Solar System Sampling

Timothy Szwarc, Ph.D.

Mechanical Engineer, Jet Propulsion Laboratory, California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Stanford University

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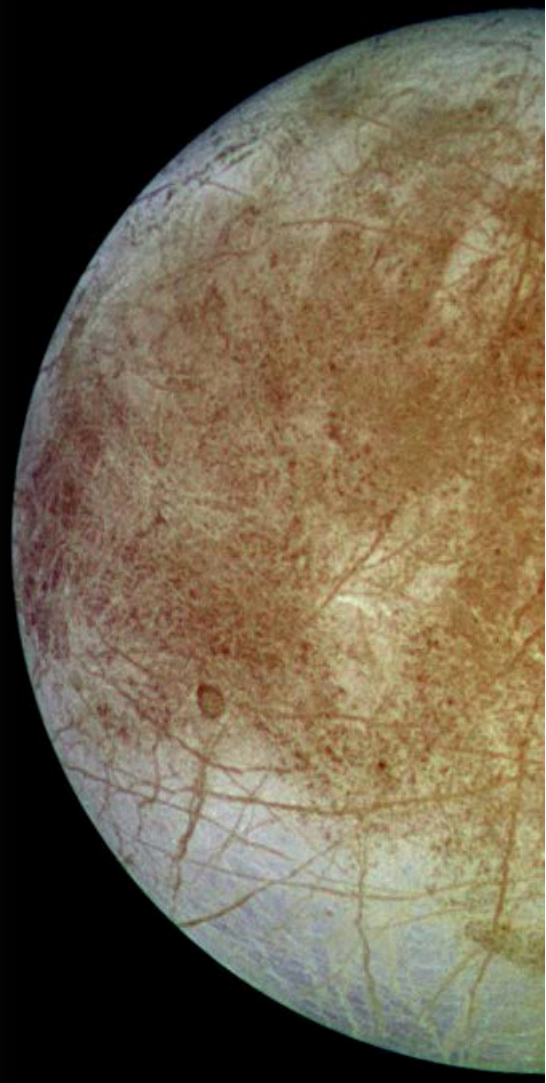
About Me

Research

Work at JPL



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BS Mechanical Engineering, Cornell 04'. JPL Co-op. By chance, assigned to MSL (Curiosity) drilling work.

MS Aeronautics & Astronautics, Stanford 09'

Ph.D. Aeronautics & Astronautics, Stanford 14'

"Thermal Modeling of Coring and Drilling Operations for Solar System Exploration Applications"

Professors Scott Hubbard and Brian Cantwell

Outdoors, Land or Sea

Motor Racing Fan and Podcaster

Homebrewer

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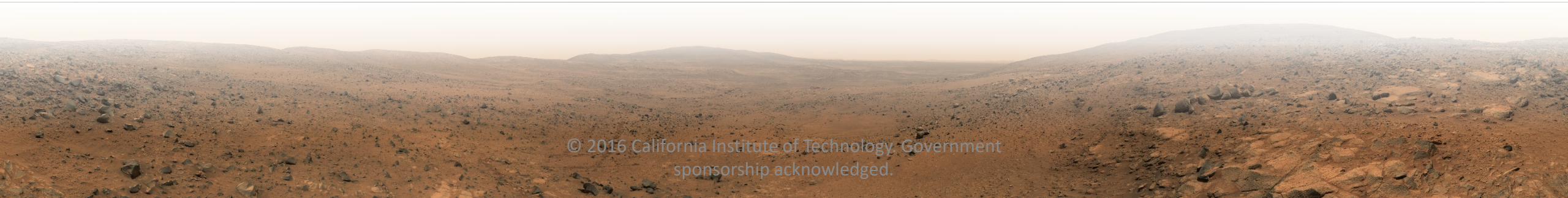
Research: Thermal Analysis in Planetary Sampling

- Protect the samples
- Protect the hardware



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Research: Thermal Analysis in Planetary Sampling

- Prevent significant alteration of samples
  - Baking of clays
    - Kaolinite (Martian analog found on earth)
    - Clay mineral named after Kao-Ling, China
    - Famous for being baked into porcelain aka “China”
  - Evolution of volatiles, especially water
- What about sample is natural, what is a side effect of sampling process?

Credit: UNESCO

“ $$\sigma_x \sigma_P \leq \frac{\hbar}{2}$$ ”

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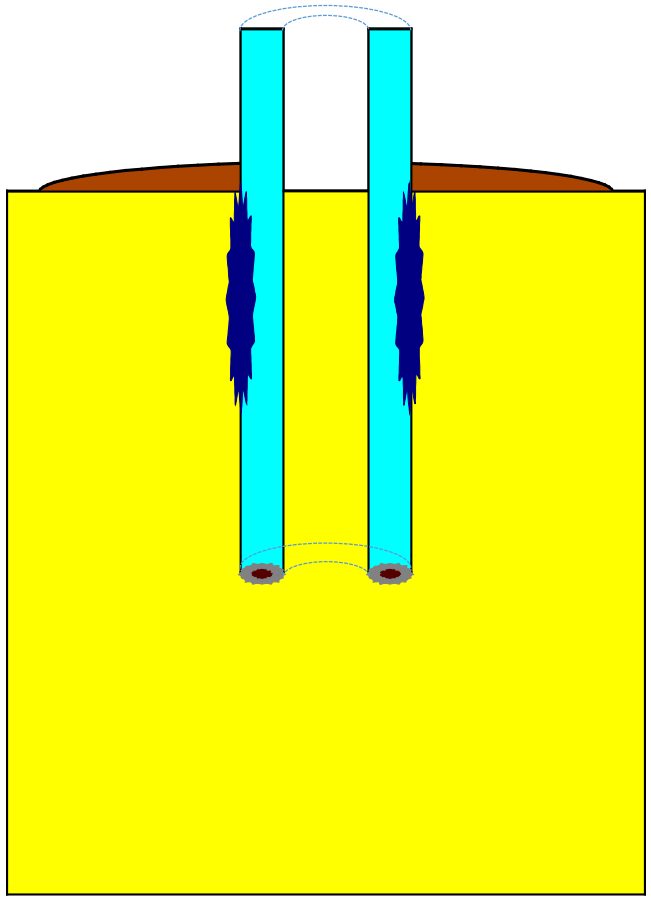
- Prevent catastrophic phase change (i.e. freeze-in)



