Mars 2020 Sampling and Caching Subsystem Environmental Development Testing and Preliminary Results

Lauren E. Chu, Kyle M. Brown, Kristo Kriechbaum
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Lauren.E.Chu@jpl.nasa.gov, Kyle.M.Brown@jpl.nasa.gov,
Kristo.L.Kriechbaum@jpl.nasa.gov

***Abstract*—The Environmental Development Testing program supported the development test efforts of the Mars 2020 Sampling and Caching Subsystem from May to November 2015. The engineering prototype Brassboard Corer was attached to a five degree-of-freedom robotic arm to execute a 96-test matrix of ambient and low pressure tests in the 10 ft. thermal vacuum chamber at the NASA Jet Propulsion Laboratory, California Institute of Technology. The Pretest, Test, and Post Test procedures are described, and some preliminary results are discussed. Data and observations from this test campaign inform the future development of the software and hardware toward the Mars 2020 flight design, including the next iteration of the rock coring drill, the Engineering Development Unit Corer.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. OBJECTIVES 1
3. TEST SETUP 1
4. TEST PROCEDURE 3
5. PRELIMINARY RESULTS 6
6. FUTURE WORK 7
7. SUMMARY 8
ACKNOWLEDGEMENTS 8
REFERENCES 8
BIOGRAPHIES 9

1. INTRODUCTION

The Mars 2020 mission, managed by the NASA Jet Propulsion Laboratory (JPL), proposes to explore a likely previously habitable site on Mars, seek evidence of past life, and demonstrate technology needed for future Martian robotic and human exploration efforts. The Mars 2020 rover (Figure 1) has been tasked with constructing a cache of samples of Martian surface material that could potentially be returned to Earth at a later date [1, 2].

The new Sampling and Caching Subsystem (SCS) includes a rotary-percussive rock coring drill and 42 sample tubes to encapsulate each Martian geological specimen. The tubes will be deposited at select locations on the Martian surface and could potentially be returned on a future mission. If returned to Earth, specimens from Mars would be analyzed for evidence of past forms of life on Mars and possible health hazards for future human missions.

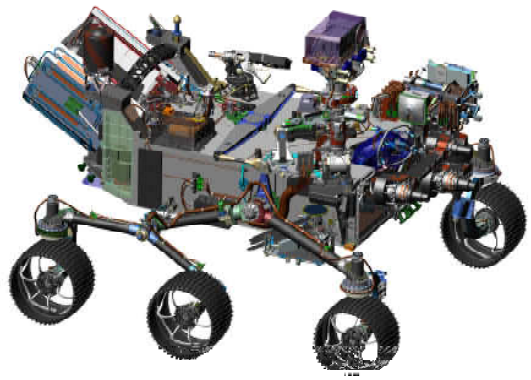

Figure 1: Computer-designed model of the Mars 2020 rover [2]

2. OBJECTIVES

The Environmental Development Testing (EDT) program from May to November 2015 at JPL was a crucial aspect of the engineering development effort for the Mars 2020 SCS. The primary test objectives of this test program were to characterize the sample acquisition process across a range of rock types and environmental conditions, understand hardware robustness and parameter sensitivities, and collect data that could be used to inform selection of flight motor actuators.

3. TEST SETUP

Vacuum Chamber

The EDT testbed venue was the 10-ft. diameter thermal vacuum chamber in JPL's Environmental Test Laboratory (ETL) Facility (Figure 2).

978-1-5090-1613-6/17//$31.00 ©2017 IEEE

Figure 2: 10 ft. thermal vacuum chamber with the floor lowered during an ambient pressure test

The chamber featured a hydraulic ram below the chamber floor to raise and lower the floor. Ambient pressure tests were run with an open vacuum chamber and the floor lowered. To mimic Mars atmospheric conditions, low pressure test environments were achieved by raising the chamber floor to the second story of the building to close the chamber, pumping down the chamber to 500 mTorr, then backfilling with 7 Torr of gaseous nitrogen.

