HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Applications of Pneumatics in Delivering Samples to Instruments on Planetary Missions

IEEE Aerospace Conference
Big Sky MT, 2019

Honeybee Robotics
Kris Zacny (COLD Tech PI)
Fredrik Rehnmark (Presenter)
Tighe Costa
Joseph Sparta
Vishnu Sanigepalli
Bernice Yen
David Yu
Jameil Bailey
Dean Bergman
Will Hovik

JHU APL
Ralph Lorenz (COLD Tech Co-I)

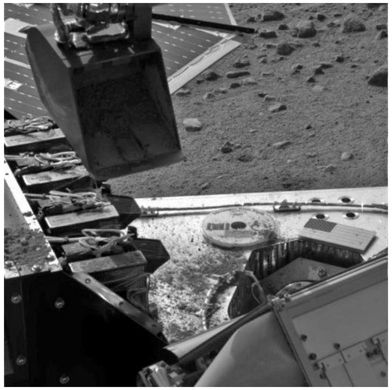
Surface Sampling on Planetary Exploration Missions

HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation
JOHNS HOPKINS APPLIED PHYSICS LABORATORY

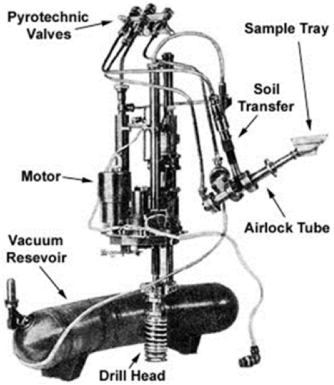
- Planetary surface exploration missions that seek to collect soil samples for in-situ analysis require a sampling system.
- The sampling system performs two primary functions:
  - Collect sample from the surface (e.g., drilling, scooping, brushing, etc.)
  - Transport sample to a remote instrument located inside a pressure vessel or heated interior aboard a lander or rover
- Operating on the same principle as the common household vacuum cleaner, a pneumatic sampling system may use airflow to pickup, transport and deliver solid particles.
  - On worlds with a dense atmosphere (e.g., Venus and Titan), pneumatic transport can leverage the natural environment.
  - On worlds with very thin or no atmosphere (e.g., the Moon, Europa, Ceres) compressed gas can be used to achieve similar results.

Mechanical vs. Pneumatic Transport

- Mechanical collection and transport methods are often power (and therefore rate) constrained and rely on gravity and are, therefore, not well-suited to adhesive/cohesive natural materials that tend to clump together and stick to exposed surfaces.
  - An example is ice on Mars, which stuck to the inside of the Icy Soils Acquisition Device (ISAD) scoop, presumably because it had time to melt and refreeze, and could not simply be dumped back out.
- For missions that can supply a short burst of pneumatic suction, either stored as delta-P or generated by a blower, solid particles can be conveyed rapidly and deposited in a sample cup without relying on gravity.
  - An example is the Soviet Venera and Vega missions to Venus, which took advantage of the high ambient pressure at the surface to create a sudden blast of air into a vacuum tank onboard the lander.



ISAD scoop on Mars (photo courtesy JPL/NASA)



Venera/Vega sampling system for Venus (photo courtesy mentallandscapes.com)

Benefits of Pneumatic Transport

HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation
JOHNS HOPKINS APPLIED PHYSICS LABORATORY

- Gravity agnostic
- Compatible with cohesive (sticky) materials
- Fast transfer minimizes heating and opportunity for contamination
- Flexible architecture (point of acquisition and point of delivery can be anywhere on spacecraft)
- Simple mechanical components
- Self-cleaning

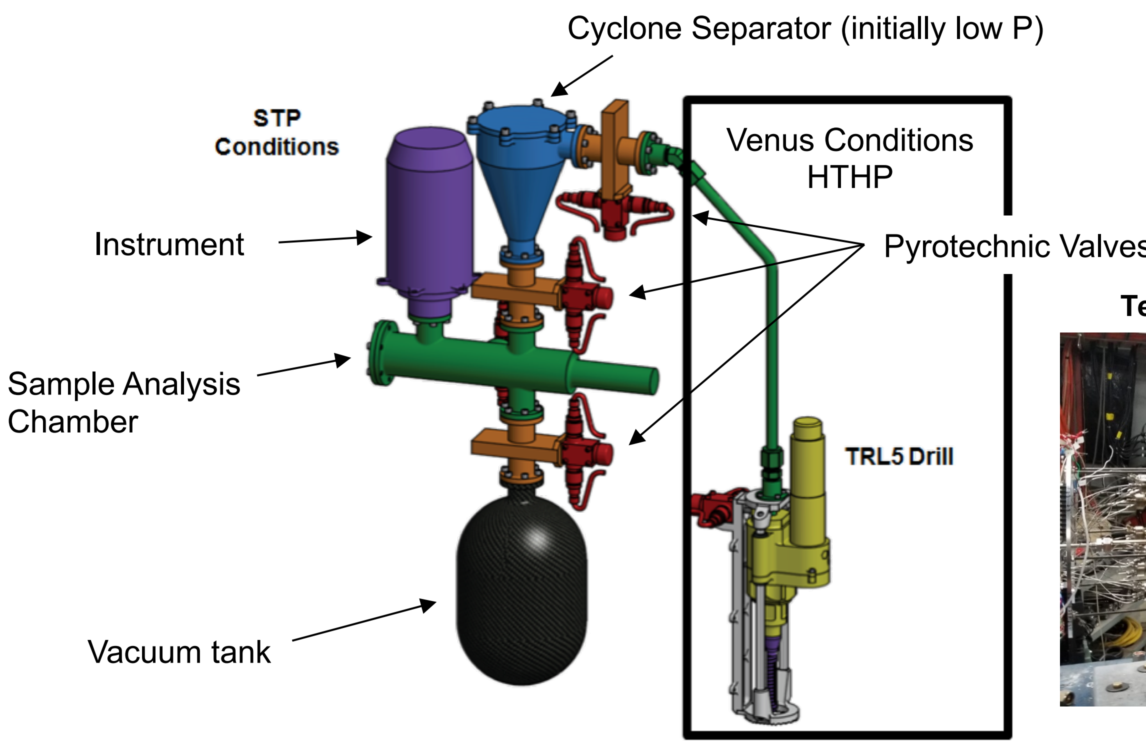
Design Drivers

- The selection of pneumatic transport method depends on several factors including:
  - Ambient environment
  - Properties of regolith (cohesiveness, particle size, density, etc.)
  - Number of samples to be collected (mobility)
  - Discrete vs. continuous collection

