Percussive and Pneumatic Approaches to Lunar Heat Flow Probe Deployments

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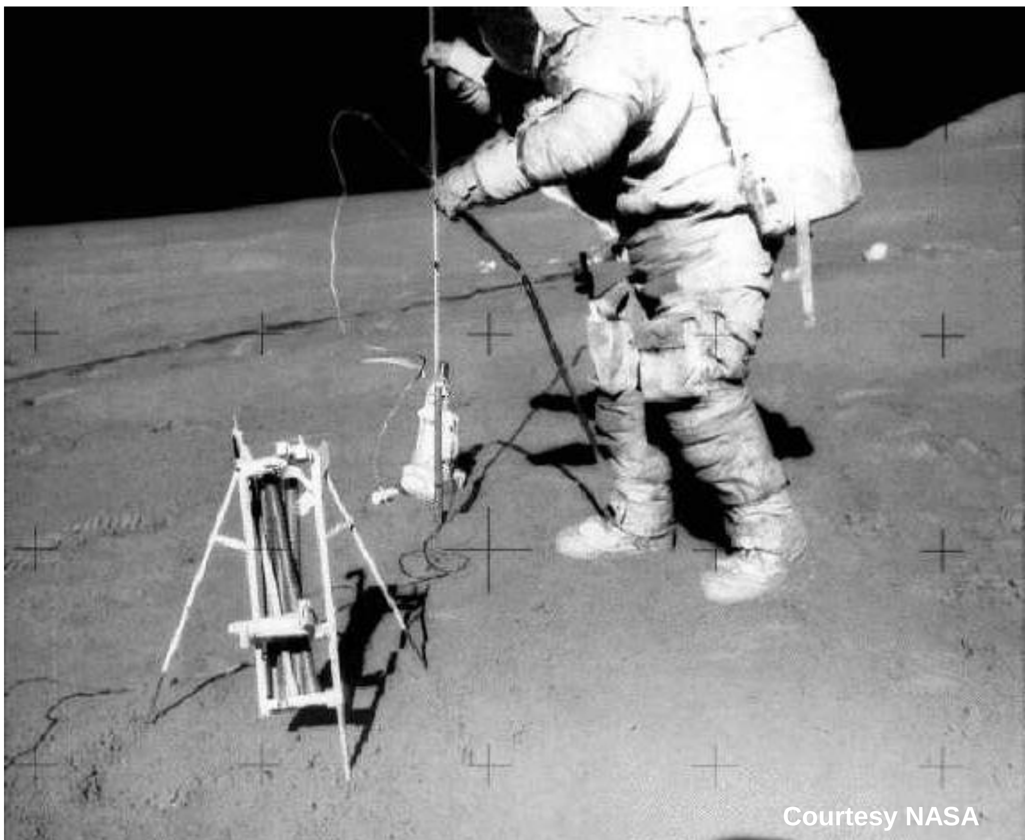
Photo by J. B. Irwin

Why measuring heat flow?

- Heat flow will tell us the bulk structure and composition of the Moon relative to heat producing elements (radioactive ^{40}K, ^{232}Th , ^{235}U and ^{238}U) and the extent of crustal differentiation.
- If we know the age of the Moon, then the heat flow will reveal if it had a hot or cold origin.



Courtesy NASA

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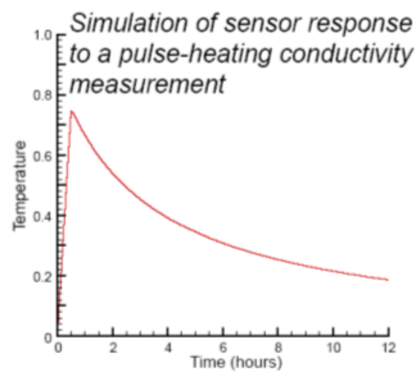
Required measurements

$$\text{Flow} = -k * \frac{\Delta T}{x}$$

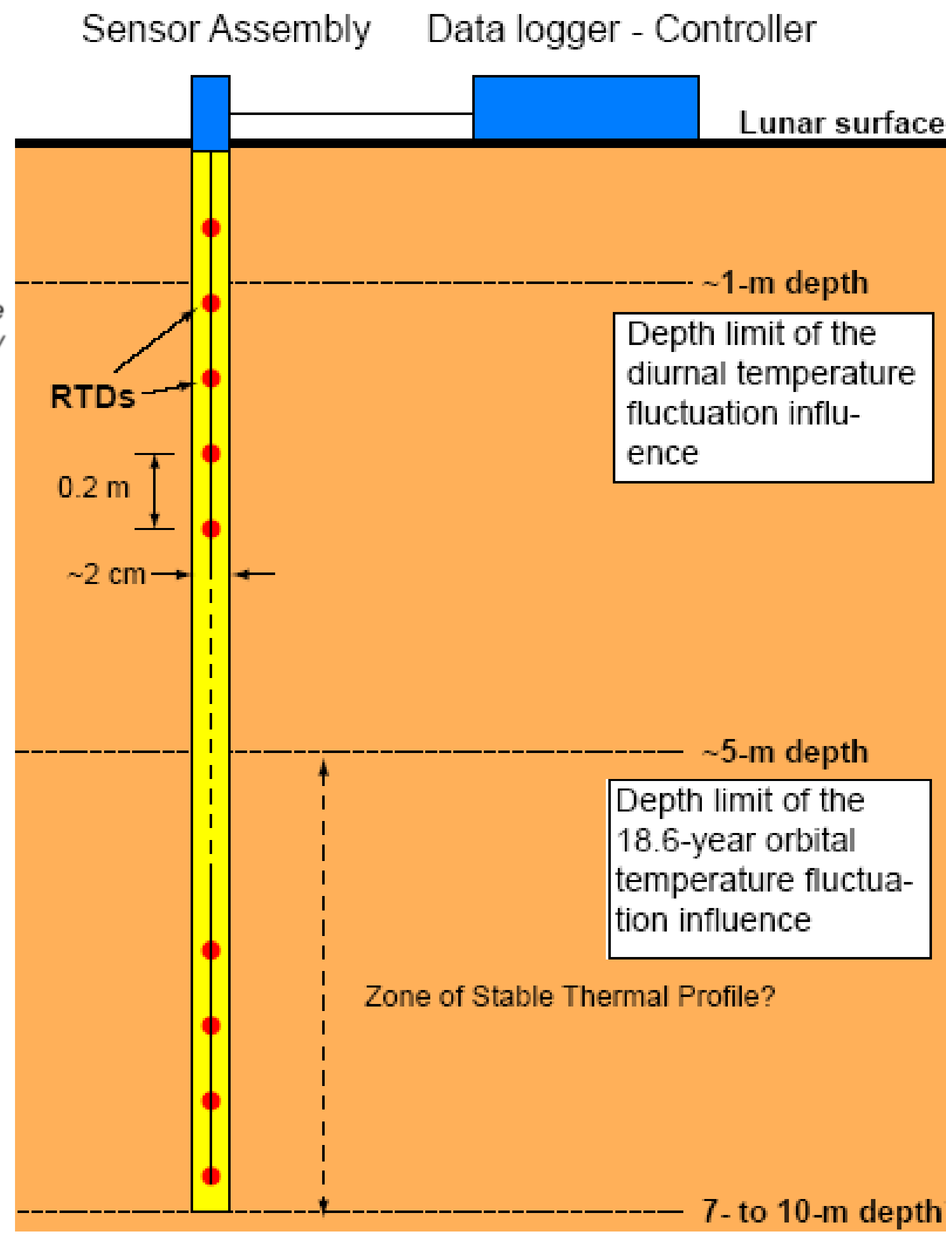
Thermal conductivity k:

- heat regolith,
- measure T change



The big issues:

