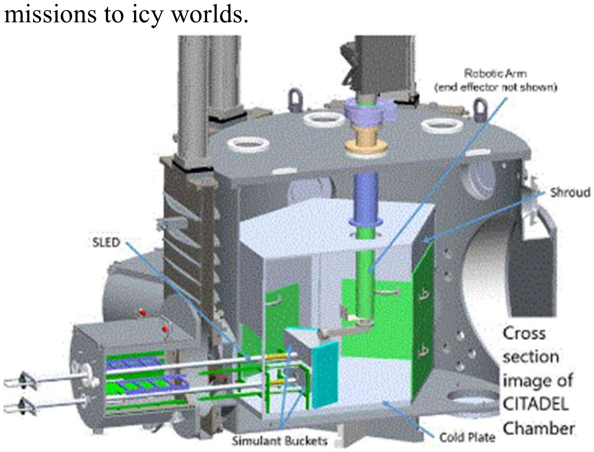
SAMPLE ACQUISITION IN ICY WORLD ENVIRONMENTAL SIMULATOR. Wade D. Smith[1], Esteben Rodriguez[1], Grayson Adams[2], [1]Jet Propulsion Laboratory – California Institute of Technology – 4800 Oak Grove Dr. Pasadena, CA 91109 – wade.d.smith@jpl.nasa.gov, Esteben.rodriguez@jpl.nasa.gov, [2]Honeybee Robotics – 2408 Lincoln Ave. Altadena, CA 91001 – gtadams@honeybeerobotics.com.

Introduction: Icy worlds present an exciting target for in-situ sample acquisition and analysis due to their potential to contain conditions necessary to support life. However, the unknown surface composition and topography of icy worlds present a challenging environment for which to develop effective sampling systems. Testing such sampling systems in a representative environment is a critical part of validating and refining their design. As such, JPL has developed the Cryogenic Ice Testing, Acquisition Development, and Excavation Laboratory (CITADEL) to enable testing of sample acquisition and transfer operations in an icy world or primitive body environment (<70K and 10-7 Torr) [1].

CITADEL provides the unique capability of multiple Load Locks, which can be isolated from the main chamber to rapidly exchange simulant samples without disturbing the main chamber environment. This enables the testing of surface simulants created outside the chamber with a wide range of compositions and morphologies, while also drastically increasing chamber throughput. The chamber serves as a platform for testing a variety of surface simulants, sampling tools, and end to end sample handling systems [1].

Testbed: The NASA Jet Propulsion Laboratory (JPL) is conducting research into excavating, collecting, and transporting a sample from an icy surface for future missions to icy worlds.



Testbed Design. The testbed consists of a vacuum chamber with cryogenic elements capable of maintaining externally generated simulant containers at cryogenic (70-100K) temperatures with a high vacuum (10-5 – 10-8 torr) atmosphere. The key elements that make this testbed an enabling technology for sampling system development include Load Locks (LLCs); a 3DOF robotic arm with 6DOF reaction load sensing; interchangeable excavation, collection, and transport tools; a camera system for in chamber viewing; interfaces for a variety of sensors that can be tailored for specific test campaigns; in chamber pneumatics for transfer operations; and a software interface for controlling the robotic system and aggregating telemetry.

Investigations: Testing in relevant environmental conditions is required to fully understand the interactions between tools and the collection target surface. There are three major phases involved in the sampling chain: Excavation, Acqusition, and Transport. Each of these phases involves interaction with the undisturbed surface or the cuttings generated in a previous phase. CITADEL is therefore intended to help characterize tool and system responses to a wide variety of surface simulants in each of these phases, as well as generally uncover unknown-unknowns relating to the system performance.

Excavation. Mechanical properties of ice change with temperature and composition, impacting the energy required to interact with solid bodies. Mass constraints on a flight system, cutting tool design, and time constraints on the excavation duration in flight require an understanding of the range of energy required to excavate to appropriate depth. CITADEL's Load Locks enable tests of a single tool with a virtually unlimited number of simulants in a single chamber pumpdown to aid in charaterization of surface composition and topography impacts on a proposed cutting tool's efficiency, power requirements, and reaction loads imparted to the lander interface.

Sample Collection. Environment-specific challenges for acquiring sample from excavated terrain must be characterized to satisfy high level science and engineering requirements. Collection mechanisms must minimize heat transfer into the sample to meet potential or notional science goals of keeping samples <150 K until processed by the instruments. The testbed provides the necessary elements and interfaces to verify this, as well as a test venue for a flight-like sample integrity verification system.