The corer was mounted on a five degree-of-freedom robotic arm called the Sampling Lab Universal Robotic Manipulator (SLURM) (Figure 3) [3]. The five joints of the arm were: shoulder azimuth, shoulder elevation, elbow, wrist, and turret. This arm was procured for the purpose of development testing and not for replicating the structural dynamics of the Mars 2020 rover flight arm.

Figure 3: Sampling Lab Universal Robotic Manipulator (SLURM)

There were four rock stations that could be configured for different radial distances from the arm mount, height, and angular orientations of 0°, 45°, and 90° with respect to gravity. A bit exchange fixture called the "bit box" allowed for up to five tests to be performed in one low pressure pumpdown event without breaking chamber. Other chamber features included sixteen HD security cameras to display and record video and LEDs for camera lighting during low pressure tests.

Brassboard Corer

The testing described in this paper featured the engineering development iteration of the Mars 2020 rotary-percussive rock drill called the Brassboard Corer (BBC) (Figure 4). The BBC included a hollow drill bit to create rock core samples stored within a sample tube assembly (STA) inside the bit [4, 5]. Some of the other main components of the BBC were: the chuck to hold the bit, the hammer-anvil percussion mechanism, the feed stage to extend and retract the drill, and a pair of articulated stabilizers to maintain arm preload during coring. The three main coring operational parameters explored during this test program were: spindle speed, percussion frequency of the hammer hitting the anvil, and weight on bit (WOB). The BBC was housed in a turret structure, which attached to the turret joint actuator of the SLURM arm.

Figure 4: Mars 2020 Brassboard Corer

Test Matrix

The EDT test matrix was formulated using Design of Experiments (DOE) methodology with the aid of JMP statistical software to optimize testing factors, input parameters, and output data [6]. A matrix of 96 tests was produced to explore such variables as rock hardness, drilling orientation, and coring parameters such as spindle speed, percussion frequency, and WOB. The test matrix listed the drill hardware (pairings of coring bits and STAs), test articles, drilling orientations, and coring parameters listed for each test. The tests were combined into groups of 3-5 tests based on atmospheric pressure (ambient or 7 Torr) for throughput efficiency.

Test Articles

Test article rock types were selected by the JPL Geo-Analogs team to represent a diverse and realistic variety of test articles that would mimic material characteristics of those potentially found on Mars. The six rock types included in the EDT test matrix were: Old Dutch Pumice (ODP), Kramer Massive Mudstone (KMM), Bishop Tuff Intermediate (BTI), China Ranch Gypsum (CRG), Napa Basaltic Sandstone (NBS), and Uniform Saddleback Basalt (USB) (Figure 5).

Figure 5: Rock sample cores created using the BBC in six types of rocks (ODP, KMM, BTI, CRG, NBS, USB)

These rocks were collected from natural outdoor sites in California and returned to the JPL Extraterrestrial Materials Simulation Lab (EMSiL). The Geo-Analogs team bonded the rocks to aluminum plates with low outgassing epoxy, attempting to preserve the rock surface and bedding plane orientation as they were found in nature. These manufactured test articles could then be bolted to the EDT rock stations at various orientations.

4. TEST PROCEDURE

Each EDT test group contained 3-5 tests and had three stages: Pretest (preparing the hardware, software, and testbed), Test (running the BBC in ambient or low pressure environments to drill into a test article and create a rock core), and Post Test (documenting hardware and analyzing the core sample and corer telemetry).

Pretest

The chamber rock stations were configured for the drilling orientations of the upcoming test group, and the test articles were bolted into their respective rock stations. The test articles were photographed so they could later be compared to their Post Test state. The coring bits and STAs were inspected and photographed so any hardware damage or wear incurred during a test could be tracked. The STAs were inserted into the bits, and the bits were loaded into their holders in the bit box (Figure 6).

Figure 6: Array of five coring bits in the EDT bit box

A test operator ran a script to generate the software sequence template for each test in the group. The operator input test parameters such as drilling orientation, coring parameters, and the location of the bit in the bit box, and the script output the software sequences in the order they would be run for the test. The operator created new entries in our team's data infrastructure tool called the Test Log Database (TLDB) for each test in the group.