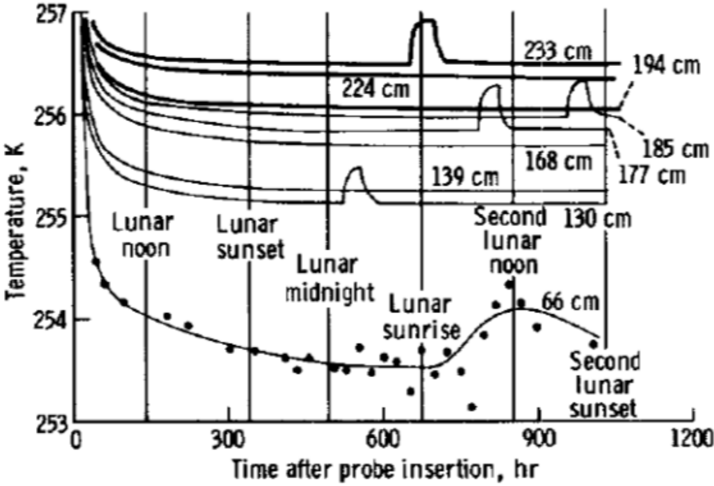
- thermal isolation between thermocouples themselves
- and from a surface lander/system

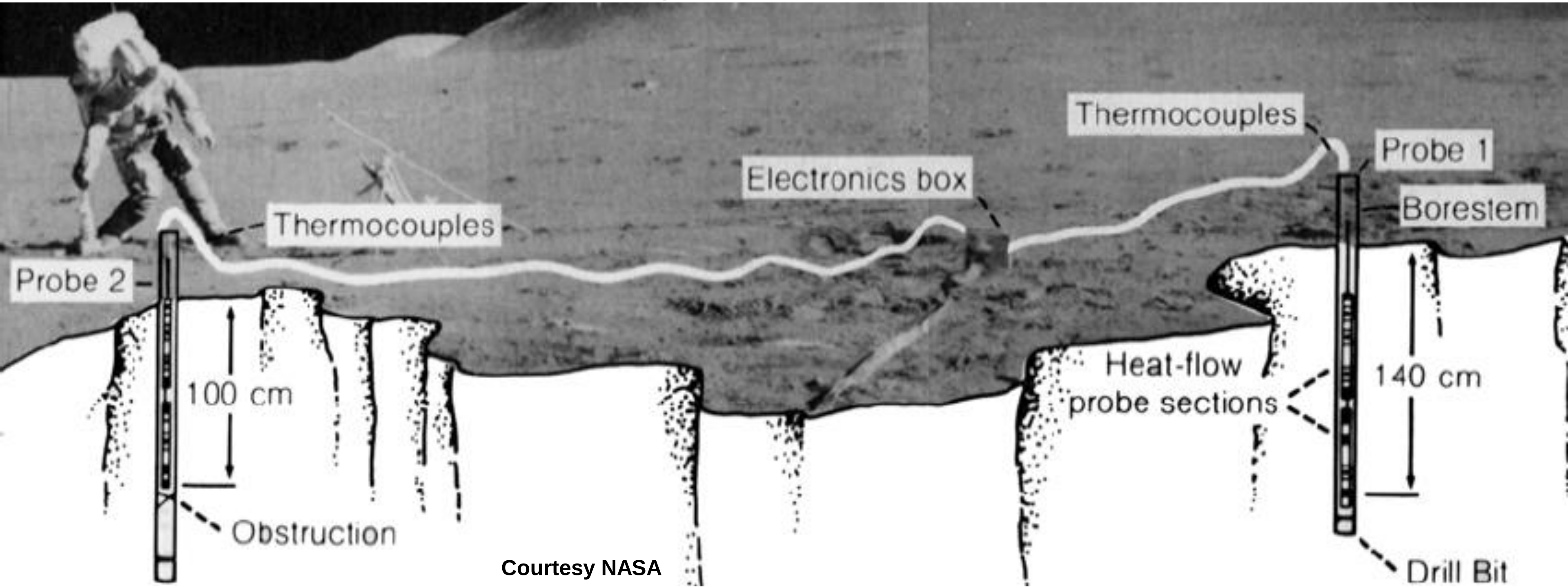


Nagihara et al., LSC, 2008

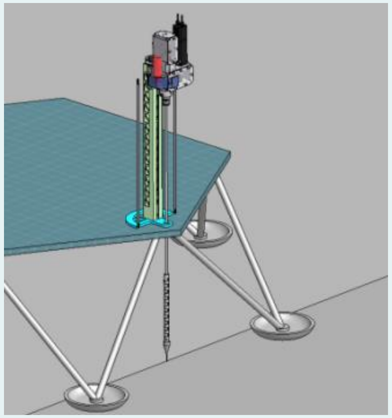
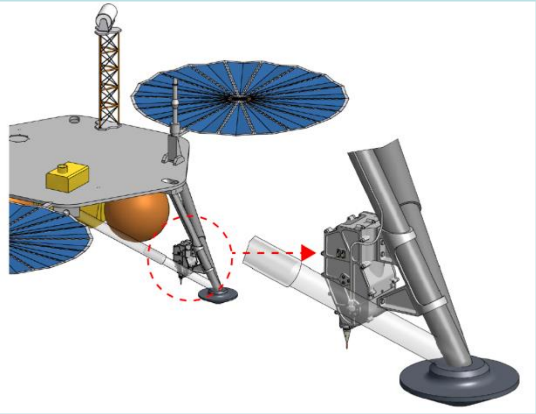
Apollo Experience

- Drill, pull out, put a probe into the hole
- 2 Heat Flow probes 10 m apart: 2 independent measurement and lateral variation
- A15: drill got ‘stuck’ and never managed to drill deep enough (2.4 m)
- A16: astronaut tripped over the cables
- A17: success but it was a tough work!





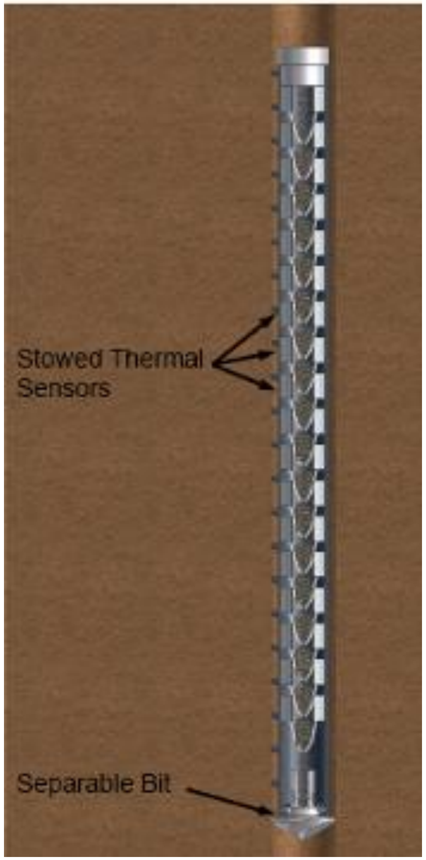
HFP Approaches

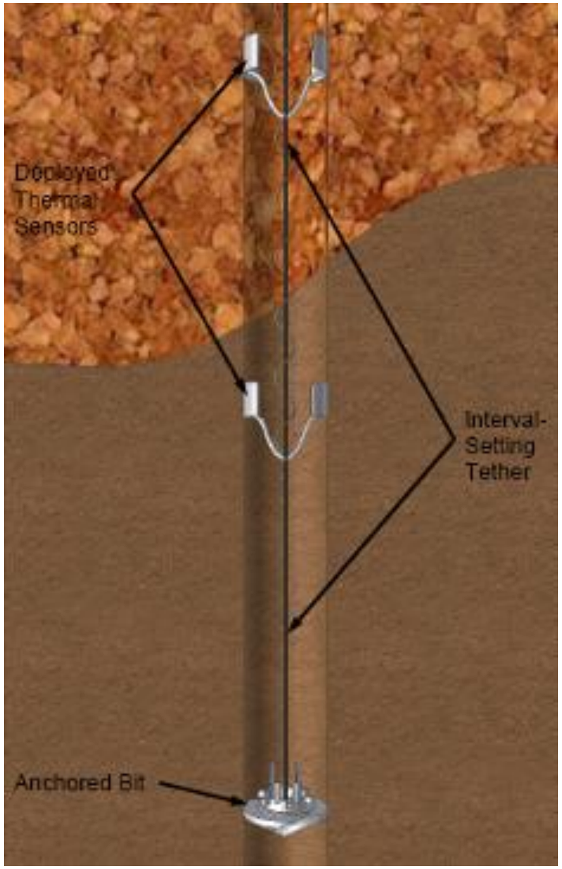
	Percussive System	Pneumatic System
		
Getting to 3 m	Hammer-driven penetrometer.	Gas driven proboscis.
Deploying thermal sensors	Ring-shaped heaters with temperature sensors deployed against the borehole as penetrometer penetrates. Conductive coupling to regolith.	Thermal sensors either housed in a flexible proboscis (radiative coupling) or spring deployed point sensors (conductive coupling).
Mass/Power/Energy	10 kg / 100 W / 100 Whr	1 kg / 10 W / 10 Whr
Advantage	- Fast penetration rate in dense soils - Conductive coupling to soil - Easy to model sensor geometry	- Low volume, mass and energy - Simple deployment
Disadvantage	- Need electrical energy (<200 Whr) - Need a carousel to feed rods	- Radiative (in worst case) coupling