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Typical Day:
7 Torr
-80 ˚C

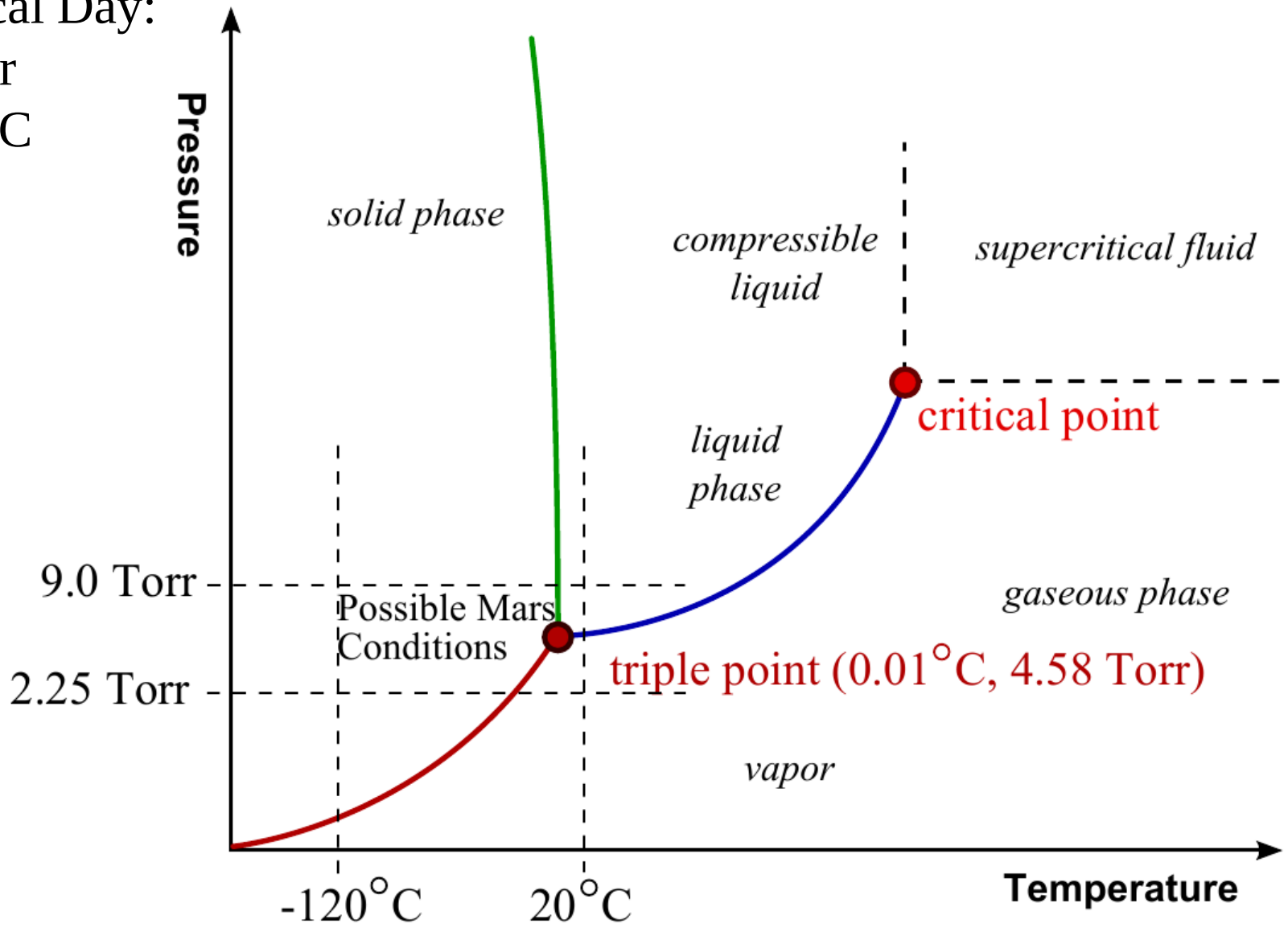

Image Adapted from Matthieumarechal

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Research Goals

1. Perform experiments on Solar System analog materials to characterize thermal profiles
2. Create a simulation code that accurately predicts thermal profiles
3. Characterize trends based on rock properties
4. Inform future spacecraft design and operations

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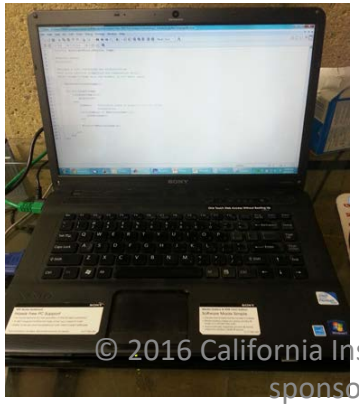

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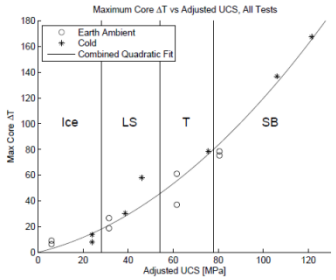

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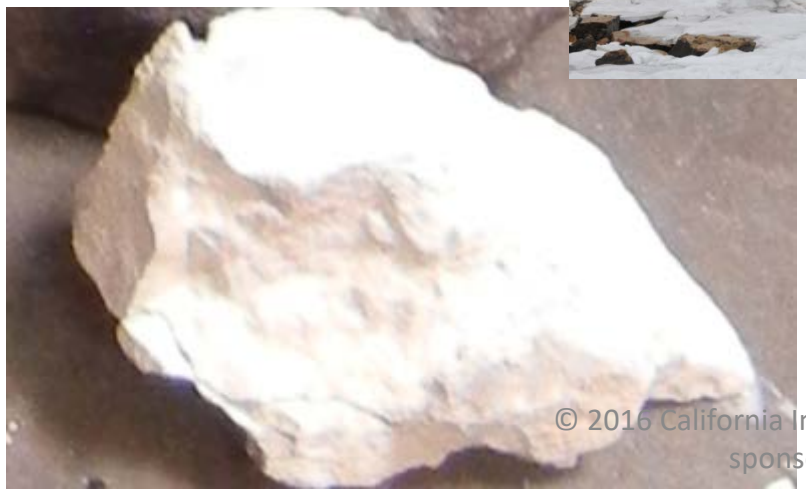
Materials Tested

Indiana Limestone (45 MPa)

Water Ice
(6 MPa)

Saddleback Basalt (115 MPa)

Kaolinite (Highly Variable)



Travertine (88 MPa)

Image: David Monniaux

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Experimental Preparation

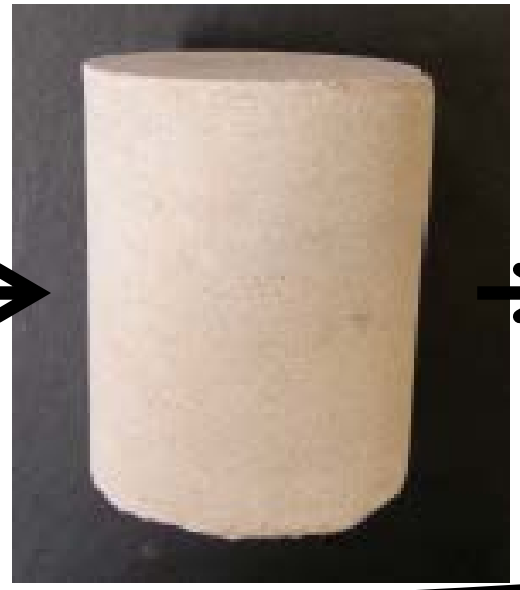
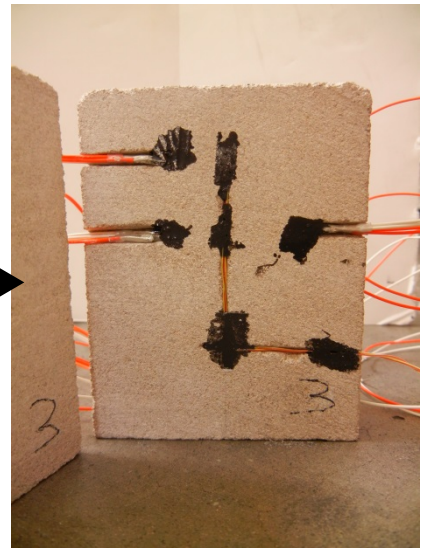