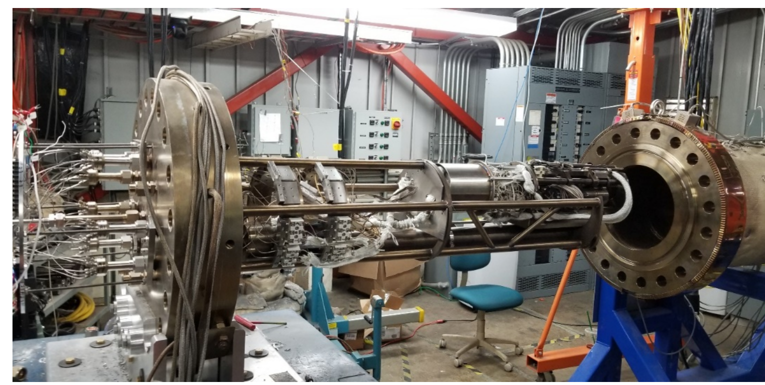
Case Studies

Venus (Atmospheric Drive)

- Surface conditions: 91 atm, 56x earth air density, 0.9 G, 462 °C, competent non-cohesive material (basalt)



Testing Honeybee drill in JPL's Venus chamber

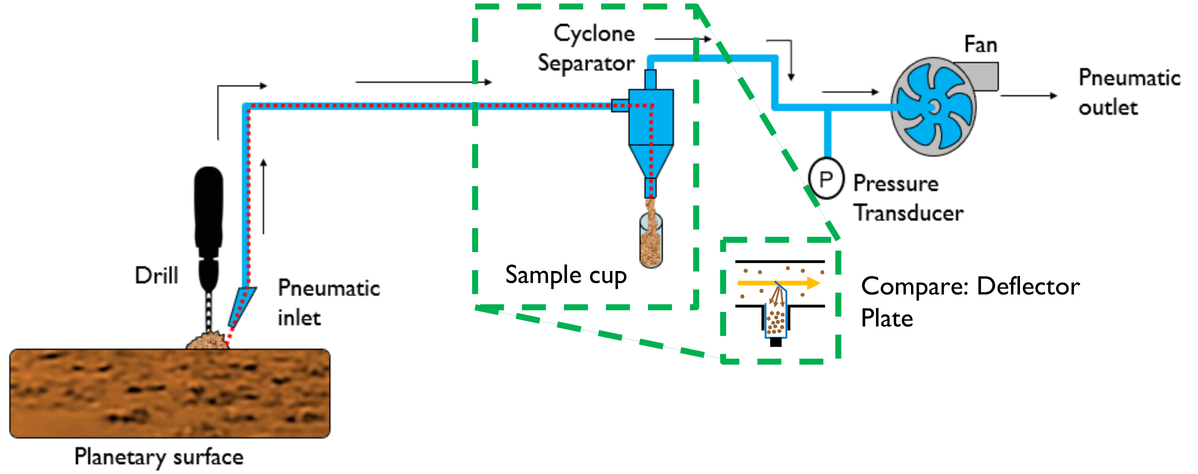


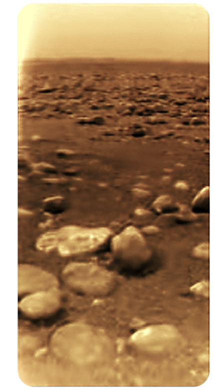
Venera-13 Lander (source: NASA History Office)

Titan (Blower)

- Surface conditions: 1.45 atm, 4.4x earth air density, 0.14 G, 94K, competent cohesive material (ice)

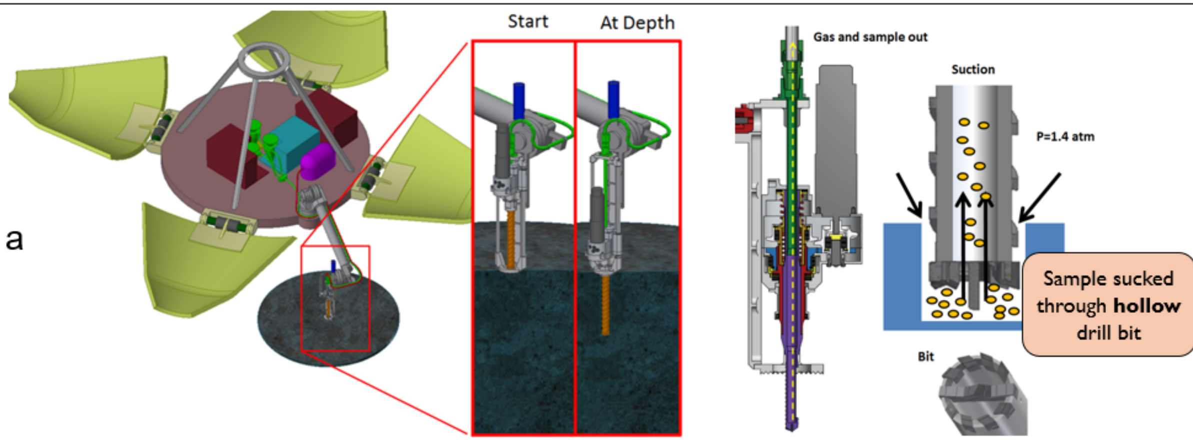
Pneumatic decoupled from drilling



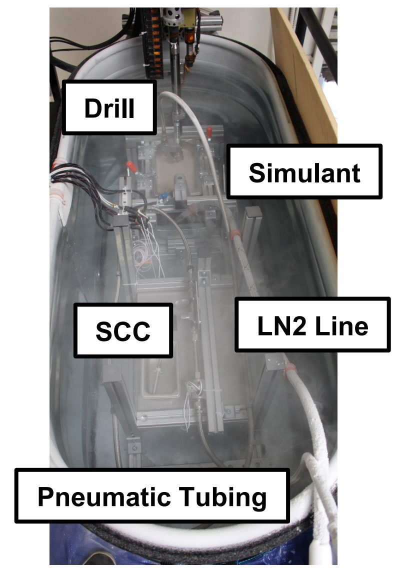


(credit: ESA/NASA/JPL/University of Arizona)