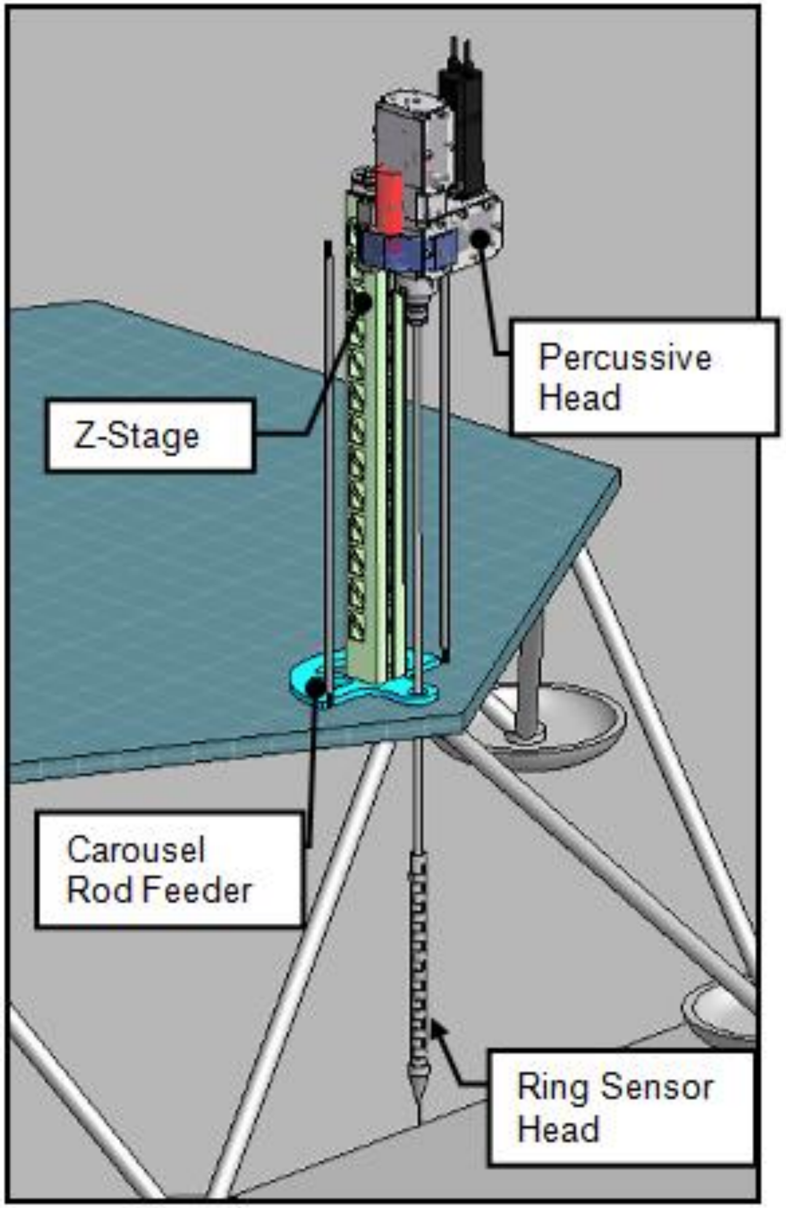
Percussive Approach

Design and Operation

- Ring sensors: T and k measurement
- Top-Down and Bottom-Up approach
- Optimum thermal isolation between consecutive heat flow sensors.
  - Sensors decoupled from the and the rest of the lander
  - The only physical connection between the borehole and the spacecraft is the electrical tether to the first sensor.
- Direct contact between the sensors and regolith.