Image: Omega



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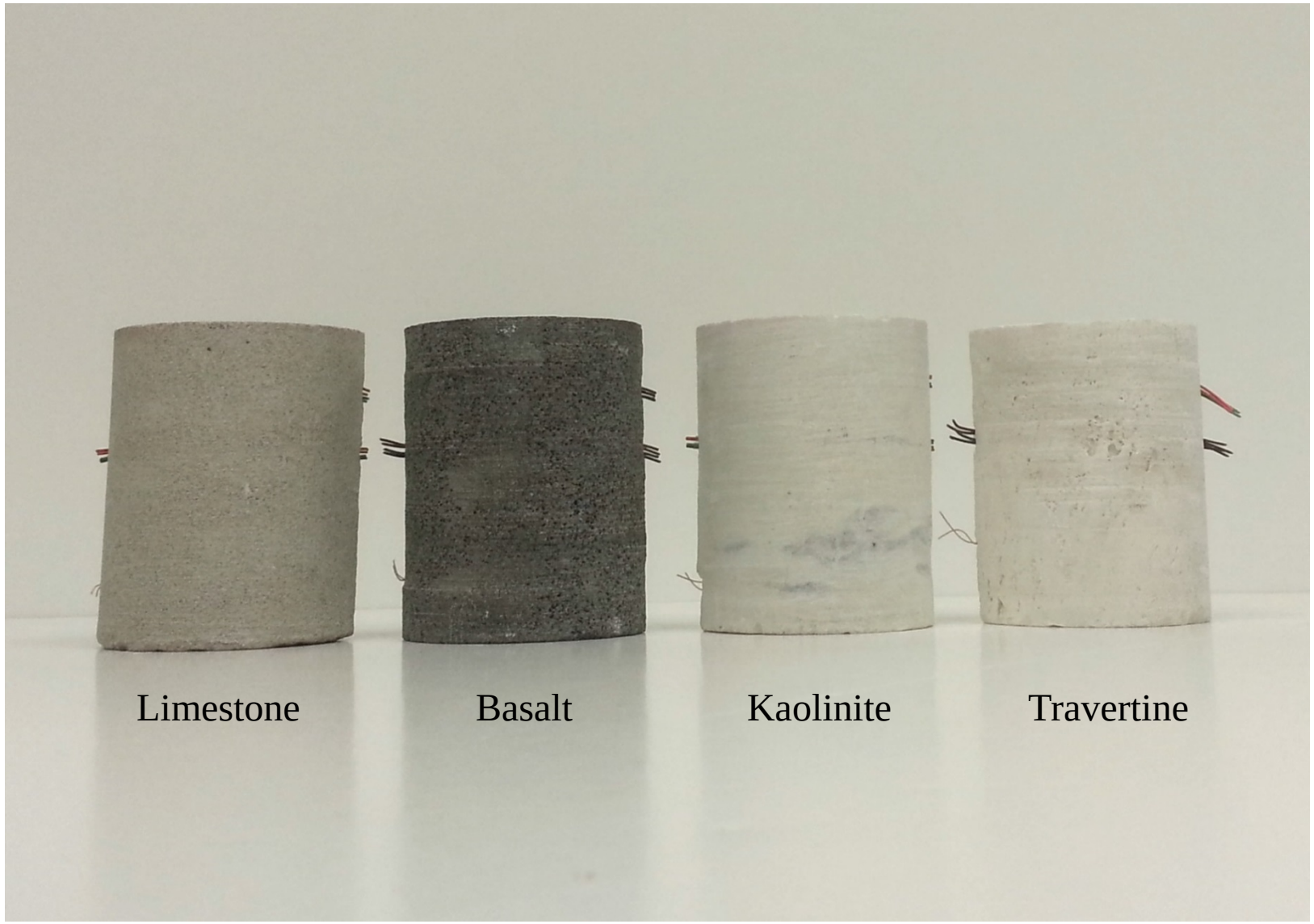

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Analog Material Experiments

3.5 m^2 vacuum chamber at Honeybee Robotics, Pasadena

Subsystems for Automated Subsurface Sampling Instruments (SASSI) Honeybee Robotics, Pasadena

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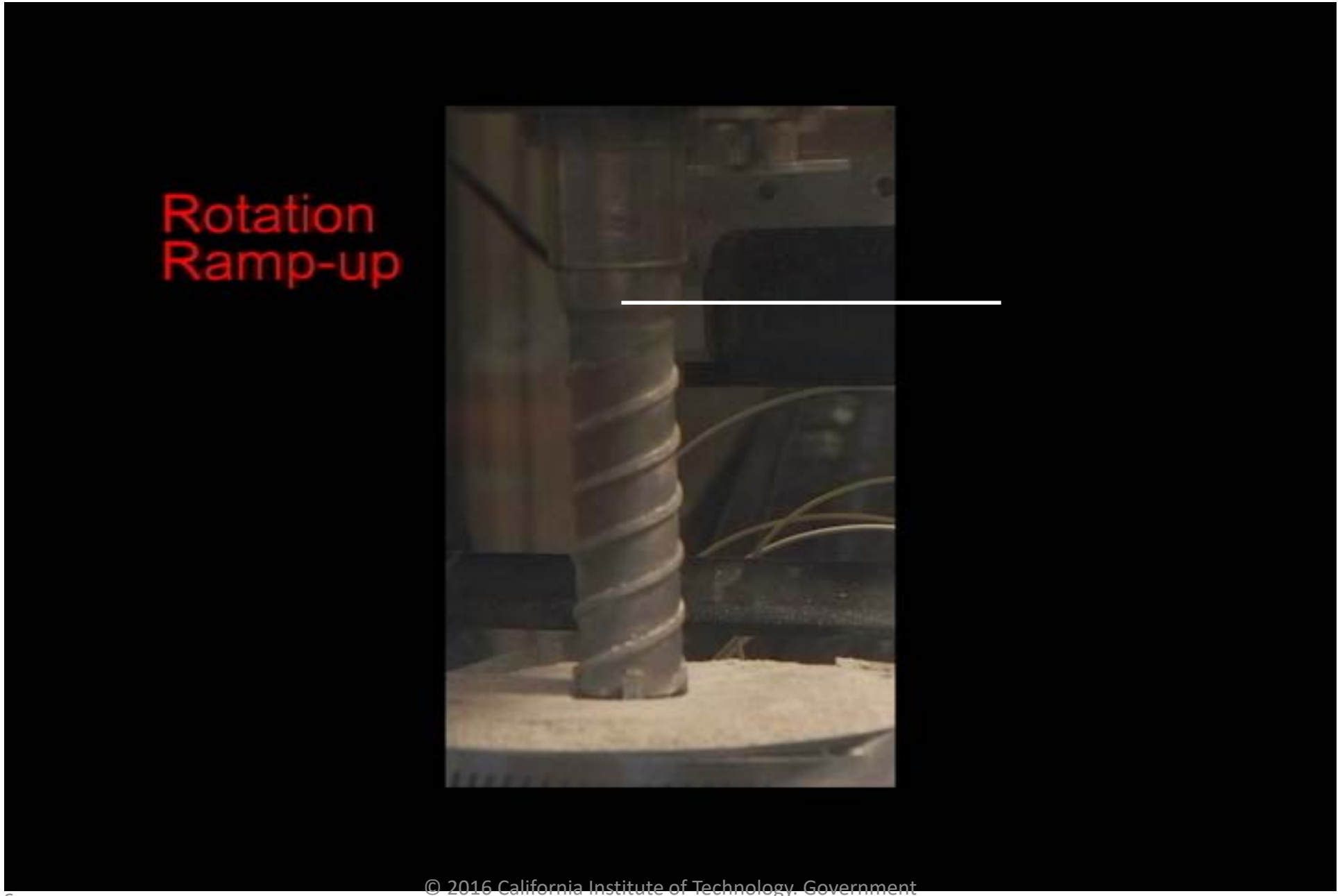