During a test, the SLURM arm was moved around the chamber by sending motion sequences linking "teach points," three-dimensional points in space determined by the positions of each of the five arm joint actuators. The test operators set a few new teach points for each test by manually commanding the SLURM arm to the new test location on each test article. These test-specific teach points were saved and then copied into motion sequence templates that included reused teach points that had already been tested as safe, intermediate positions for the arm. The in-chamber cameras were positioned so each new test location could be filmed clearly.

When all of the new test-specific teach points had been saved for the test group, the operators ran the motion sequences with the new teach points to test hardware safety and obstacle avoidance, and edit the sequences if needed. These safety checks of the new teach points allowed the operation of the real test to go more smoothly because all of the arm motions had already been rehearsed.

Lastly, the chamber and support hardware were inspected cleaned. For a low pressure test, the ETL staff raised the chamber end bell up to the second floor, sealed the chamber closed, and pumped it down.

Test

Every EDT test required two operators for safety and procedure efficiency. The operators started the SLURM and BBC motor control software and then booted the camera software program to record video of the entire test. Each test began by running the same functional sequences to check consistency of hardware and actuator performance. The operators sent a series of SLURM arm functional commands, which moved each of the five joint actuators ten degrees in the positive direction and then negative to return to their initial position; the operators monitored the live actuator current telemetry while comparing them to baseline plots. Then a series of BBC functionals were run to check certain components such as the feed stage, spindle and percussion mechanism; the operators similarly monitored the live telemetry and checked them against historical values.

The arm was positioned in front of the chamber camera called Mastcam, named after its analogous position and the types of photos it would capture similar to the photos that the Mars 2020 rover will take from the camera on the rover mast. The operators took a photo at this time to confirm an empty chuck. Then the arm was commanded to the bit box to retrieve a bit. To ensure consistent positional accuracy necessary to accommodate the tight tolerances of the alignment of the corer chuck with the back of the bits, each of the five bit stations had an alignment cone that would mate with the post on the corer turret (Figure 7).

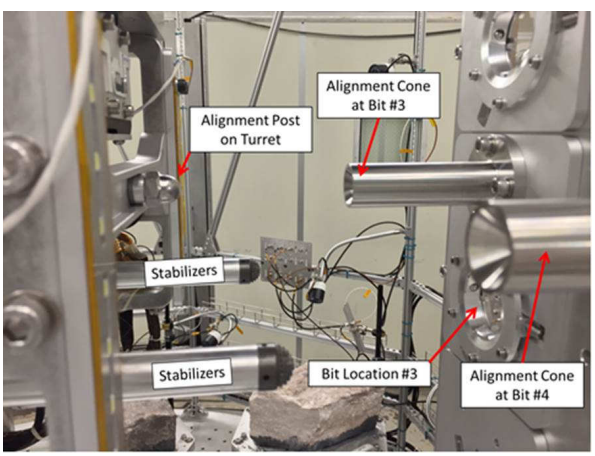

Figure 7: Turret and docking alignment features for bit exchange

The software's force control algorithm centered the turret post into the corresponding cone, and then the feed stage was extended to place the chuck around the back end of one of the bits in the bit box. The chuck was engaged to hold the bit, and then the spindle was rotated clockwise to unlock the bit from its holder. The feed stage was retracted slowly to take the bit away from the bit holder, and then the arm was moved away from the bit box to Mastcam to confirm that a new bit had been picked up (Figure 8).