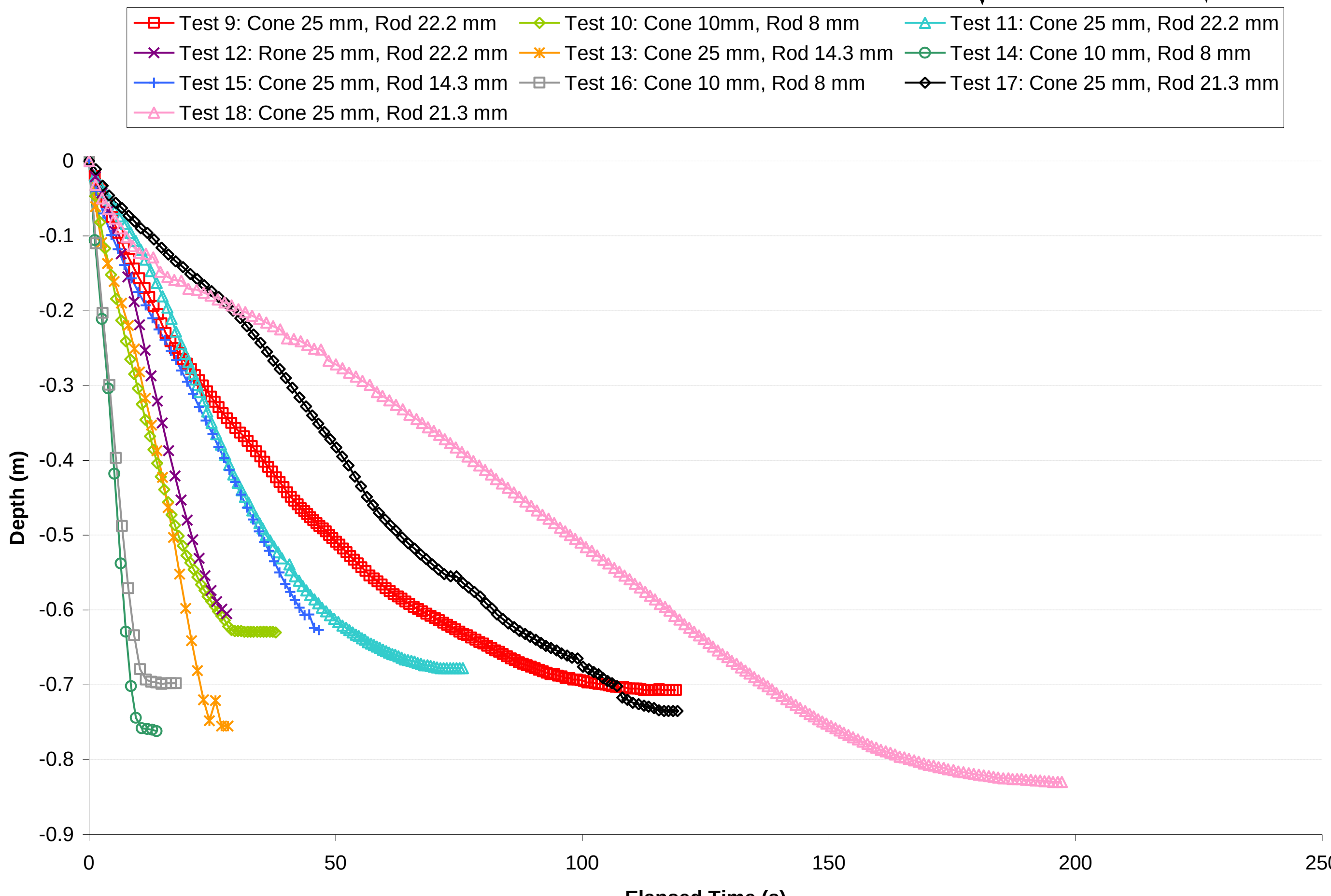




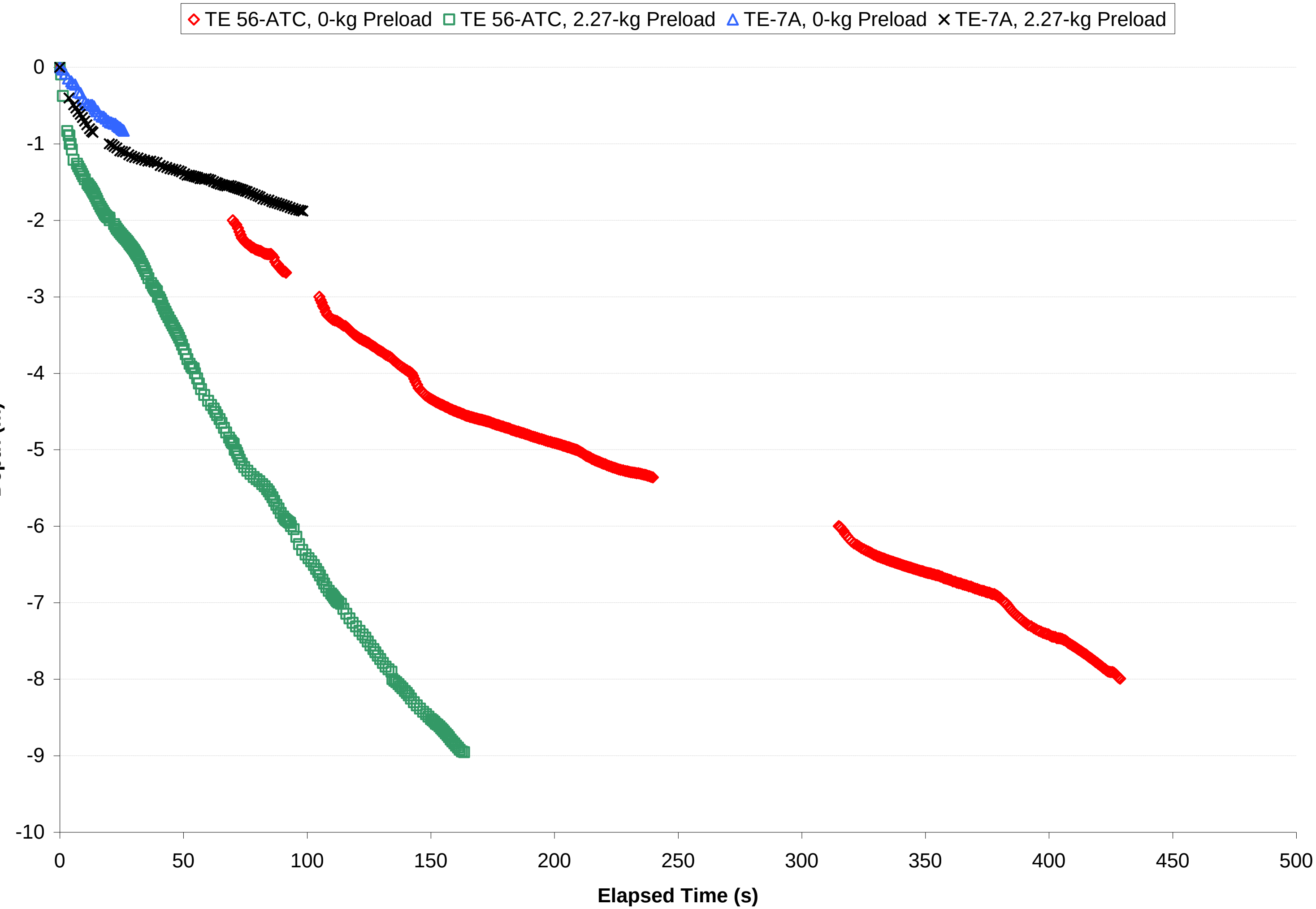


Tests in compacted JSC-1a

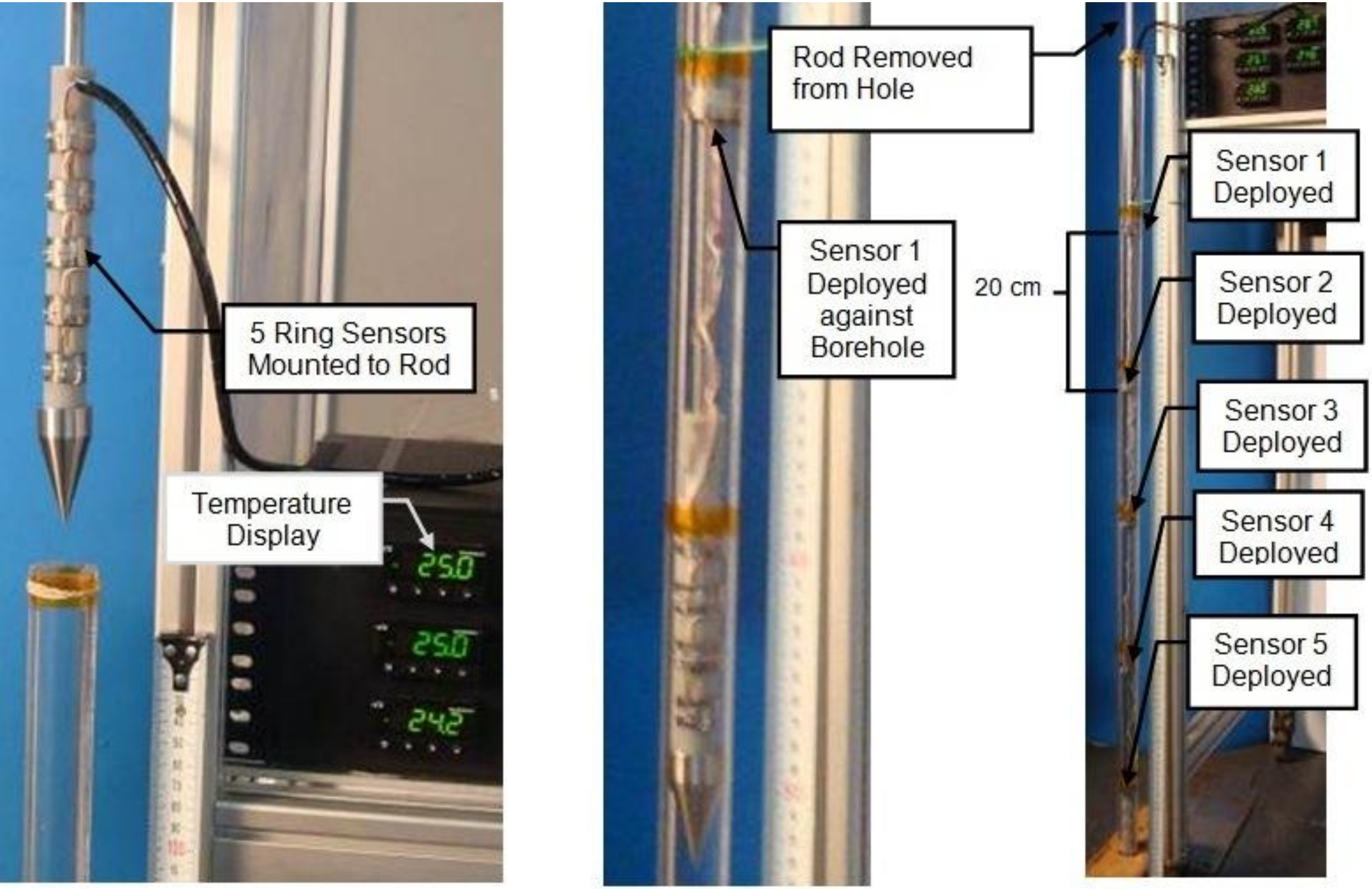
- Resistance is a function of a cone diameter and rod diameter
- 1 meter reached in 1-3 minutes