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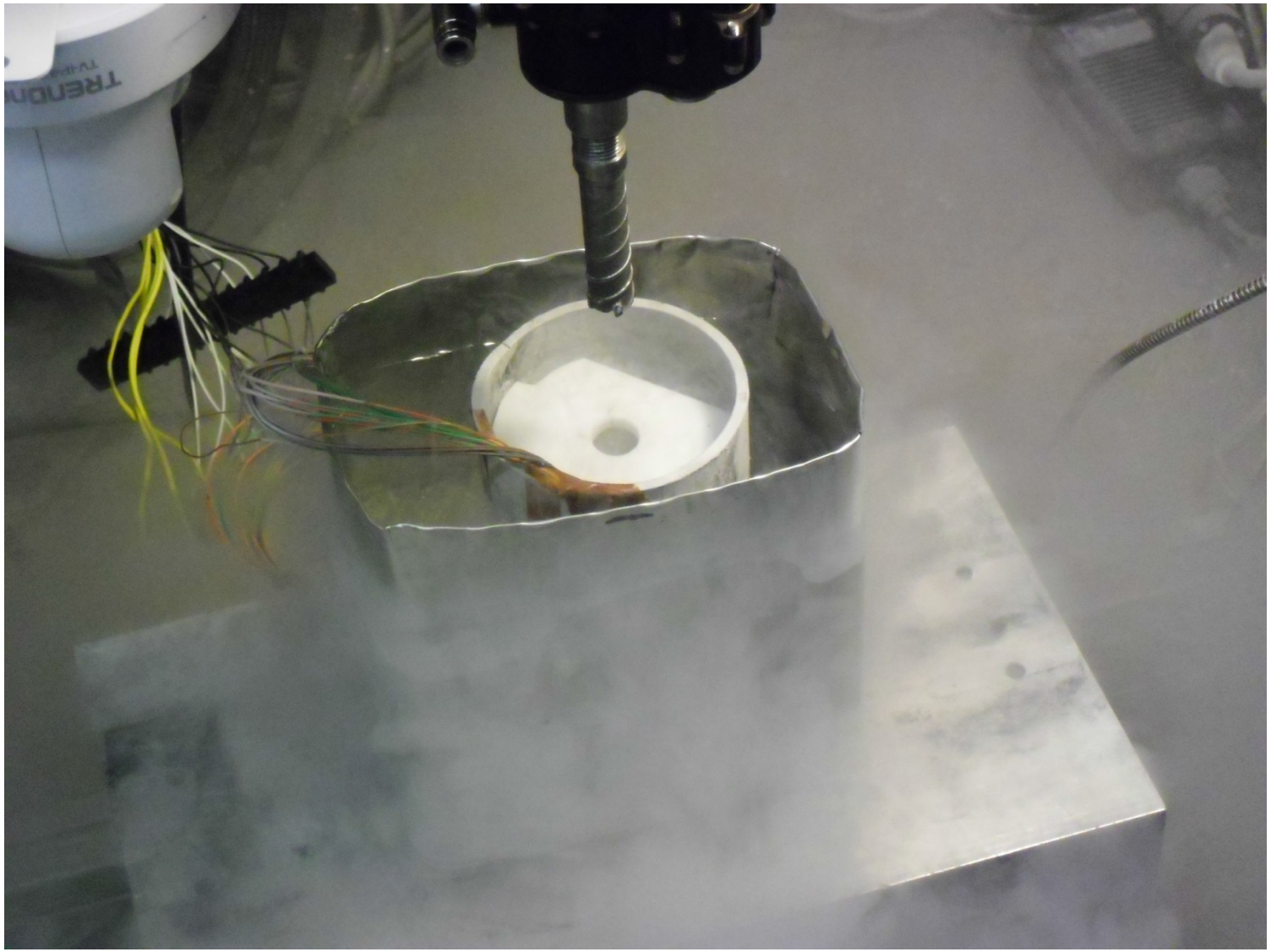

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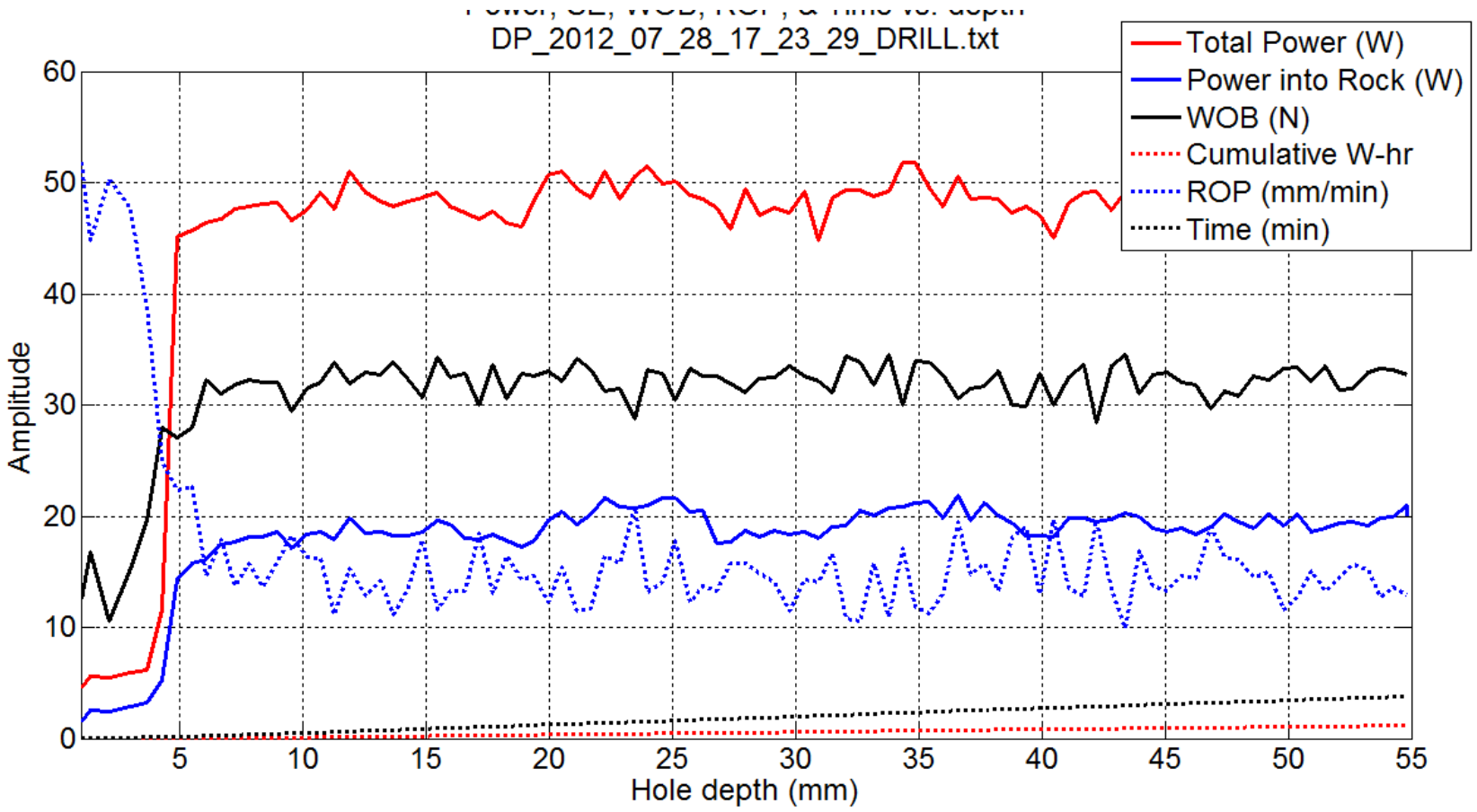
Drill Data Products



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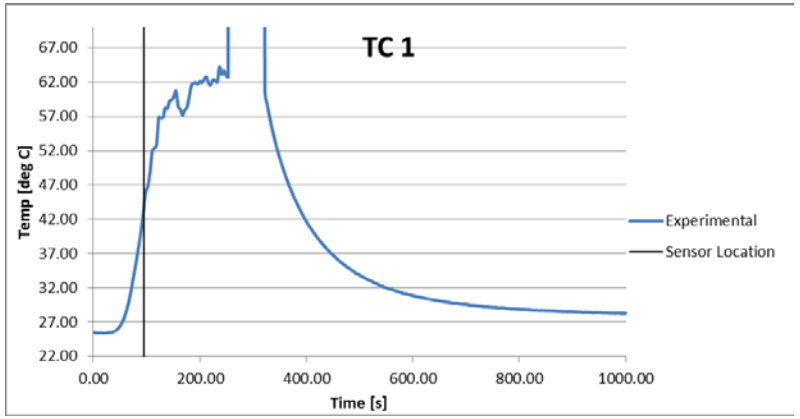

