism can only operate within a narrow speed range and still be effective. Excessive hammer energy losses can occur if the mechanism rotates too slowly, and rotating too fast can prevent the hammer from contacting the bit. The rotary-percussive events occur over a period of milliseconds. Having hammer position and/or impact feedback, for example, would enable better assessment of what is really happening in the mechanism and prevent erroneous conclusions.

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