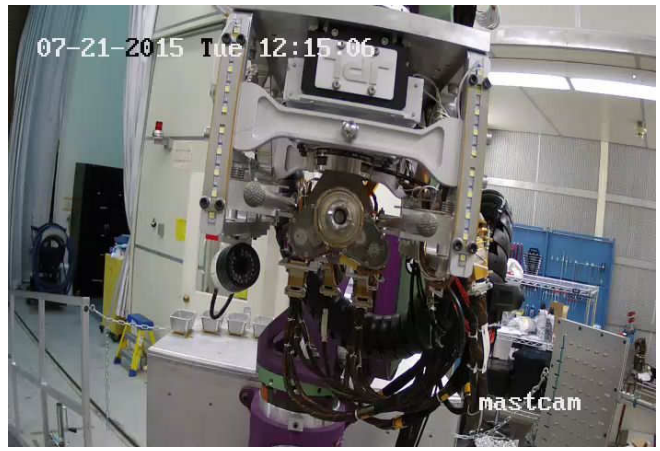

Figure 8: Mastcam photo confirming retrieval of a new bit

The operators then ran the test-specific motion sequence, already verified during Pretest, that moved the arm from Mastcam to the test location on a test article. A subset of corer functionals were run a few centimeters from the rock surface and in the same drilling orientation so that they could be used as baseline data to offset the telemetry acquired during the coring test. The arm was then preloaded onto the test article with 300 N on the pair of stabilizers in the axis of the bit. Operators checked that the preload force did not compromise the rock surface, especially for fragile rock types like KMM. A photo was taken by the camera on the turret, "Turretcam," of the test article to document its state just before bit contact.

In order to prevent bit walking on an uneven rock surface during coring, a process called "hole start" preceded each coring event to create a flat annulus. The coring bit was extended to 30 N of normal force onto the test article surface and then percussed in place for 5 s to knock down any peaks on the rock surface. The bit was retracted, rotated, and then reapplied to the article surface at this new location. It percussed in place again for 5 s, and this procedure was iterated eight times until the bit had rotated around completely. Then a "clearout" sequence was sent to percuss the bit while rotating slowly a few revolutions to create a continuous annulus. The bit was fed forward to measure the depth progress made during this cycle of hole start. If there had been less than 1 mm depth progress achieved, the next cycle of hole start would use increased WOB and percussion frequency, and vice versa if more than 1 mm depth was achieved. Hole start was repeated until 5 mm of depth had been accomplished. A Turretcam photo was taken at this time to document the test article state after hole start and right before coring.

The operators double checked the coring parameters with the test matrix before sending the coring sequence, which commanded the corer to drill into the test article and create a rock sample core within the STA inside the hollow drill bit. The desired drill depth was set to 70 mm with no duty cycling, and the coring control algorithm attempted to maintain the set WOB, spindle speed, and percussion

frequency. The rate of penetration (ROP) into the test article would change depending on the characteristics of the article, such as bedding planes, fractures, and other inhomogeneous features found in rocks. One operator watched the live video while the other monitored telemetry, being vigilant of any off-nominal behaviors or degradation of the test article that could endanger hardware. Software controls would automatically stop the coring operation if it detected high side loads or if the ROP was below a time-averaged threshold, indicating that the coring parameters were insufficient to make reasonable progress into the test article, and the bit could be incurring excessive wear.

When 70 mm of drilling depth was achieved, the core break sequence was sent (Figure 9). A lockout rod extended to engage the back of the STA and keep it stationary while the spindle rotated the coring bit 180° around the STA. This caused eccentric features between the STA and the bit to misalign, creating a force couple that fractured the core in shear and separated it from the parent rock. The core sample was retained inside the STA due to the misalignment of the eccentric tube and the opening of the bit. The feed retracted and the spindle rotated in a calculated "unscrewing" motion determined by the pitch of the bit flutes to extract the bit from the test article. A Turretcam photo was taken at this step to document the post-coring state of the test article (Figure 10).