Pneumatic coupled with a drill

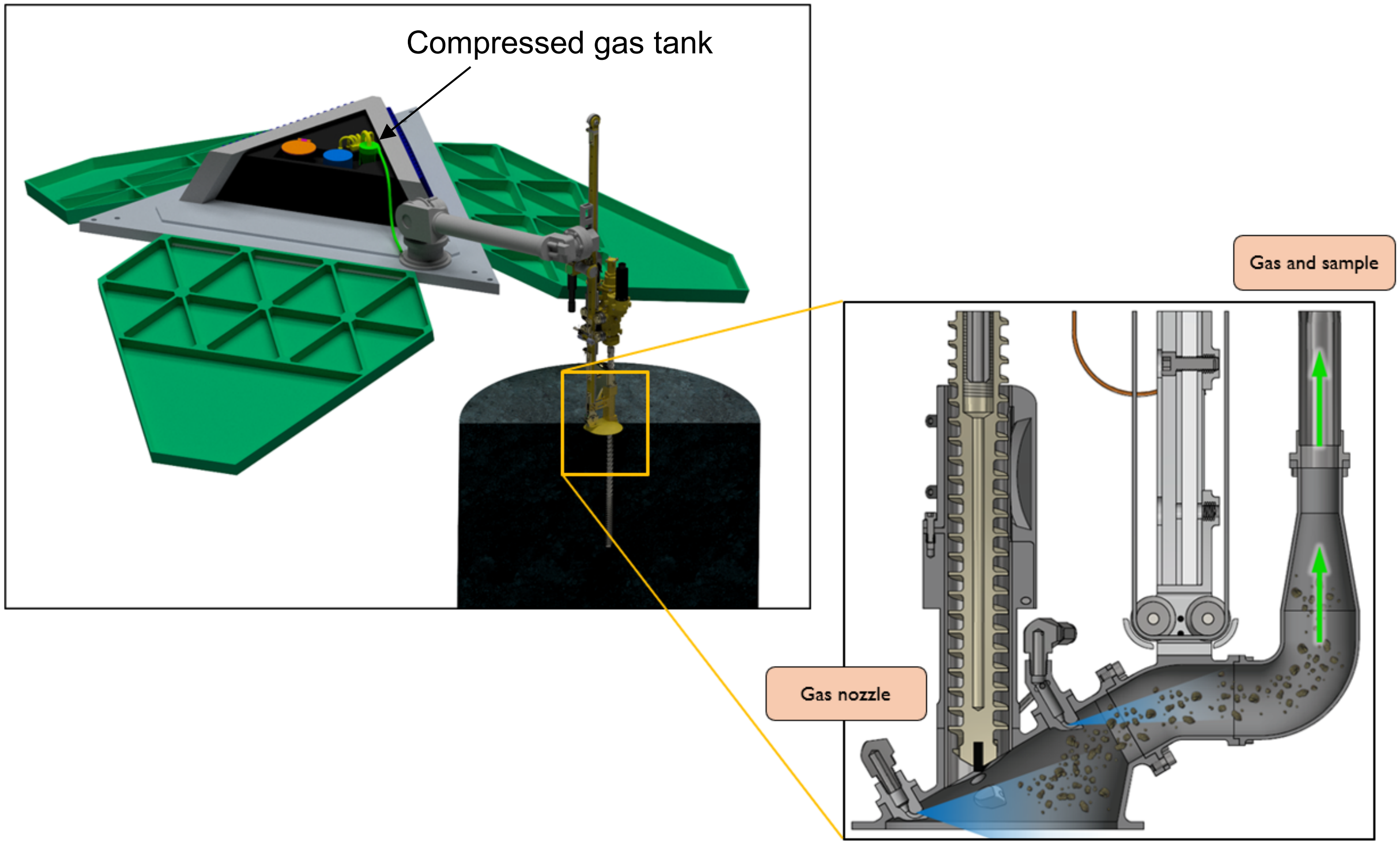


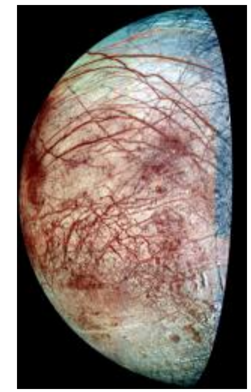
Cold box drilling test



Europa (Compressed Gas)

- Surface conditions: ~0 atm, 0.134 G, 100K, competent cohesive material (ice)