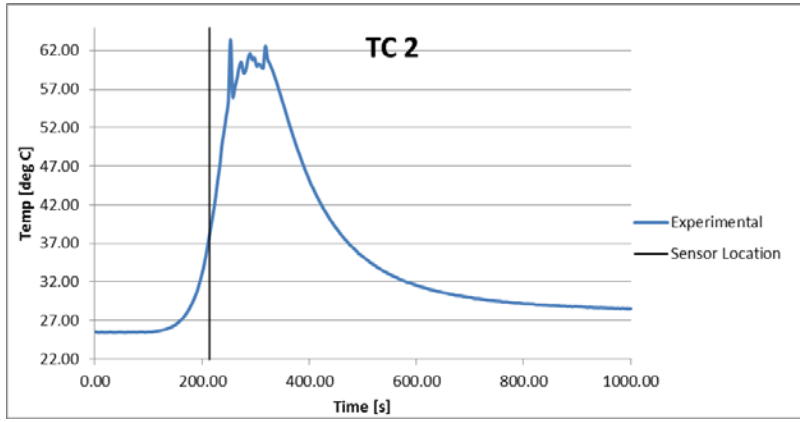

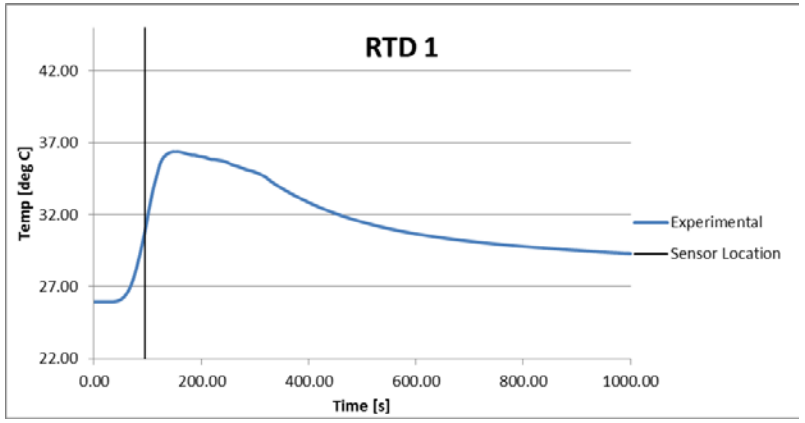

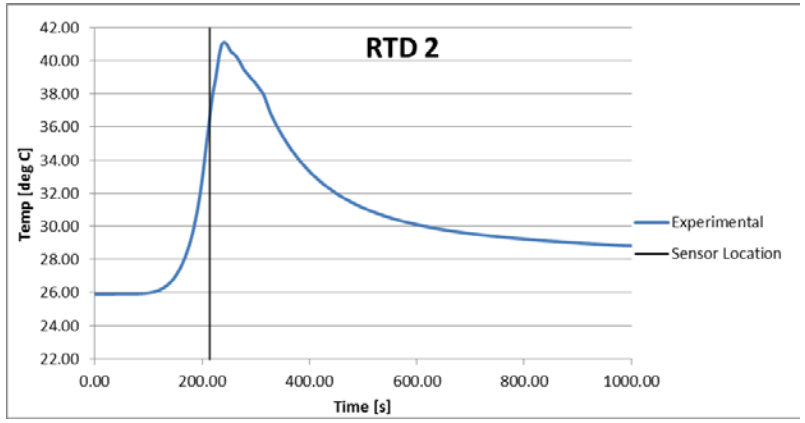

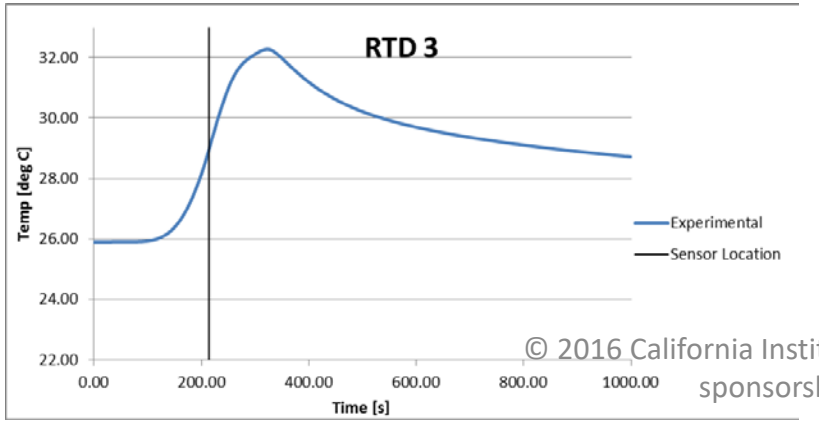

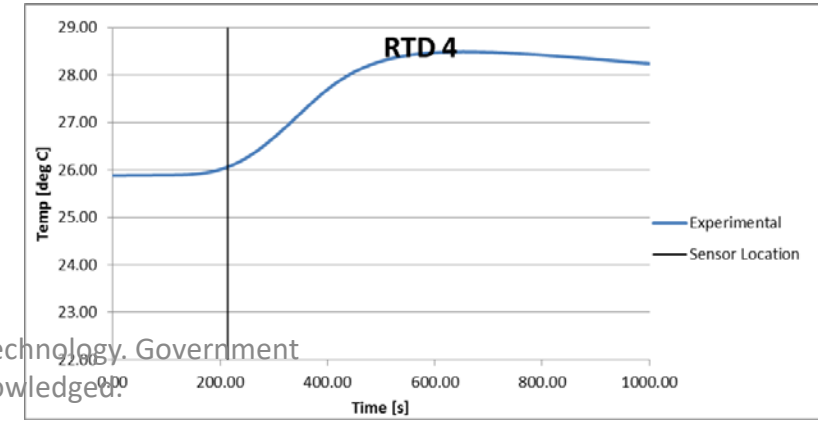

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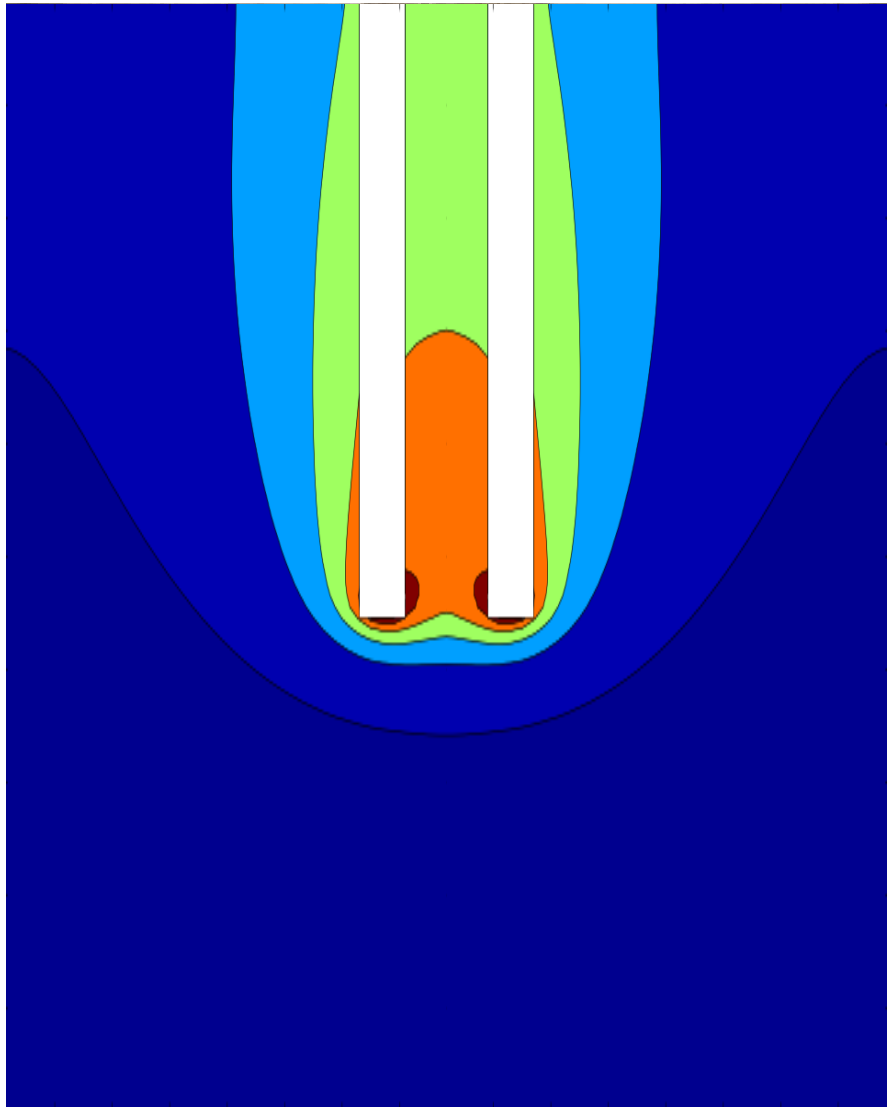