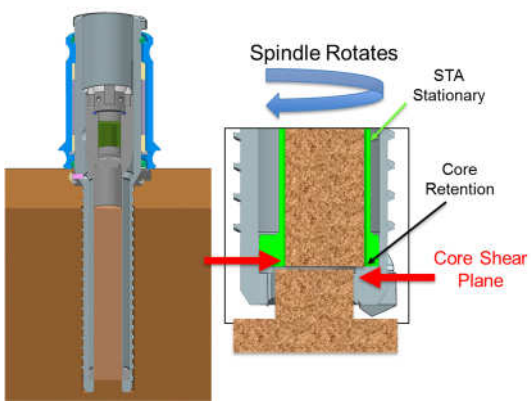

Figure 9: Cutaway of the coring bit showing the core breakoff sequence

The arm was moved away from the rock and to Mastcam so the operators could confirm that the core sample had successfully been retained in the STA after retraction from the hole. The arm was then moved to the bit box so the used bit could be returned to its holder in the bit box using a similar procedure for bit retrieval. This step would conclude the procedure for one EDT test; the next test would begin by picking up a new bit from a different location in the bit box and coring in a different location on the same or another test article, as dictated by the test matrix. In between tests, the software was shut down so telemetry files and photos could be transferred to the fileshare system and test reports could be generated and reviewed.

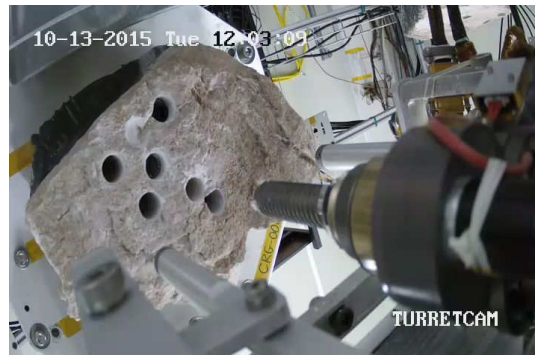

Figure 10: Turretcam photo of bit retraction from a CRG test article

Post Test

For an ambient pressure test, a test operator would manually retrieve the used bit from the bit box to begin Post Test analysis. However, all of the tests in a low pressure test group had to be completed before the vacuum chamber could be backfilled to ambient pressure and opened to allow an operator to enter and retrieve the used bits.

The operator took the used bit(s) to the Sample Plugging and Core Extraction (SPaCE) Station for Post Test analyses. The tube was extracted from the bit using a motorized force stand to measure any additional force needed to separate the hardware as a result of powder jamming interfaces or hardware degradation. A rod on the force stand was inserted into the tube and pushed onto the core sample to mimic the force required to plug the sample tube on the Mars 2020 rover. The STA was removed from the force stand, and then the core was extracted from the sample tube and photographed (Figure 11), weighed, and sieved. The STAs were cleaned in an ultrasonic alcohol bath and the exterior was photographed to track wear from the recent test (Figure 12).

Figure 11: Post Test photo of a USB core sample after extraction from the STA

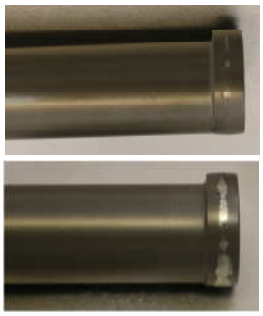

Figure 12: Photos comparing wear on the STA eccentric race before and after an EDT test

The vacuum chamber Post Test procedure began with photo documentation of the undisturbed tailings (powder) states of each of the test articles. The tailings were collected and the hole depths and diameters were measured. The vacuum chamber floor and other surfaces were vacuumed of any fine powder that had accumulated on exposed during the test group. If it were the end of a low pressure test group, the ETL staff would lower the chamber floor to fully open the chamber for easier access.

5. Preliminary Results

The large amounts of diverse types of data and observations collected during the EDT DOE test program of 96 tests are still being mined and analyzed to better understand the behaviors of the corer system. Only a small representation of preliminary results and observations will be highlighted in this paper.

Core Breakoff Torque

The spindle actuator current was measured during the core breakoff sequence, the operation that requires the most current from the spindle. These data were used to calculate the maximum torque exerted by the actuator, and then organized by rock type (Figure 13). In addition to the six rock types used in the EDT test matrix, a seventh type called New Jersey Diabase was tested as a special case for comparison; this rock was expected to be a much stronger outlier than the six rock types used in our nominal development testing.

Out of the six types of rocks in the test matrix, USB required the highest mean torque for core break, so these data were used to inform the selection of the spindle actuator that will be used in the next engineering iteration of the Mars 2020 corer, the Engineering Development Unit (EDU) corer, as the corer design matures to the flight corer.