10 Meter Tests in GSFC-1



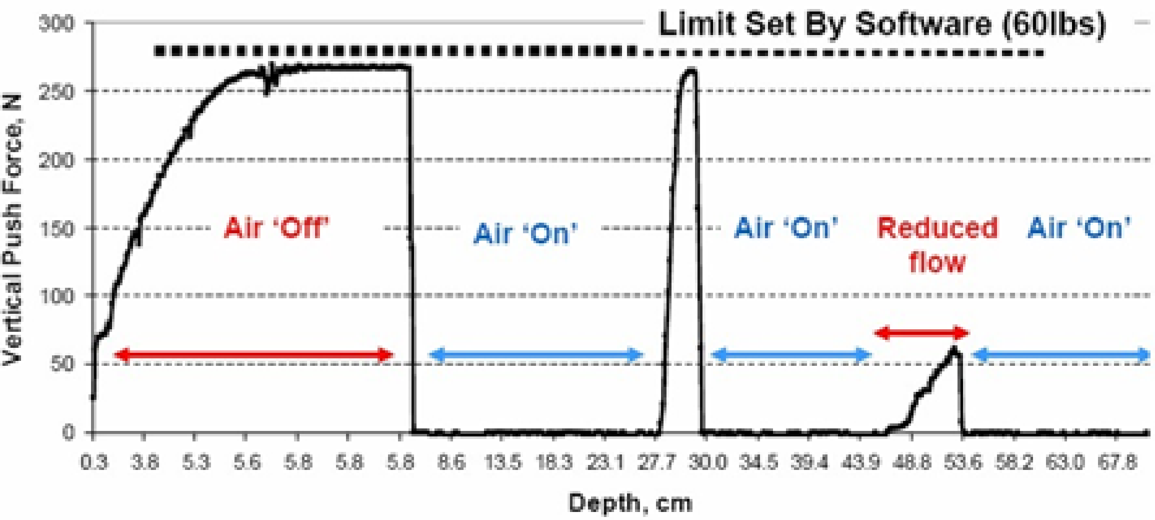
Top-Down Demonstration

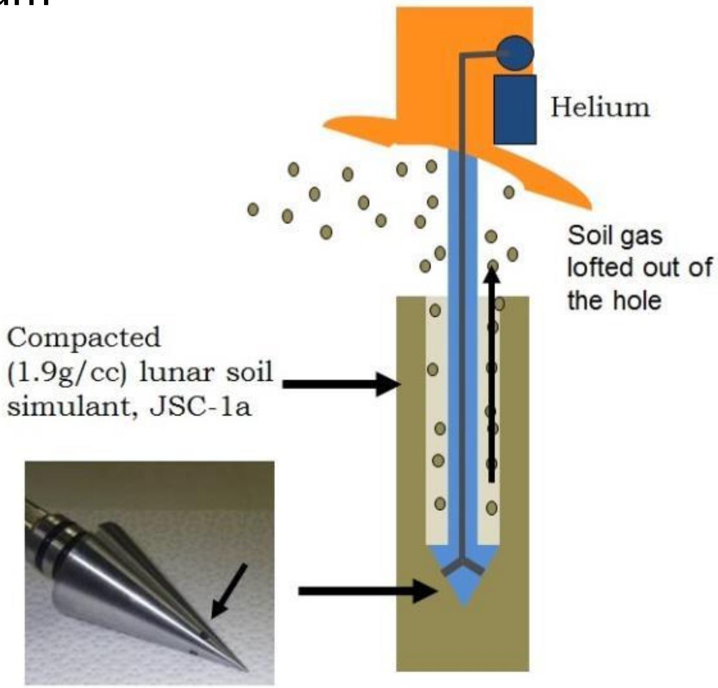


Pneumatic Approach

Proof of Concept

- Excavation accomplished by injecting gas
- Use dedicated gas tank or He from propulsion system
- Large gas efficiencies possible if deployed in vacuum





Test#	Cone Geom.	Gas Type	Regulator Pressure [PSI]	Measured Vol. Flow Rate [SCFM]	Gas Density [kg/m^3]	Mass Flow Rate [grams/sec.]	Actual Avg. WOB [lbf.]	Depth Penetrated [in.]
1	no hole	n/a	n/a	n/a	n/a	n/a	100	<2
2	4 holes	air	20	1.5	3	2.12	0	25
3	4 holes	air	5	0.8	1.7	0.65	0	25
4	4 holes	He	5	0.8	0.2	0.09	0	25

Components and Deployment

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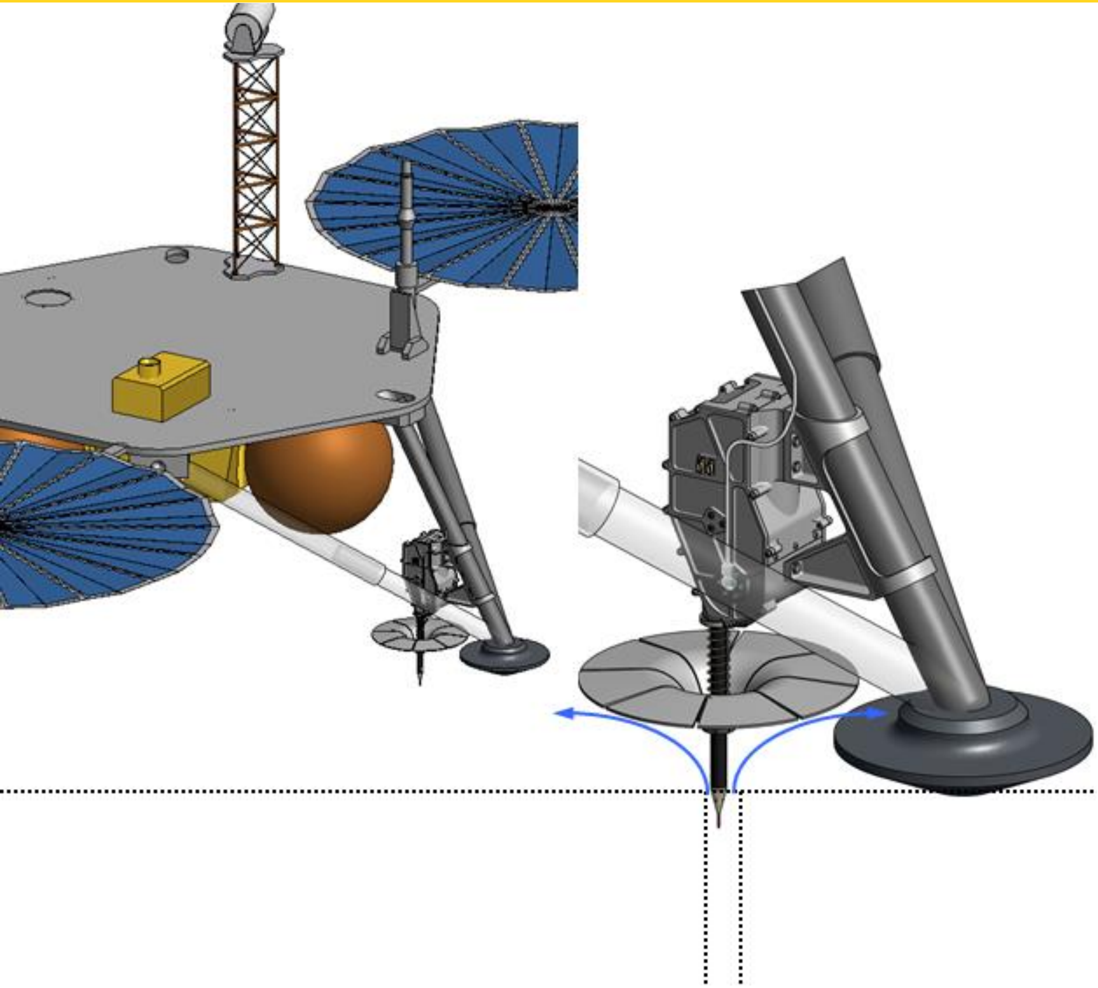
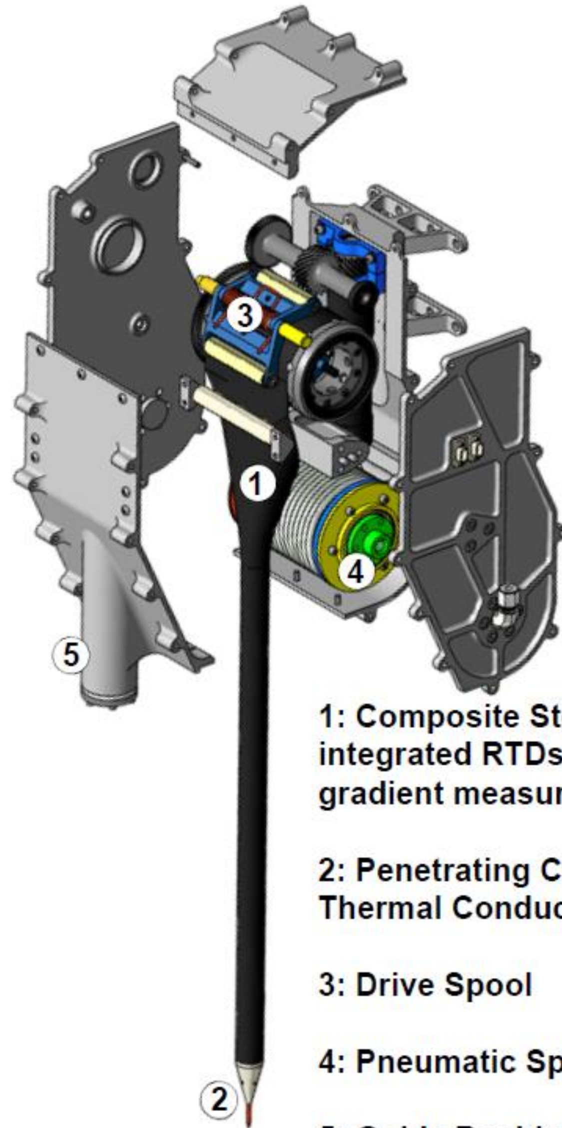