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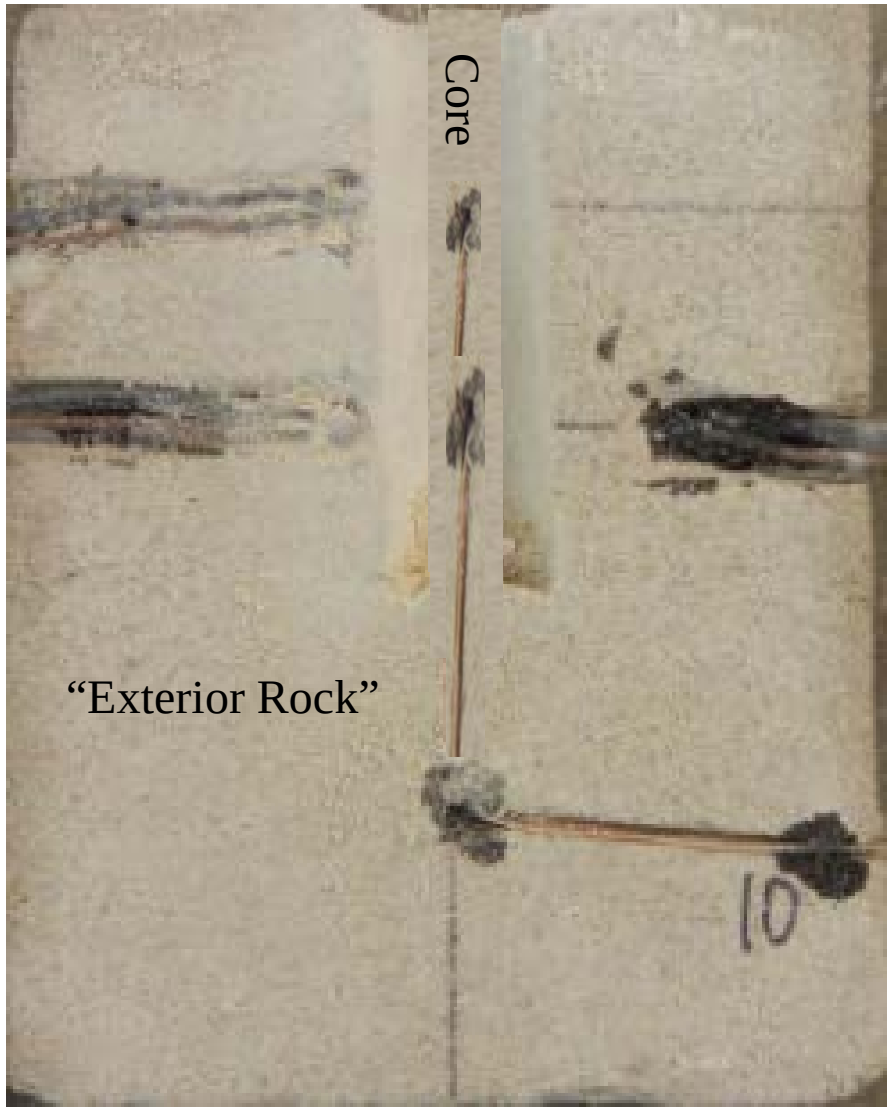

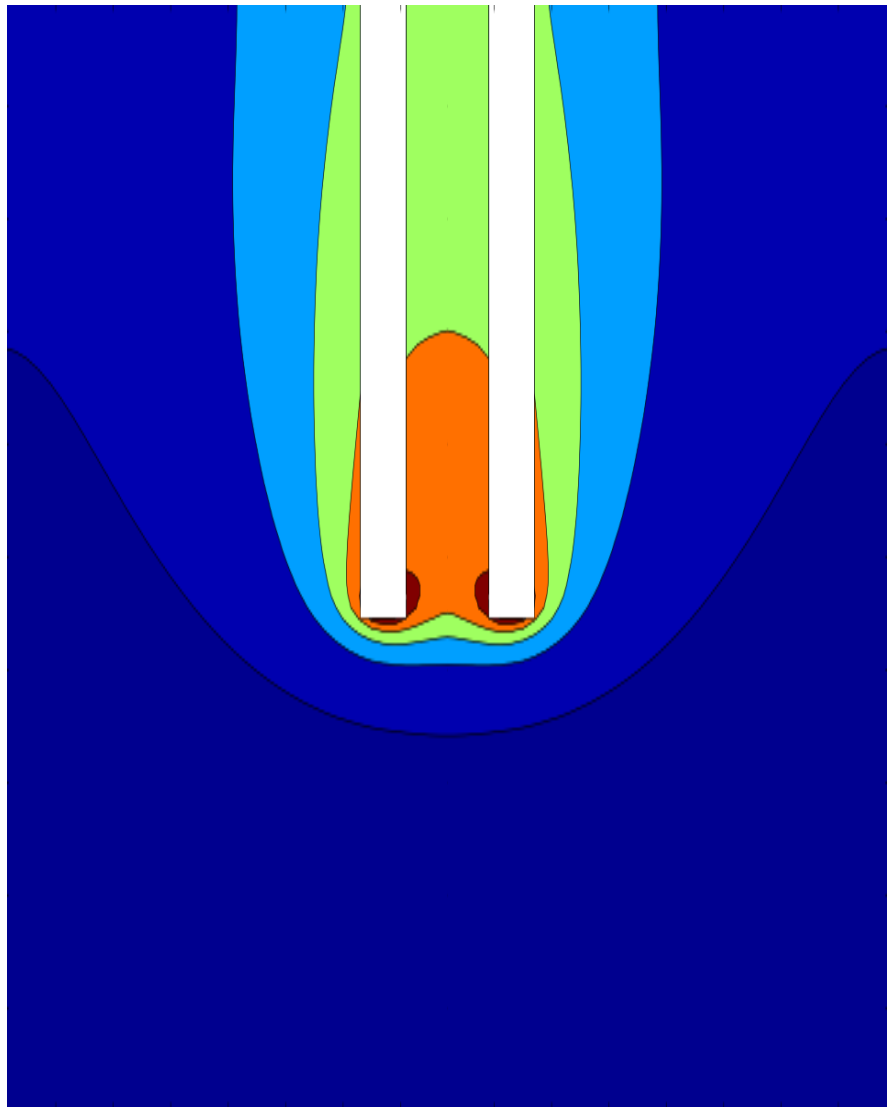

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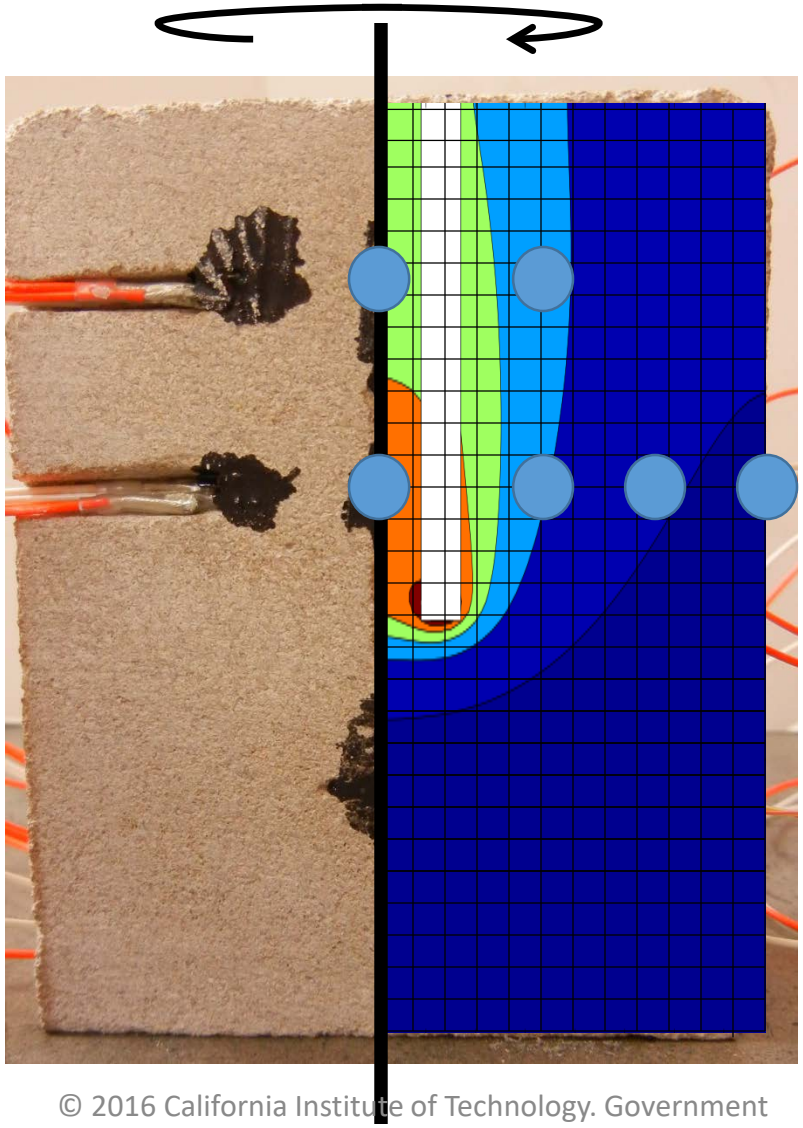
Finite Element Model