Core Mushrooms

Following the core break off sequence and retraction from the hole, 33% of tests featured chunks of core sample stuck in the bit teeth through the STA opening, nicknamed a core "mushroom." (Figure 14) Sometimes the mushrooms were detached from the rest of the core in the STA and remained stuck in the teeth even after the STA was extracted from the bit during Post Test. The Mars 2020 rover will carry only six

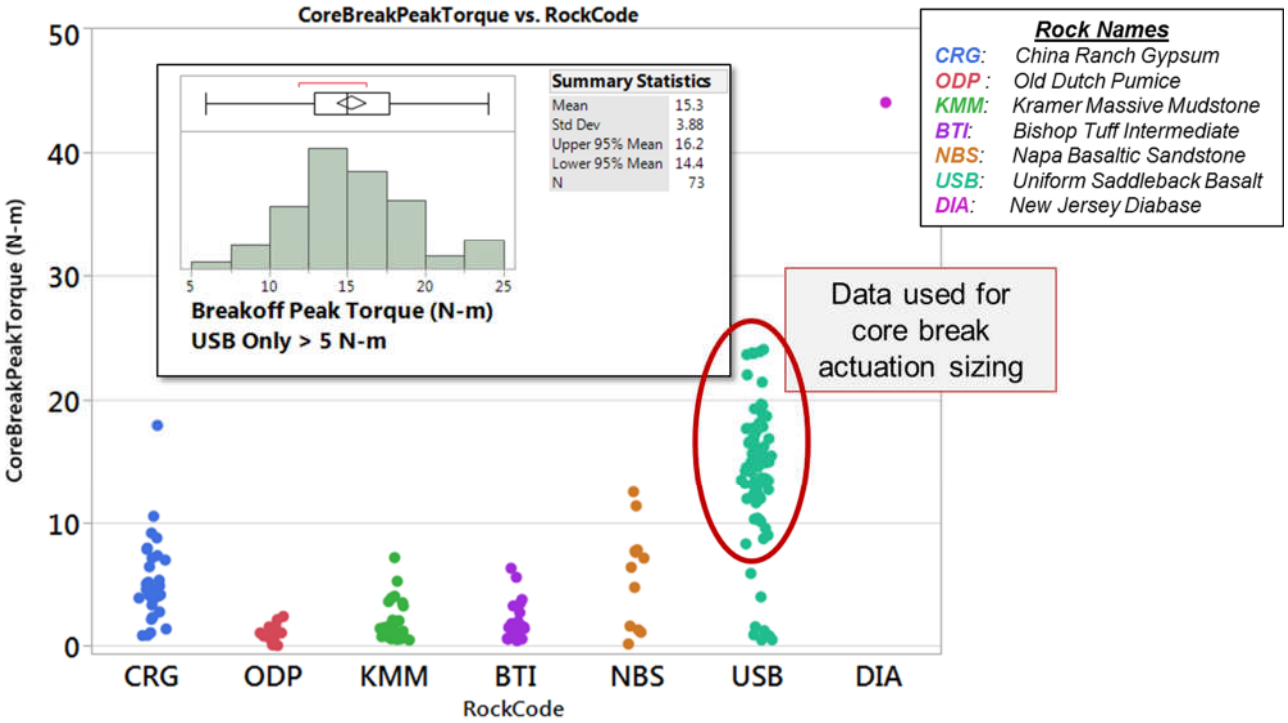

Figure 13: Statistical software analysis results of maximum core break torque by rock type. The inset table summarizes the statistics for the USB data used for spindle actuator sizing, indicated by the red oval [7]

Figure 14: USB core mushroom stuck between bit teeth following STA extraction from the bit

coring bits that will be reused to drill up to 42 core samples, so core mushrooms are a threat to the reusability of these bits.