Dynamic behavior of chips/shavings will change in the absence of atmosphere, and may not melt and refreeze (as is typical on earth). These factors will affect debris pile-up and tool function in ways that cannot be effectively modeled or simulated in an ambient environment. Cameras, witness surfaces, and other inspection methods can be employed to understand these dynamic behaviors, the efficacy of current cutting tool designs, and feed forward into the next iteration of collection mechanisms.

Sample Transport. Sublimation rates drastically increase above 150K; along with the potential reaction of volatiles. The lack of free moisture, both from low temperature and low pressure, may affect granular solid clumping behavior. To analize the impacts to sample handling, testing must be done at representative environmental conditions; both to validate the system design and attempt to develop equivalent ambient simulants. CITADEL has been and will continue to be used for transporting sample via mechanical and pneumatic transport systems.

Testbed Elements:

Environmental Control System. The environmental control system for CITADEL is comprised of a 2 stage vacuum system and a thermal control system. Three dual stage rotary vane roughing pumps are used to pump down the main chamber pressure to 10-3 Torr. A turbomolecular pump is then used to bring the main chamber down to pressures less than 10-5 Torr. The thermal system uses closed loop helium compressors that feed coldhead cryocoolers. The cryocoolers are thermally connected to a cold shroud thermally isolated from the outer walls of the chamber. The cold shroud, reaching temperatures < 70 K, is equipped with PRTs and heatsink structures known as backstops that are used to chill any simulants inserted through one of the Load Lock chambers. A suite of resistive heaters are used to actively maintain safe temperatures for the robotic arm and end effector assemblies.

Load Lock Chambers. The Load Lock Chambers (LLC) on CITADEL enable samples to be loaded and removed from the chamber without altering the environment inside the cold shroud. This allows for high throughput of tests with a varierty of different simulants without having to wait for chamber cycle times that can exceed 24 hours. LLCs can be manually loaded with simulant buckets at ambient pressure and then evacuated with a 4^{th} roughing pump. Once the LLC reaches the proper pressure it can be opened up to the larger chamber volume via gate valve, allowing for the sample bucket to be pushed into the main chamber. The sample bucket rests on a long linear motion sled that can be manually pushed into the chamber. The sample buckets can be preloaded against the backstops to allow for the chilling of simulants to < 150K. The sleds include feedthroughs for passing thermocouple and other generic electrical signals through the chamber to the data acquisition rack.

Robotic Manipulator and End Effector. The robotic arm assembly mounts to the lid of the chamber and features 3 degrees of freedom. A vertical feed axis and rotational axis located outside of the chamber are used for sweeping cuts and drilling activities. A third wrist actuator in the chamber allows for 180 degree rotation of the cutting tools. A 6DOF force torque sensor is mounted between the end effector and arm structure to measure reaction loads imparted from a sample bucket to the arm. The end effector mounted at the distal end of the arm is equipped with mounting hardware for a wide varierty of different sampling tools.

Pneumatic Transport System. Pneumatic tubing in the chamber connects to an external bottle of gas via a feedthrough port into the main chamber volume. This enables the chamber to complete pneuamtic transfer of sampled simulants into a variety of measurement tools.

Completed and Future Tests:

Completed Testing. CITADEL completed a suite of commissioning tests proving the functionality of the main chamber elements. Upon completion of commissioning testing, a wide variety of simulant cutting tests were also completed. After cutting tests, the pneumatic system was used to transfer material in vacuum. Lastly, in a cryogenic vacuum environment, CITADEL was used to excavate and sample solid ice at less than 150 K and transfer the sampled tailings into a representative sample cup for scientific analysis. After proving end to end functionality, CITADEL was used to investigate sample integrity, a process developed to measure simulant temperature increases during sampling and transfer operations in cryogenic ice at high vacuum

Future Testing. Up next, CITADEL will be used in conjuction with other NASA centers to simulate dark side lunar enviroments for hardware thermal testing and verification. Also, CITADEL will be used for sampling, collection, and transfer for additional upcoming icy moon projects.

Summary: The CITADEL testbed has conducted and will continue studying surface interactions of sampling systems for missions to icy bodies. JPL has completed, in CITADEL: Surface interaction dynamics, sample acquisition, sample transfer, and sampling tool investigations. Future planned investigations in CITADEL include simulant integrity of sampled material, hardware characterization at cryogenic temperatures, and end to end testing for future icy moon programs. To collaborate with the JPL team at CITADEL please reach out to Wade Smith (wade.d.smith@jpl.nasa.gov) or Lori Shiraishi (lori.r.shiraishi@jpl.nasa.gov).

Acknowledgments: The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

References:

[1] Grayson Adams et al. (2021), CITADEL: An Icy World Simulation Testbed. *ASCE*, 1-10