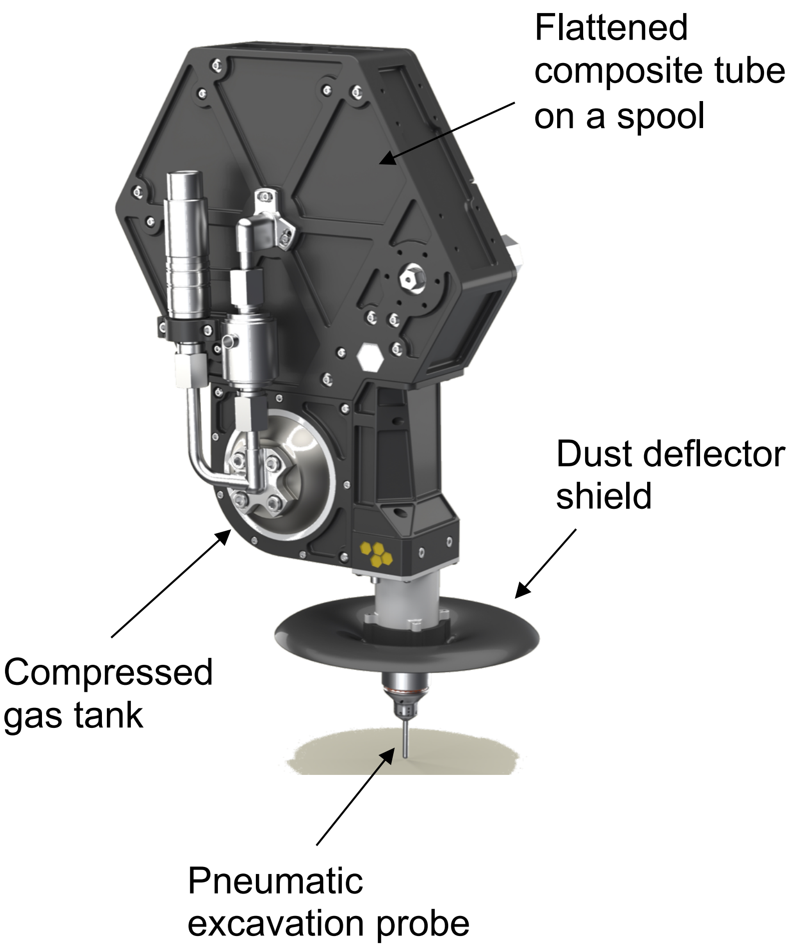


(credit: NASA/JPL/University of Arizona)

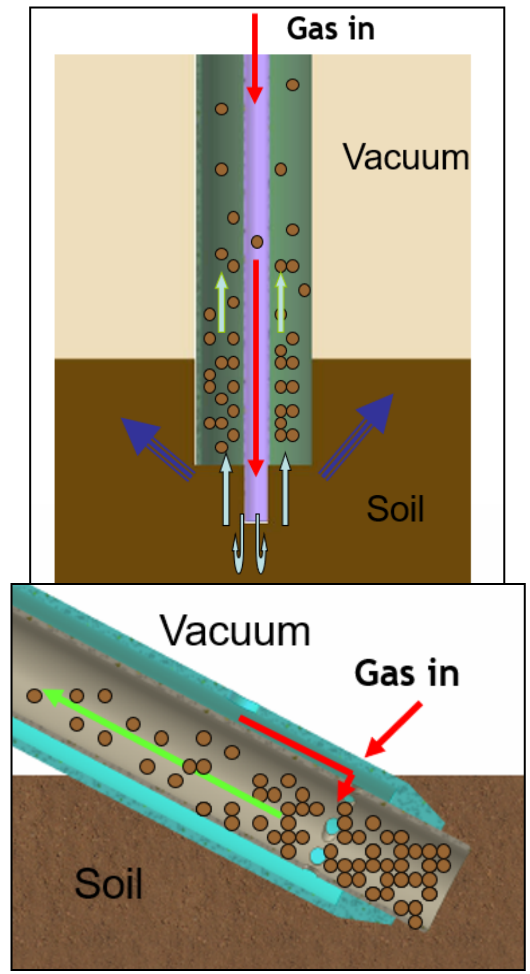
Planet Vac

Moon (Compressed Gas)

- Surface conditions: 0 atm, 0.17 G, 100K, loose non-cohesive material (dust)



Two possible transport methods

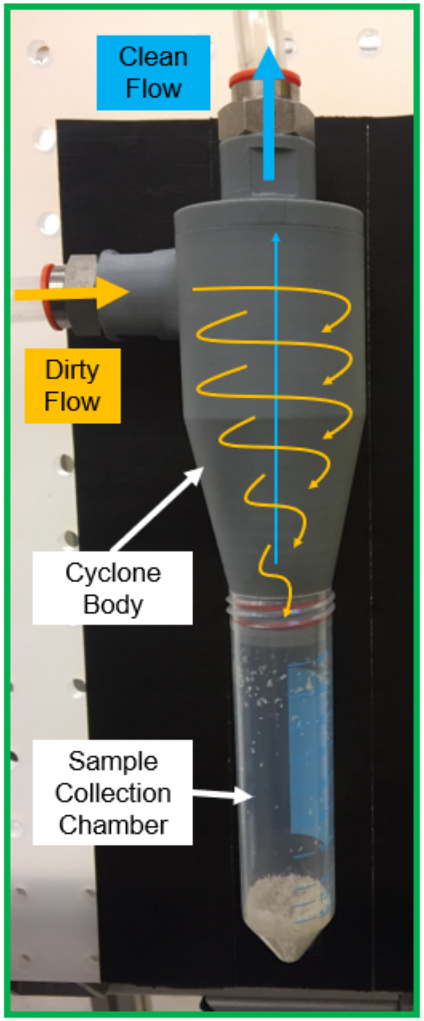


(credit: NASA)

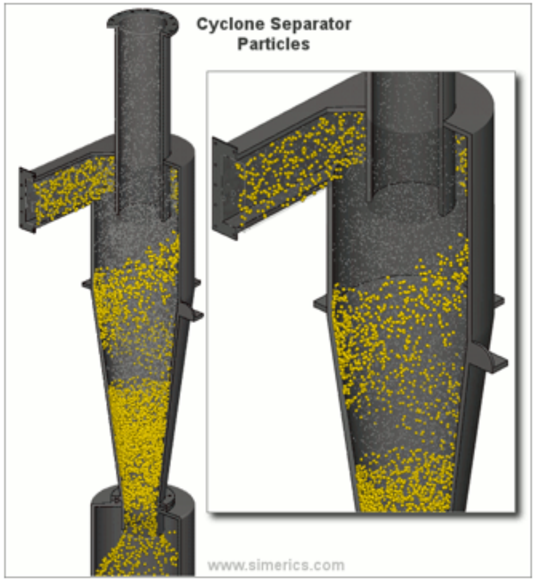
Pneumatic excavation in a vacuum chamber