Operational mushroom removal procedures were also explored to find ways of getting them unstuck from the bit teeth. An operation called "Percuss to Ingest" (PTI) was developed, which was added into the Test procedure after the Mastcam photo confirming core sample retention in the STA and bit. If the operators observed in the Mastcam photo that a mushroom was stuck in the bit teeth, the turret would be maneuvered so the bit opening pointed up. The STA and bit eccentric features were realigned by engaging a lockout rod in the back of the STA and rotating the spindle 180° back to the coring configuration. Then five one-second bursts of 32 Hz percussion were sent in an effort to jostle the mushroom loose from the teeth and cause it to fall into the open STA or ejecting it outside. Of the 33% of tests that yielded mushrooms, PTI was successful in removing the mushroom 96% of the time, showing that it is an effective mushroom removal procedure that can significantly decrease the risk of the inability to reuse coring bits on the Mars 2020 rover.

Sample Volume Variation

The sample acquisition process caused variation in the effective volume of the plugged core sample in the STA. Rock type, coring parameters, and drilling orientation affected the sample volume despite a constant drilling depth of 70 mm. KMM cores showed pieces separated and reoriented bedding planes, resulting in more sample volume than an ideal one-piece core (Figure 15). Certain coring parameters and drilling orientations, such as 90° with respect to gravity, could cause more powder to be ingested into the STA while coring, also resulting in increased sample volume (Figure 16). The ingestion of the core mushroom from PTI could also increase the volume of core contained in the STA.

On the Mars 2020 rover, these variations in sample collection volume could potentially leave the STA with insufficient empty volume at the tube opening for the plug to fit and properly seal the tubes. These data on sample volume variation were shared with the Mars 2020 flight systems engineer team to inform the flight requirements that will dictate the design and operation of the flight corer.

Figure 15: KMM core with separated bedding planes and reoriented pieces

Figure 16: BTI core with powder that was ingested by the STA during coring

6. FUTURE WORK

The Mars 2020 SCS team is continuing to understand the results of the EDT DOE test program and use the wide range of data to inform the maturation of the engineering design of hardware and software toward the flight model.

Software Development

The corer telemetry collected from these tests will inform the development of Kyle Edelberg's coring estimation and control algorithm. Data from hundreds of BBC tests on EDT and other Mars 2020 testbeds will form a database of coring parameters as a function of rock type, drilling orientation, and bit wear. On the Mars 2020 rover, the depth progress from each cycle of hole start can provide an estimation of rock strength, which could then be combined with the database to output a desired set of coring parameters to produce high quality core samples.

EDU Corer

The next engineering development iteration of the Mars 2020 corer is the EDU Corer, currently in development and heavily influenced by results of the EDT test program. The EDU

Corer will be larger than the BBC and include more flight-like features (Figure 17). The BBC actuator motors were oversized, but the EDU Corer actuators will have torque and speed performance similar to those that will be used in flight, informed by the EDT program results. The Spindle Twin Input Gearbox (STIG), developed by Timothy Szwarc, will makes its debut in the EDU Corer, and will allow the spindle to change gear ratios between coring and core break operations. The fight flight prototypes of the railizers (corer stabilizers on rails), feed stage, and flex cabling will be included in the EDU Corer design.

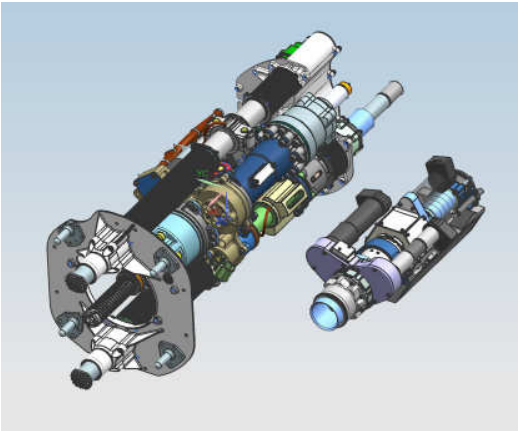

Figure 17: Computer models of the EDU Corer (left) and BBC (right)

The EDU Corer will replace the BBC in the 10 ft. thermal vacuum chamber for the EDU test program. New test articles, ground support equipment, and test matrices will be made to support the new program. Software commands and sequences will be updated to support the added functionalities of the EDU Corer.