1: Composite Stem with ~10 integrated RTDs for thermal gradient measurement

2: Penetrating Cone with Thermal Conductivity Needle

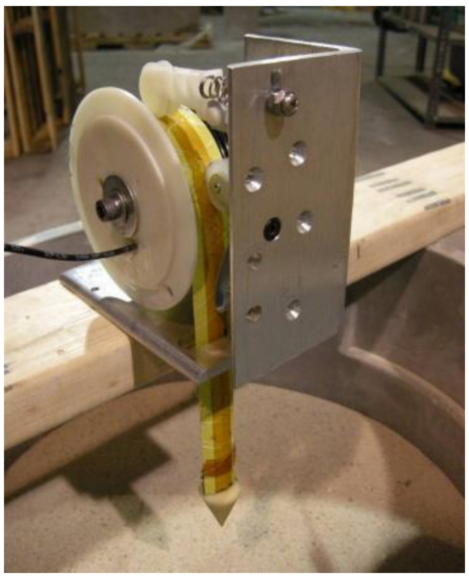
3: Drive Spool

4: Pneumatic Spool

5: Guide Bushing and Brushes

Development History

2008/09
1st generation
TRL 3



2009/10
2nd generation
TRL 3/4

2011
3rd generation
TRL 4

2012-14
4th generation
TRL 5

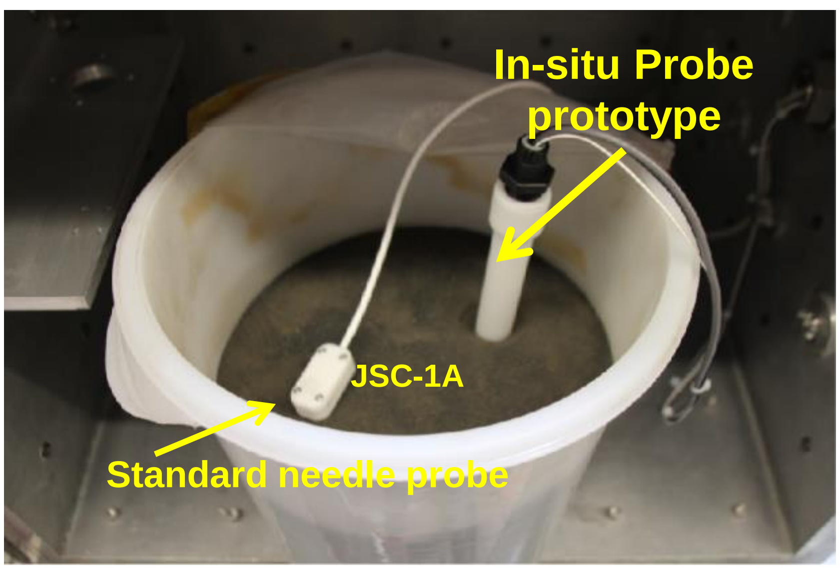
TRL 5 (1.2 kg)

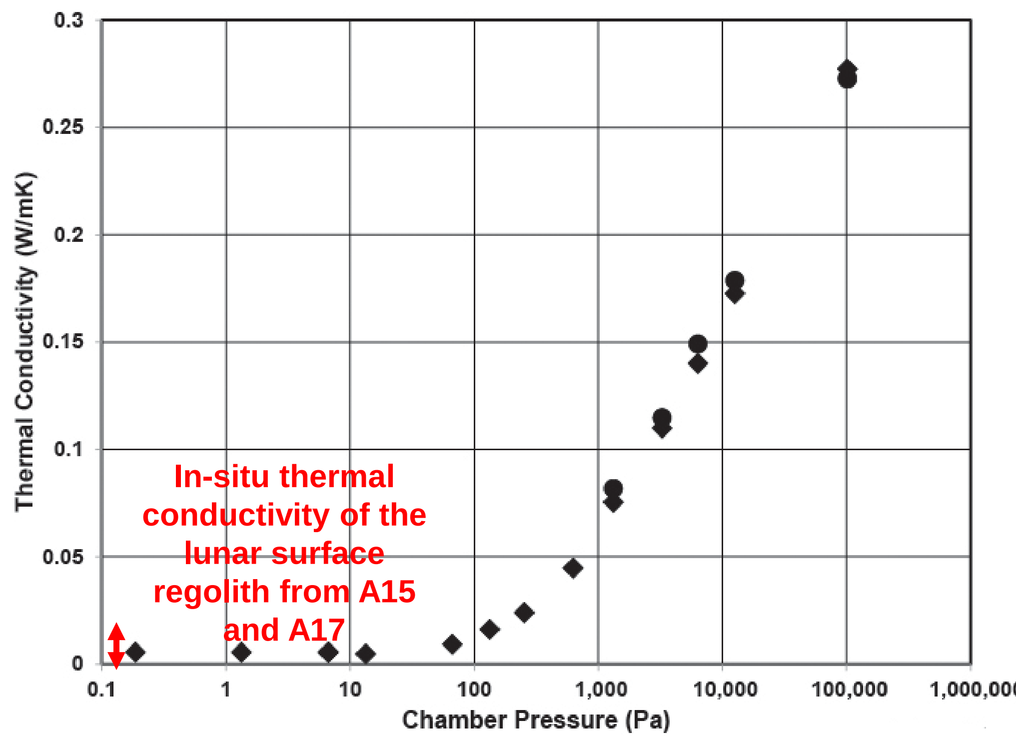
HONEYBEE ROBOTICS

Thermal Conductivity Probe Tests

HONEYBEE ROBOTICS

- Conducted k tests in JSC-1a
- Varied pressure from 760 torr to 1 mtorr
- Used standard needle probe as reference
- Data agrees with A17 data