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Thermal Model

Heat Equation

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\nabla^2 T$$

Discretized in Z

$$\frac{\Delta T_z(r,z)}{\Delta t} = \frac{k}{\rho c_p}\frac{T(r,z-\Delta z) - 2T(r,z) + T(r,z+\Delta z)}{(\Delta z)^2}$$

Discretized in R

$$\frac{\Delta T_r(r,z)}{\Delta t} = \frac{k}{\rho c_p}\frac{\left(r-\frac{\Delta r}{2}\right)\left[T\left(r-\Delta r,z\right) - T\left(r,z\right)\right] + \left(r+\frac{\Delta r}{2}\right)\left[T\left(r+\Delta r,z\right) - T\left(r,z\right)\right]}{r(\Delta r)^2}$$

Discretization:

dr = 1 mm	Second-order in space
dz = 1 mm	
dt = 0.01 s	First-order explicit in time

CFL = 0.1 (stable)

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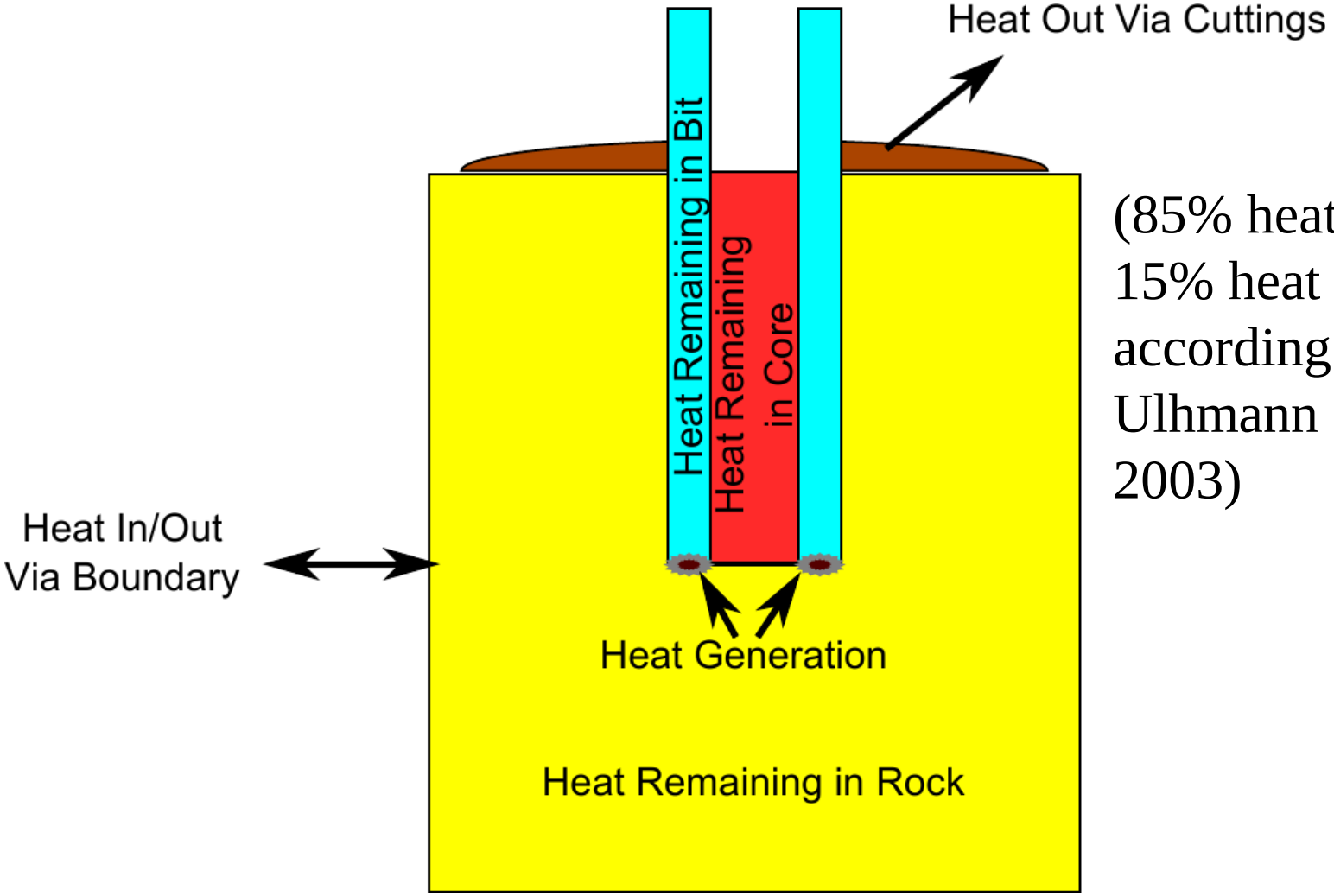
Energy Balance



(85% heat to rock
15% heat to bit
according to
Ulhmann et. al.,
2003)

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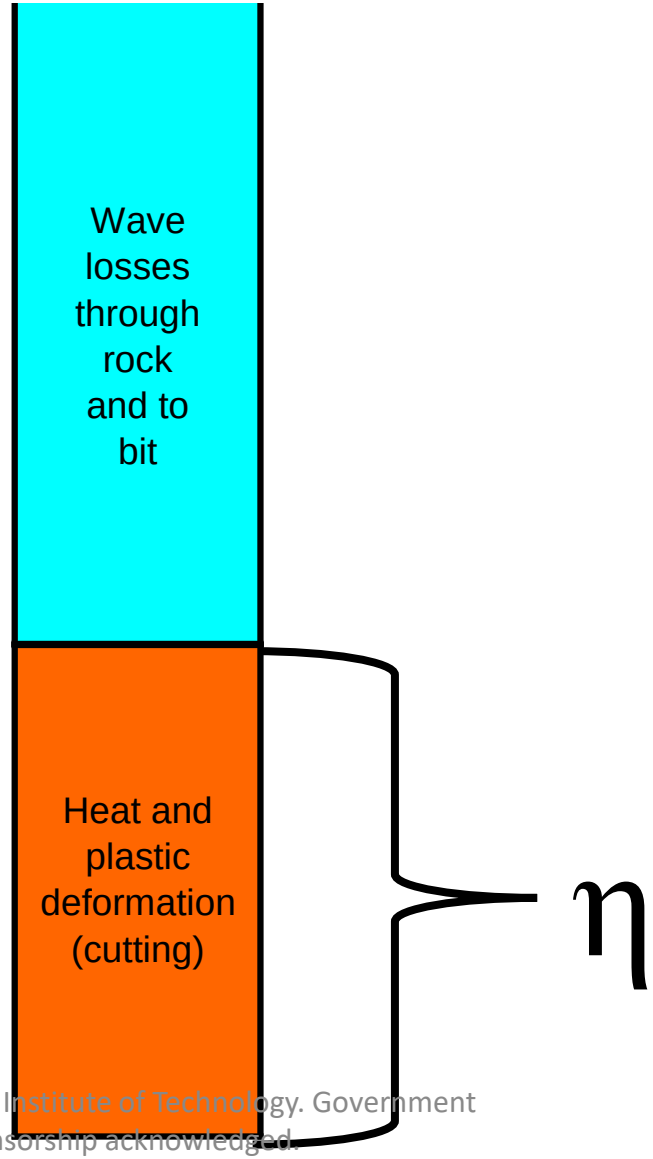
Energy of Impact