7. SUMMARY

The Mars 2020 mission will collect and package Martian surface samples for potential future return to Earth. The EDT test program was executed in the 10 ft. thermal vacuum chamber at JPL to support the development testing of the Mars 2020 Sampling and Caching Subsystem. The BBC was operated on the end of the five degree-of-freedom SLURM arm to execute ambient and low pressure coring tests in rock test articles.

The Pretest, Test, and Post Test procedures were explained and a small subset of preliminary results were highlighted. The results from EDT tests will inform the software and hardware development toward the flight models, including the next iteration of the Mars 2020 Corer, the EDU Corer.

ACKNOWLEDGEMENTS

The author would like to thank the following members of the Mars 2020 SCS team for the engineering development and technical support of the hardware, software, and facilities used in the EDT test program and other SCS development test activities.

Kyle Brown's corer team included Timothy Szwarc, Rick Musgrave, Kenneth Glazebrook, and Anthony Barletta. Jeff Biesiadecki led the software development team of Kyle Edelberg, Peter Vieira, Brandon Metz, Todd Litwin, and Marc Pomerantz.

Cambria Logan's testbed development team included Mason Brody-Carney and Charles Dandino. The testbed operations team included Elizabeth Duffy, Michael Lashore, Daniel Balentine, Charles Morris, Errin Dalshaug, and Robert Uyeda. Paul Van Velzer led support by ETL, with help by Anton Ovcharenko and Sanford Bush. The Geo-Analogs team was led by Gregory Peters and included Elizabeth Carey and Lara Panossian.

Darrin Tidwell led the mechanical design team and Tim Monzello from the JPL Machine Shop coordinated hardware fabrication. Robert Kovac provided expert mechanical design and machining services. Louise Jandura, Avi Okon, Mark Balzer, and Lori Shiraishi lent valuable technical guidance and support.

This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
© California Institute of Technology. Government sponsorship acknowledged.

REFERENCES

[1] A. Steltzner, L. Shiraishi, L. Jandura, *et al.*, "Sampling and Caching Subsystem: Mars 2020 Mission Concept Review," unpublished presentation, Aug. 5, 2013.

[2] mars.jpl.nasa.gov/mars2020

[3] K. Kriechbaum, "SLURM FAQ," unpublished presentation, July 8, 2014.

[4] K. Brown, "M2020 Brassboard Corer Hardware Design Handout," unpublished presentation, May 1, 2014.

[5] K. Brown, "M2020 Brassboard Corer: Hardware Function Description for Software and Algorithm Development," unpublished presentation, June 23, 2014.

[6] K. Brown, "Coring and Drill Development Test Plan: EDT and ARC Testbeds," unpublished presentation, December 16, 2014.

[7] K. Kriechbaum, "Mars 2020 Coring Drill: Prototype Testing and Analysis," presented at the JMP Discovery Summit, Cary, North Carolina, 2016.

BIOGRAPHIES

Lauren Chu *received a B.S. in Mechanical Engineering from the California Institute of Technology and a M.S. in Aerospace Engineering from the University of California, Los Angeles. She performed graduate research in experimental plasma physics from 2011-2014 under the National Science Foundation Graduate Research Fellowship Program. Lauren began supporting the Mars 2020 mission as the Lead Testbed Operations Engineer for the Environmental Development Testbed. Currently, Lauren is the cognizant engineer responsible for the development and delivery of the Mars 2020 coring drill bit.*

Kyle Brown *received a B.S. and M.S. in Mechanical Engineering from Ohio State University. Since joining JPL in 2004, he has worked on UAVSAR and Phoenix, and was a cognizant engineer for the Mars Science Laboratory drill. Kyle is currently the cognizant engineer for the Mars 2020 corer.*

Kristo Kriechbaum *received a B.S. in Mechanical Engineering from Carnegie Mellon University and an M.S. and Ph.D. in Mechanical Engineering from the California Institute of Technology. He has worked on various sampling system concepts, in addition to being part of the team that built the sampling subsystem for the Mars Science Laboratory. He is currently the lead data analyst for the Mars 2020 sampling and caching subsystem.*