TRL5 1 m test in JSC-1a in Chamber

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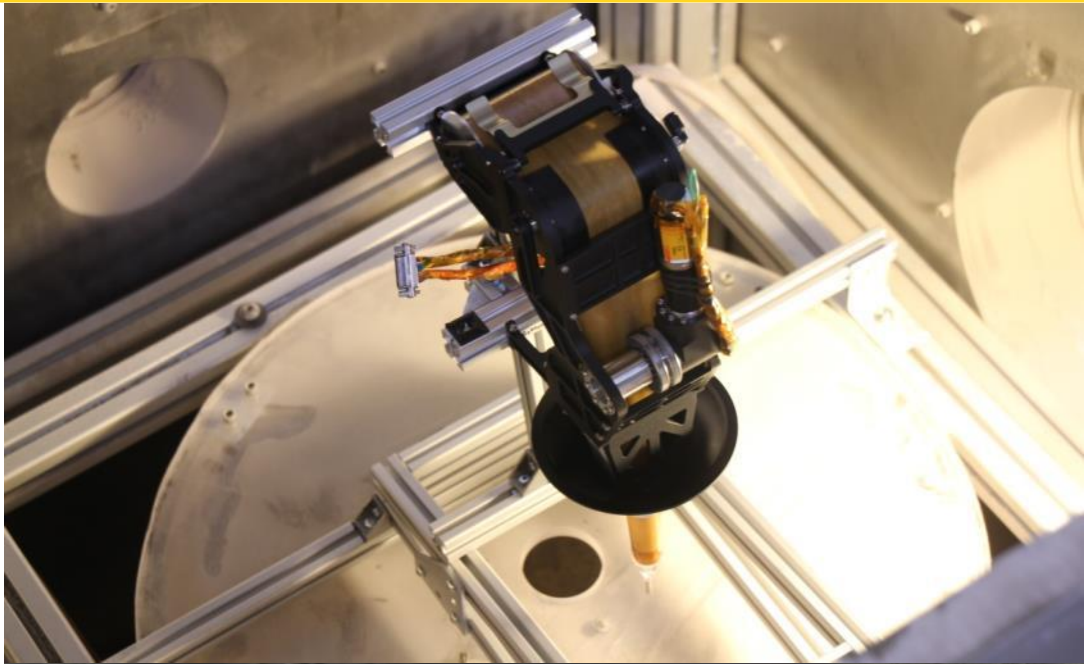
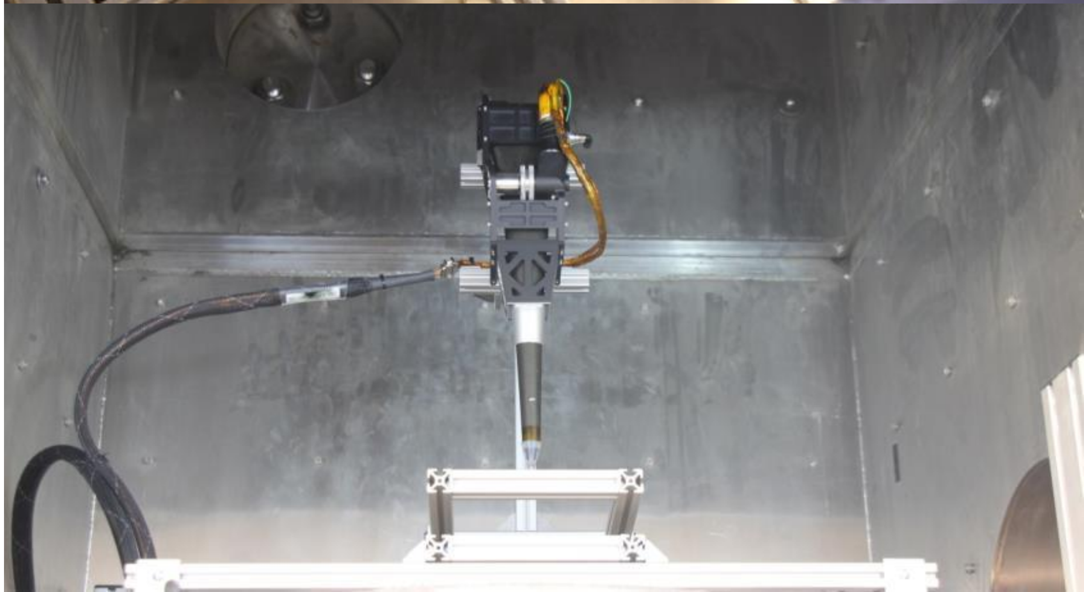
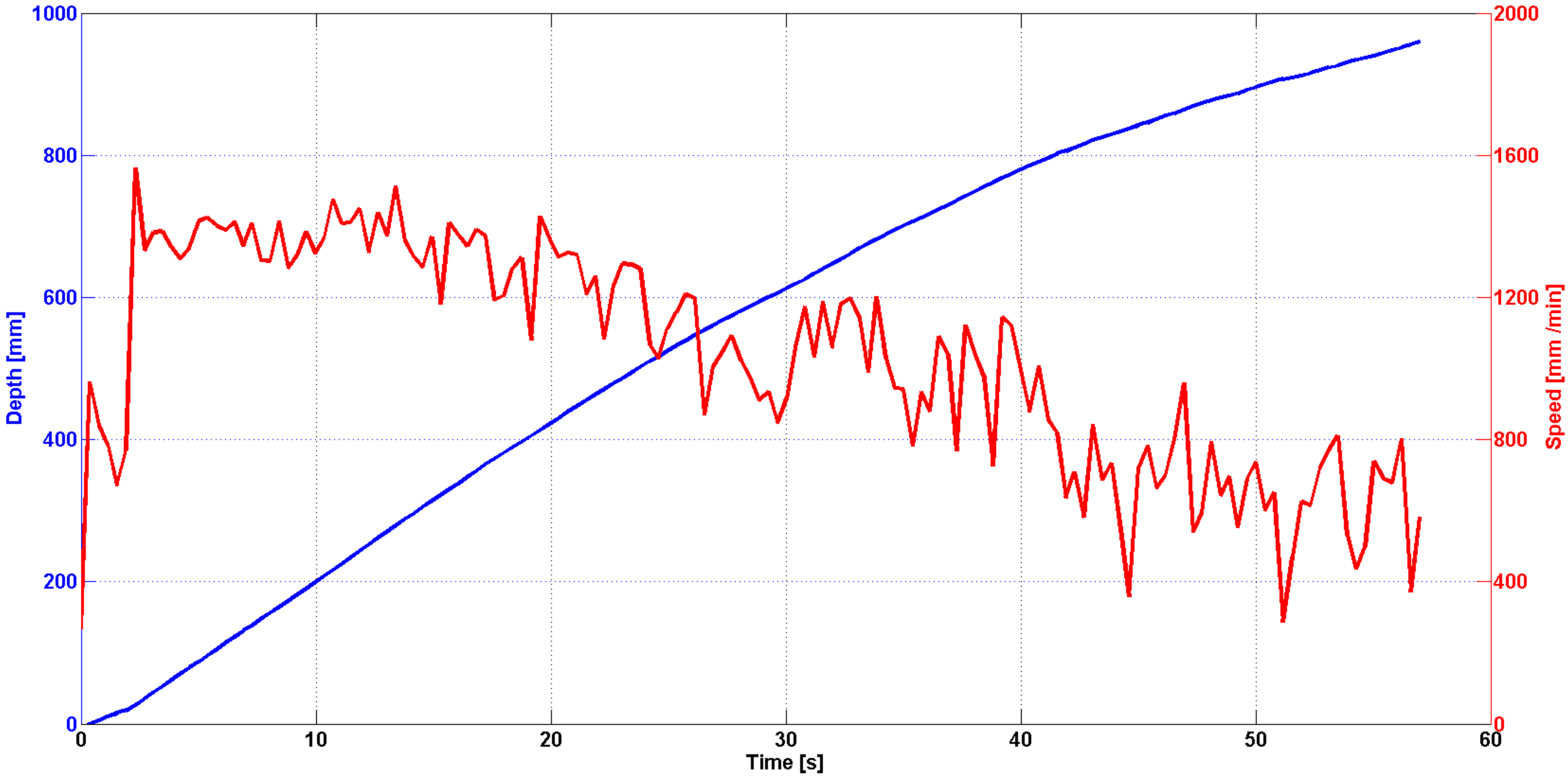
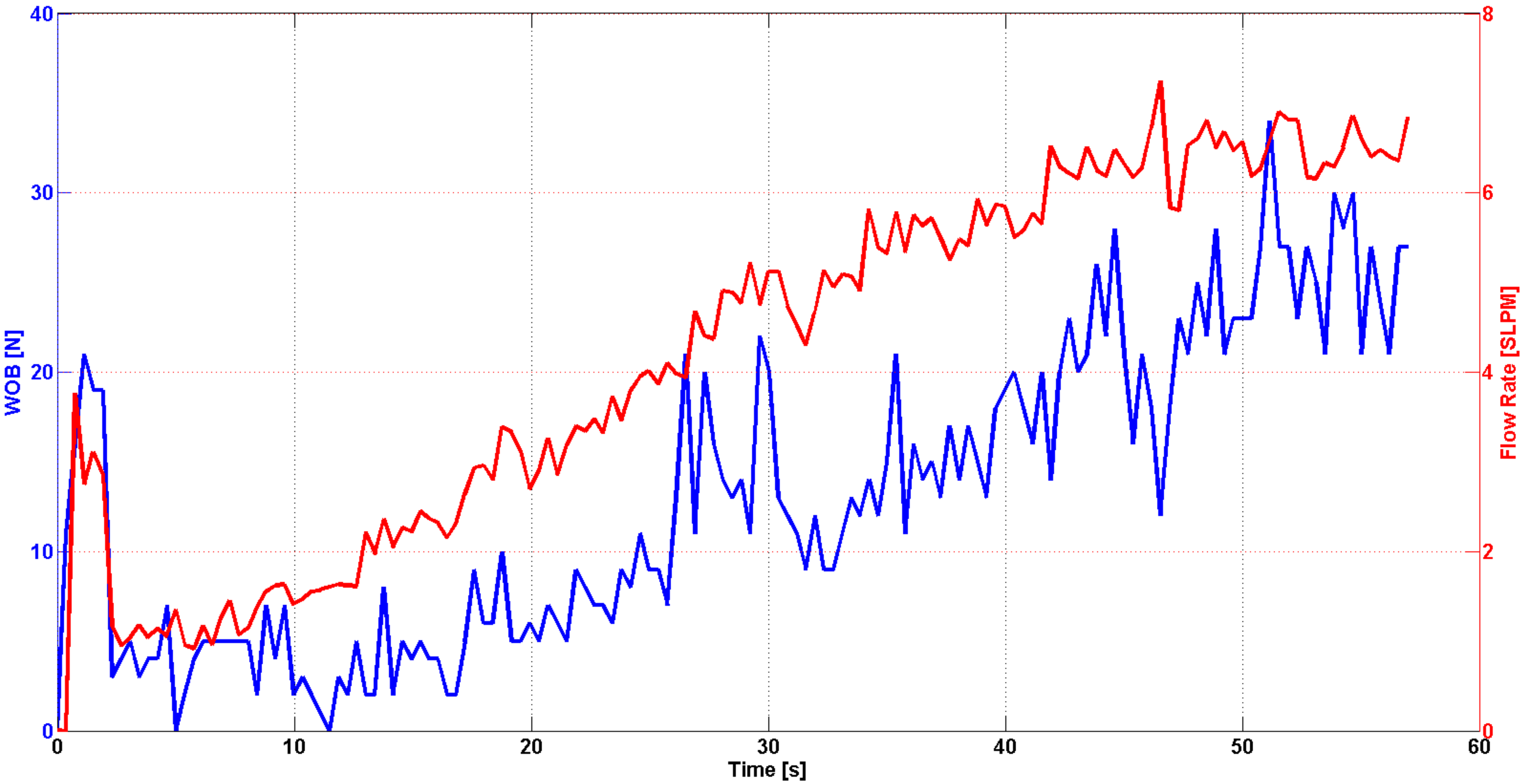