Sample Collection (Cohesive vs. Non-Cohesive Material)

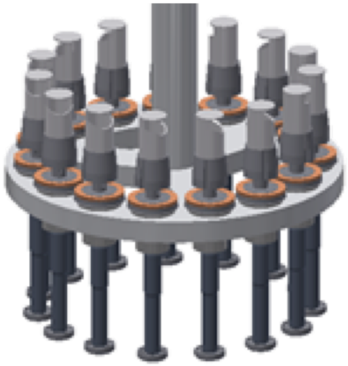
Cyclone Separator



- Creates gas vortex or "cyclone" which separates particles from gas
- Depends on gravity for final delivery into cup
- Bulk collection – widely used in industrial conveying
- Requires metering for some instruments
- More efficient with DRY material
- **Uncollected mass is stuck inside system**

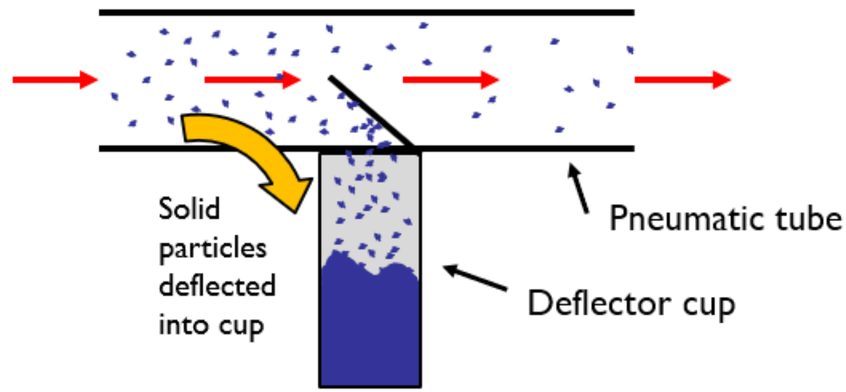


Carousel used to deliver full sample cups to instrument

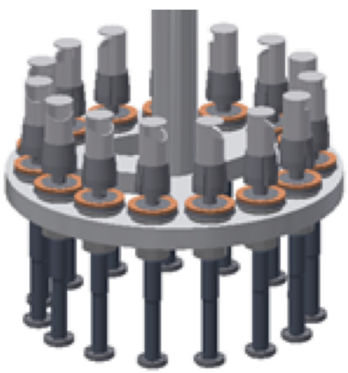


Deflector Cup

- Deflects particles into cup using mesh
- **Gravity independent**
- Clean / minimal cross-talk between samples
- Sample metering – fills the cup with set volume
- More efficient with STICKY material
- **Uncollected mass is expelled to the outside**

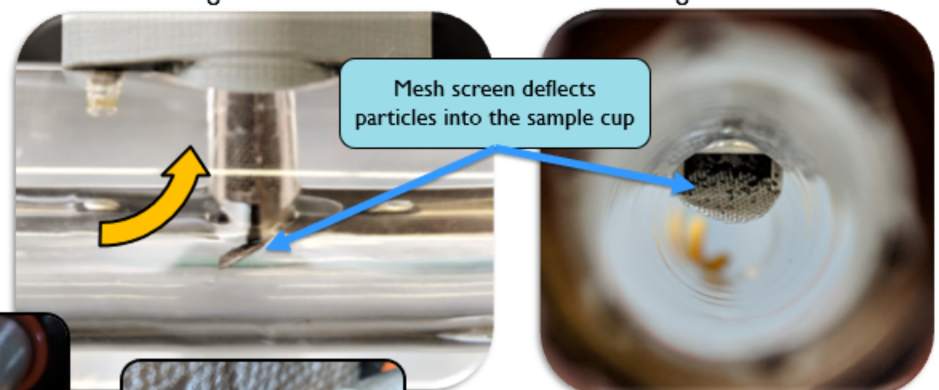


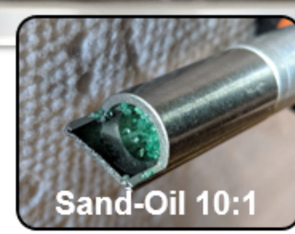
Carousel used to deliver full sample cups to instrument



Looking from above:

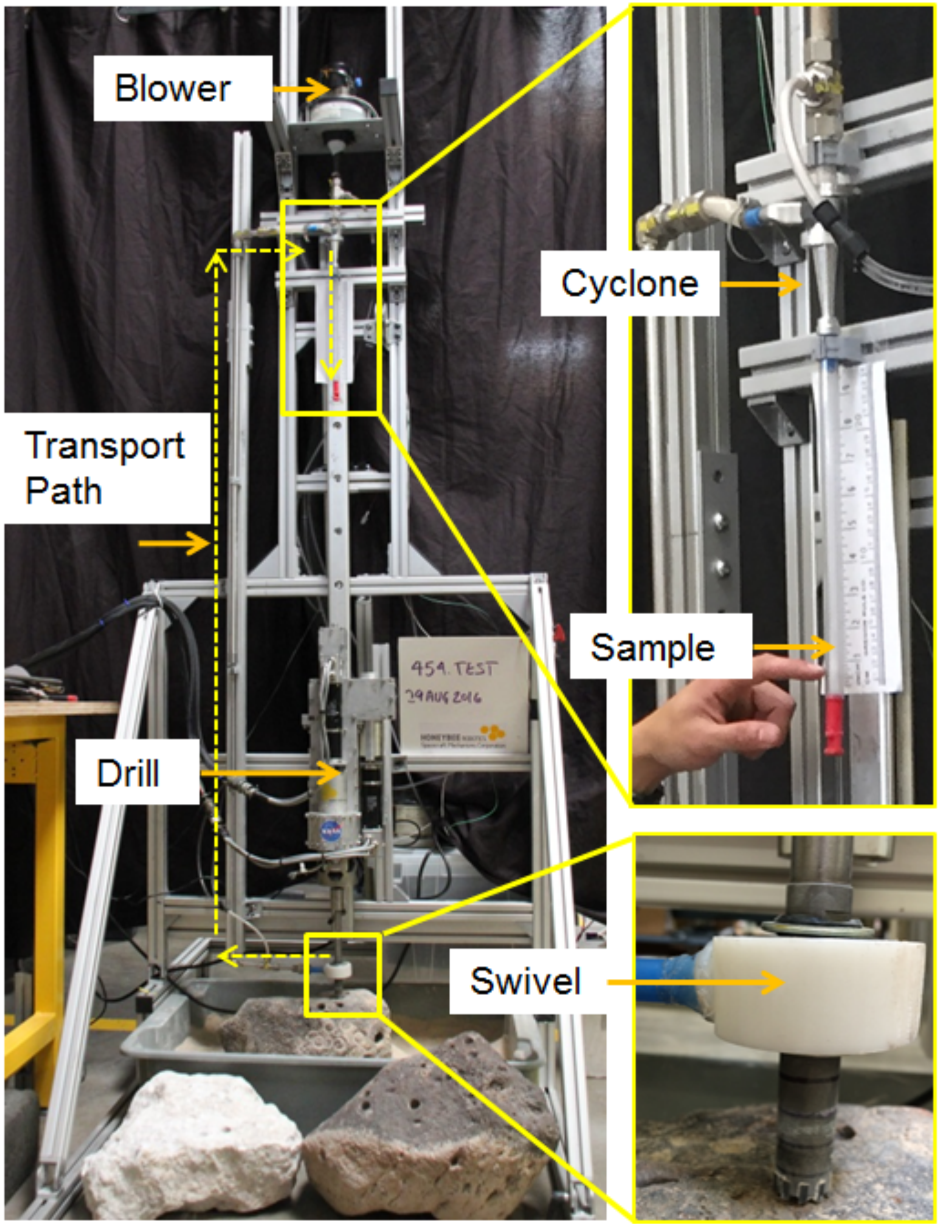
Looking down the tube:



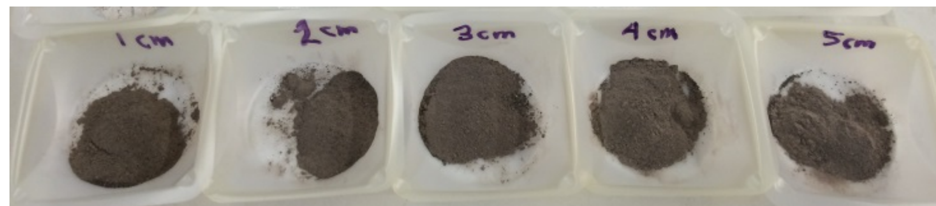


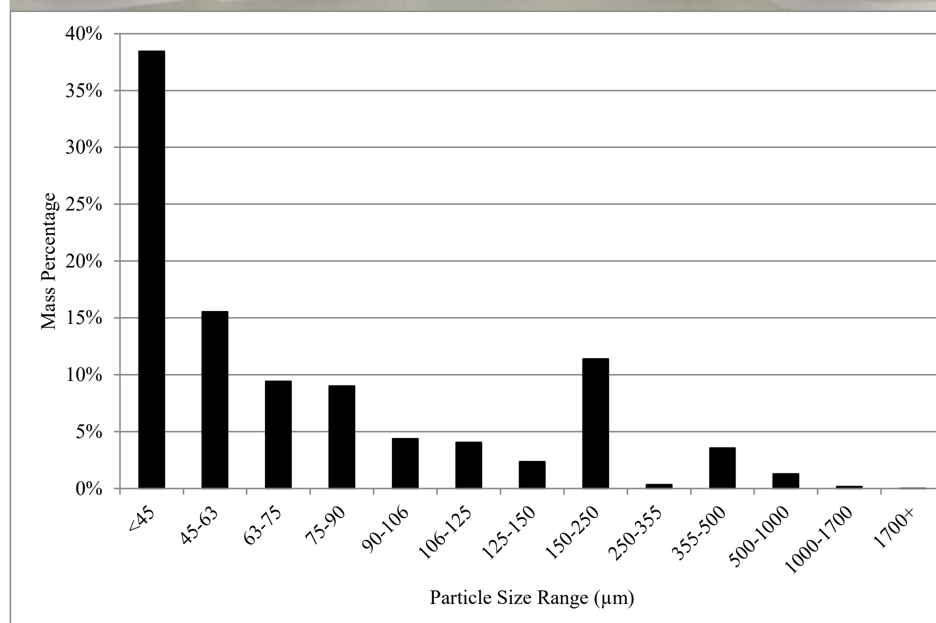
Proof-of-Concept Testing

Blower Transport of Dry Powder from a Drill



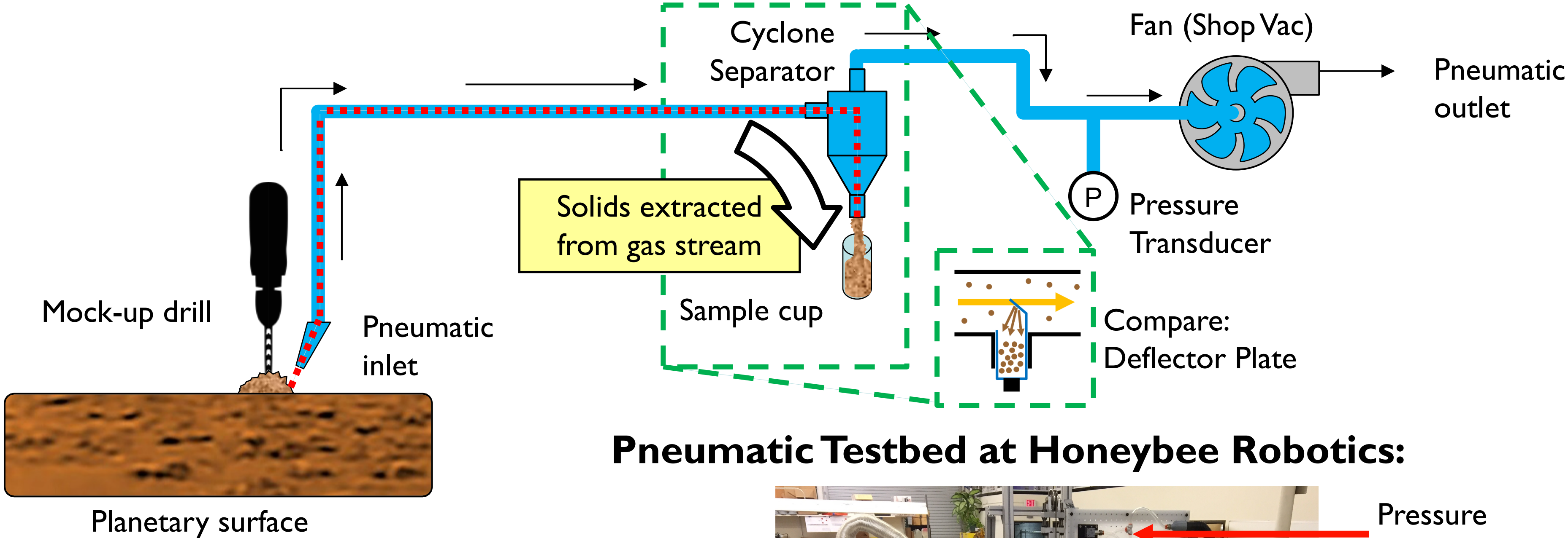
Suction	Mass of Sample Transported	Flow Velocity (Ave.)	Pressure Drop (Ave.)	Volumetric Flow Rate
Type	g	m/s	Pa	m^3/s
Continuous	25.27	8.6	4137	1.09E-03
Discrete, Percussion Assisted, 10s suction per 1cm depth	1.61	9.4	5723	1.19E-03
	4.24	8.8	5792	1.11E-03
	5.12	8.5	5861	1.08E-03
	5.67	8.7	5792	1.10E-03
	5.68	8.8	5861	1.11E-03



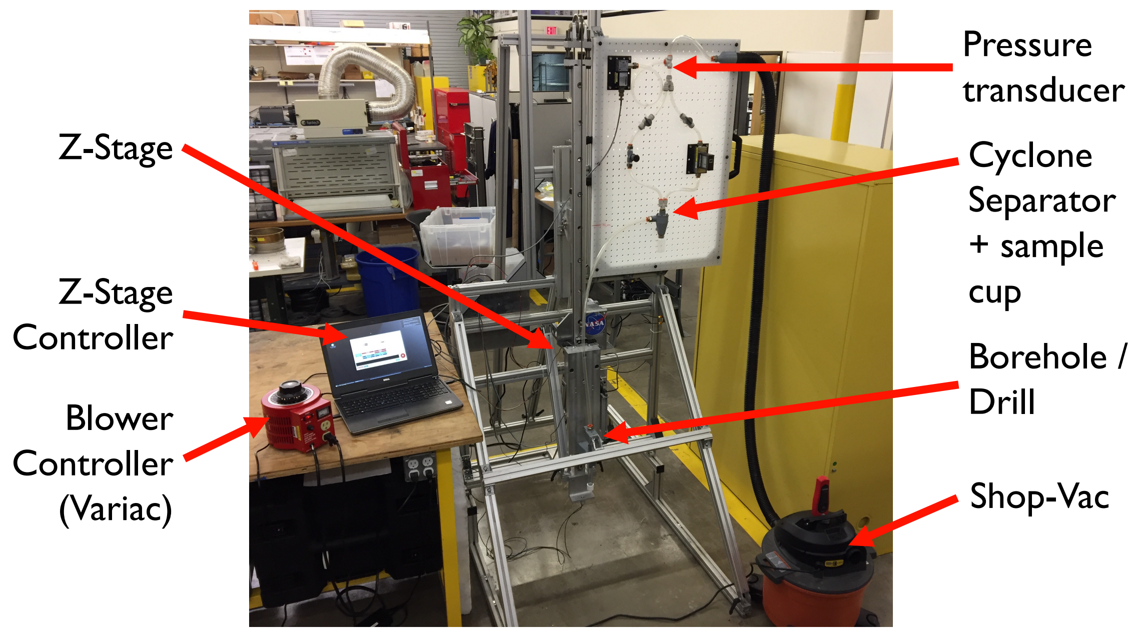


Blower Transport of Cohesive Loose Surface Material

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation
APL JOHNS HOPKINS
APPLIED PHYSICS LABORATORY



Pneumatic Testbed at Honeybee Robotics:



Pneumatic Transport Velocity Benchmarks

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

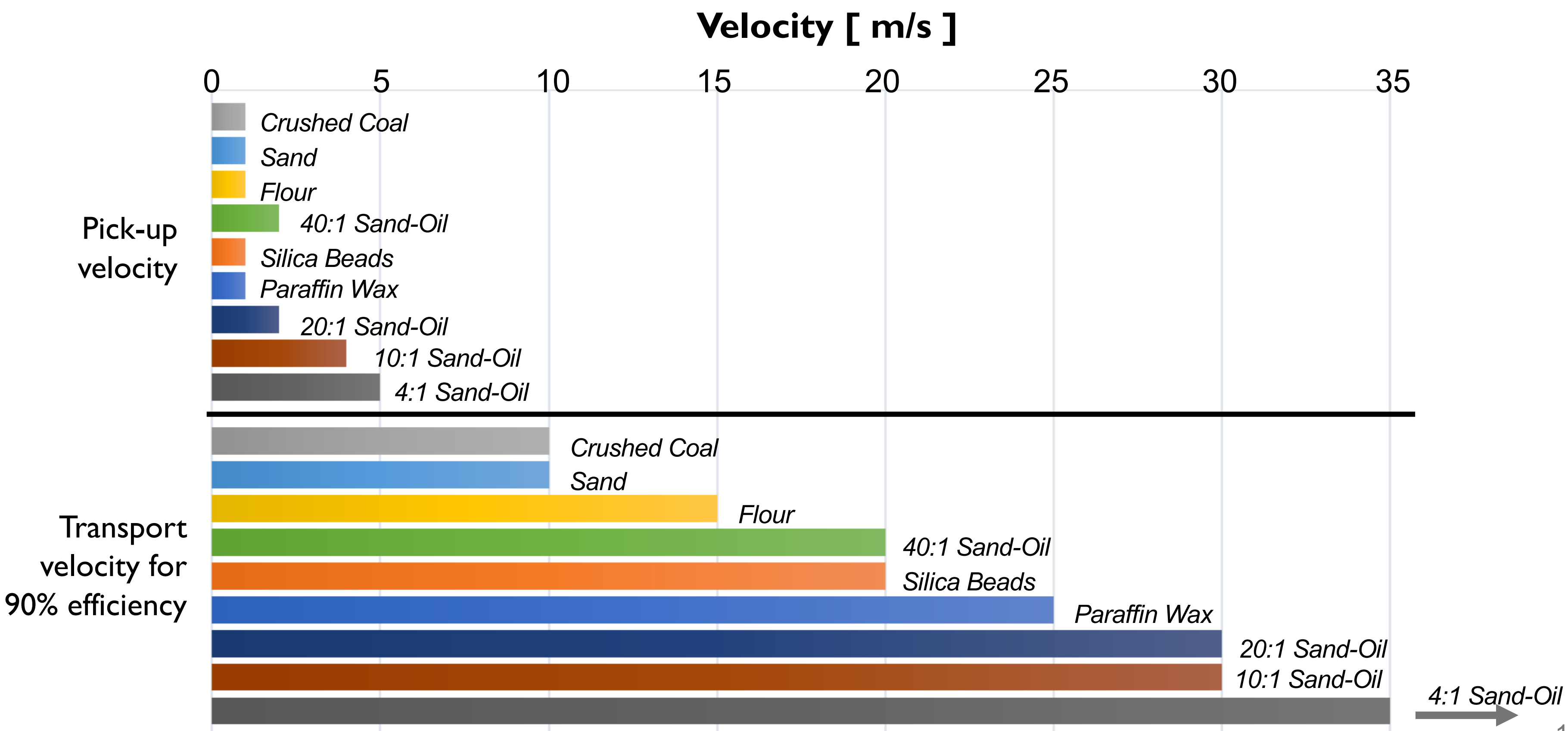
Non-sticky Simulants:

- Silica sand (250-500 um)
- Silica beads (40-80 um)
- Coal (0-1700 um)
- Ground walnut shells

Sticky Simulants:

+

→

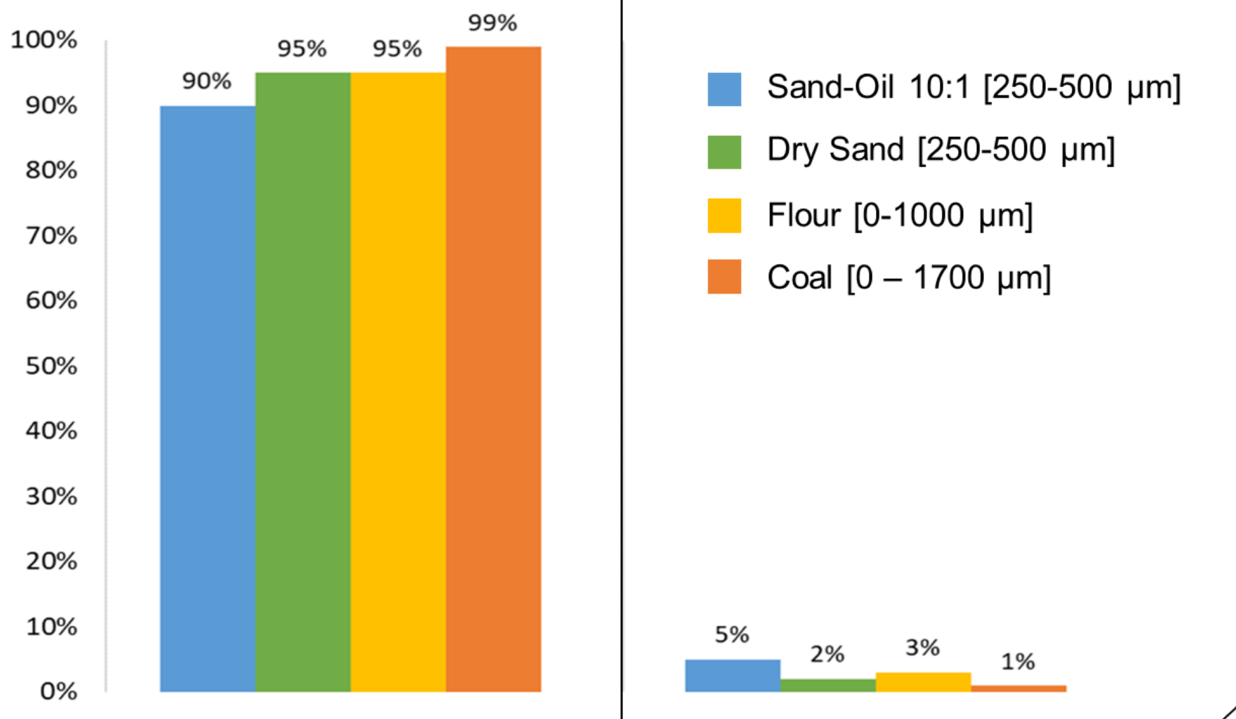


Collection Efficiency

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation
APL JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

$$\text{Collection Efficiency} = \frac{\text{mass collected in sample cup}}{\text{mass of sample ingested by pneumatic system}}$$

Cyclone | **Deflector Cup**



Acknowledgements

This work was made possible through the support of NASA's Small Business Innovation Research and COLDTech programs.