TRL5 1 m test results in JSC-1a



TRL5 1 m test results in JSC-1a

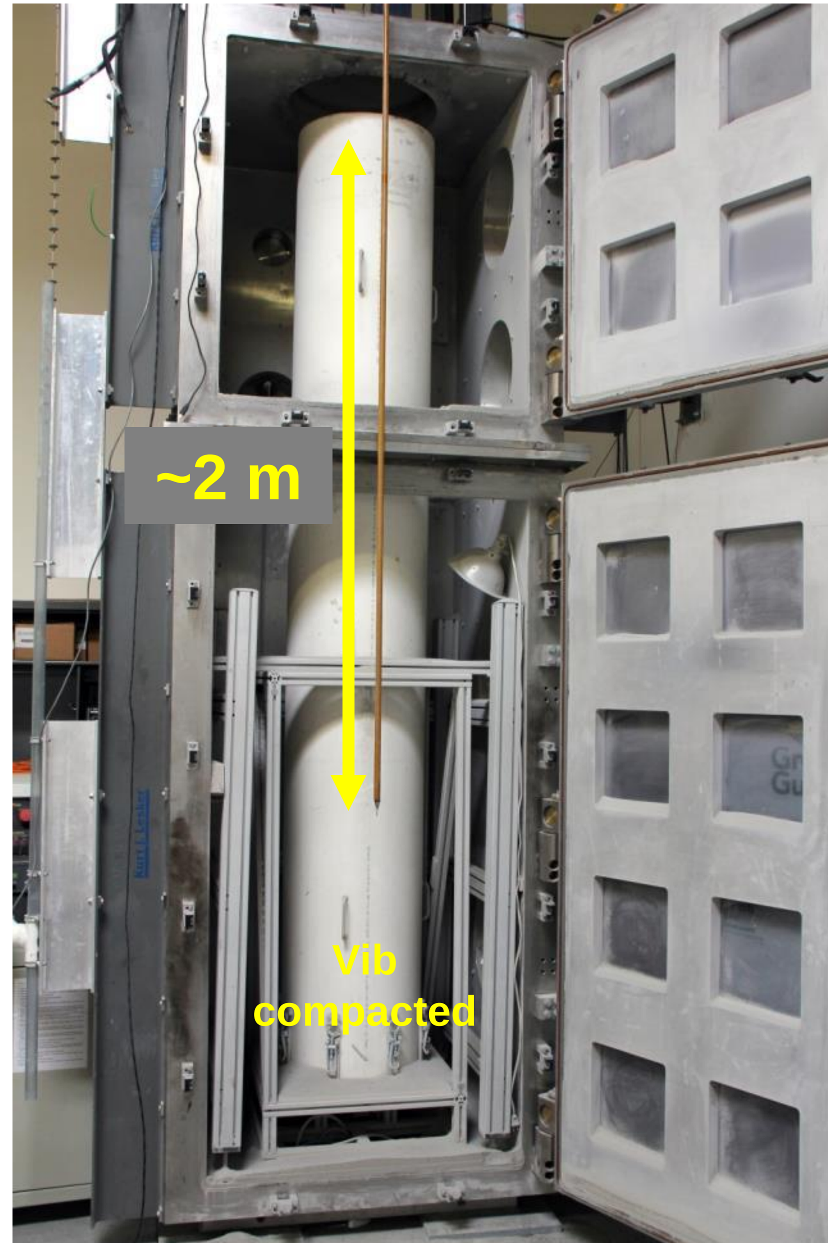


Pneumatic Spear

- Tests at 760 torr
- 20 N Force
- Approx. 1 min to 3 m
- Gas Flow 2-2.5 ft^3/min. Approx. 67-83 grams of air at 120 PSI.

Tests in NU-LHT-2M

- **Approx 2 m**
- **Stop and Go successful (required for getting k at various depths)**



Acknowledgements

- NASA Small Business Innovation Research
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Thank You!

HONEYBEE ROBOTICS
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