Based on Hack, 2002 and Simon, 1963

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Results

Test No.	Material	Pressure [Torr]	Temperature	η
6	Indiana Limestone	760	Earth	0.4
8	Indiana Limestone	7	Earth	0.3
9	Indiana Limestone	760	LN_2 Dipped	0.4
10	Indiana Limestone	6	LN_2 Dipped	0.4
14	Saddleback Basalt	760	Earth	0.65
15	Saddleback Basalt	7	Earth	0.4
16	Saddleback Basalt	760	LN_2 Dipped	0.75
17	Saddleback Basalt	7	LN_2 Dipped	0.6
11	Kaolinite	760	Earth	0.3
12	Kaolinite	7	Earth	0.35
13	Kaolinite	760	LN_2 Dipped	0.5
22	Travertine	760	Earth	0.5
23	Travertine	7	Earth	0.4
24	Travertine	760	LN_2 Dipped	0.8
19	Water Ice	760	Earth	0.35
20	Water Ice	7	Earth	0.35
25	Water Ice	760	LN_2 Dipped	0.7
27	Water Ice	7	LN_2 Dipped	0.9

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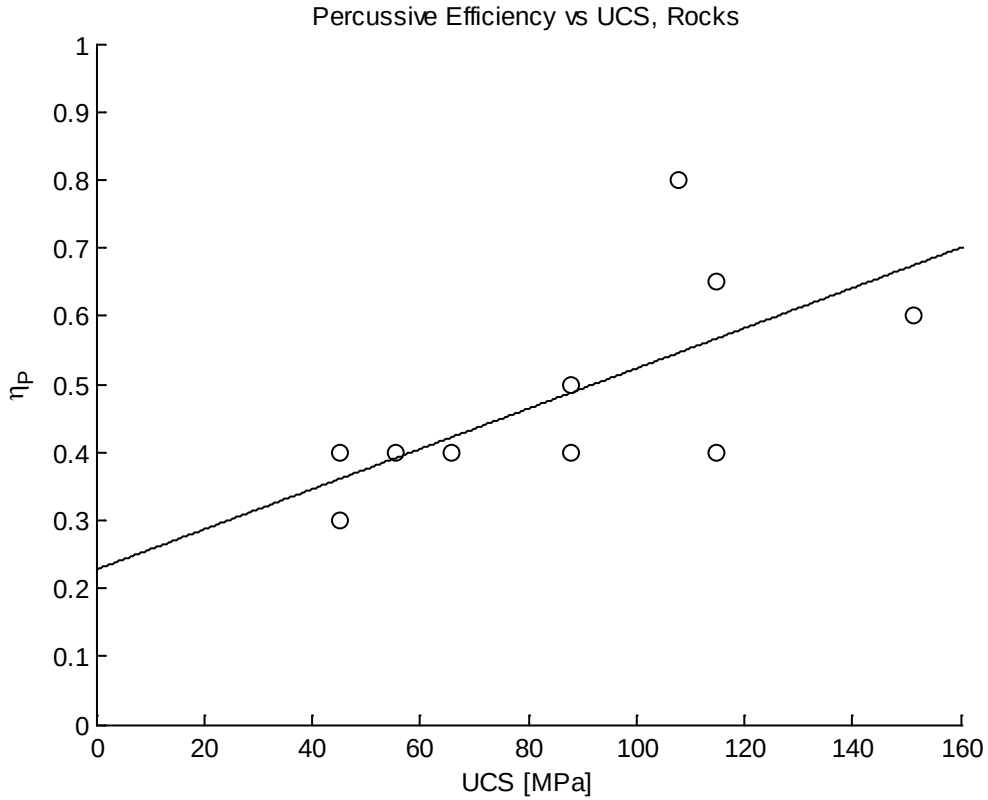

Ranges agree with Hustrulid and Fairhurst, 1972 for drop tests

UCS = Unconfined Compressive Strength. A measure of how hard it is to crush rock

Higher UCS → more energy localized to impact area → higher efficiency

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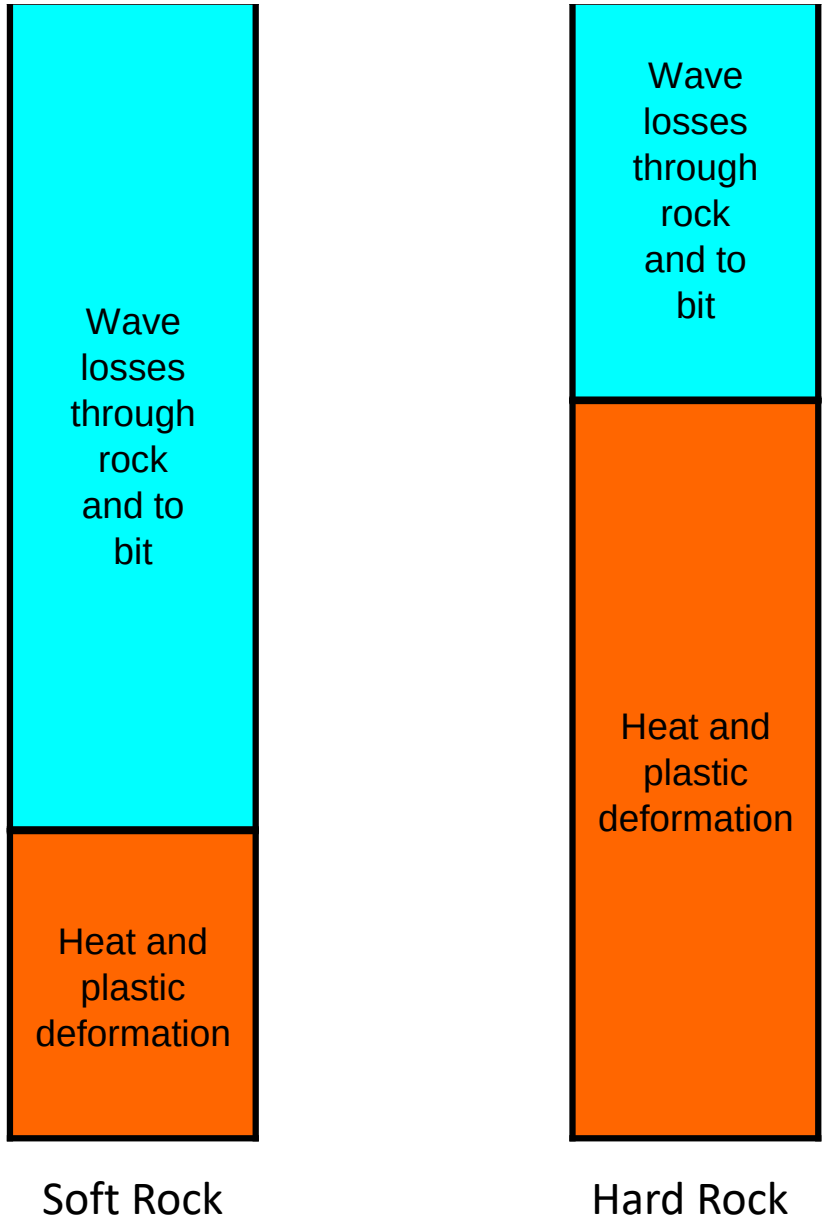

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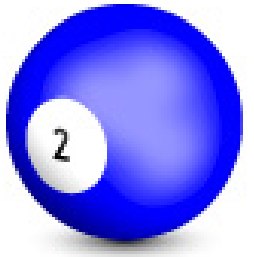
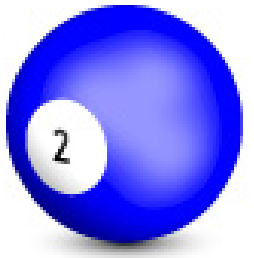
Hard rock →higher η, an analogy



Hard material undergoes localized damage at impact site



Soft, compliant, material disperses energy via waves

Not a perfect analogy because even with lower η, softer rocks still drilled faster

Image credit: www.jacorre.com
www.time.com
www.kold-draft.com

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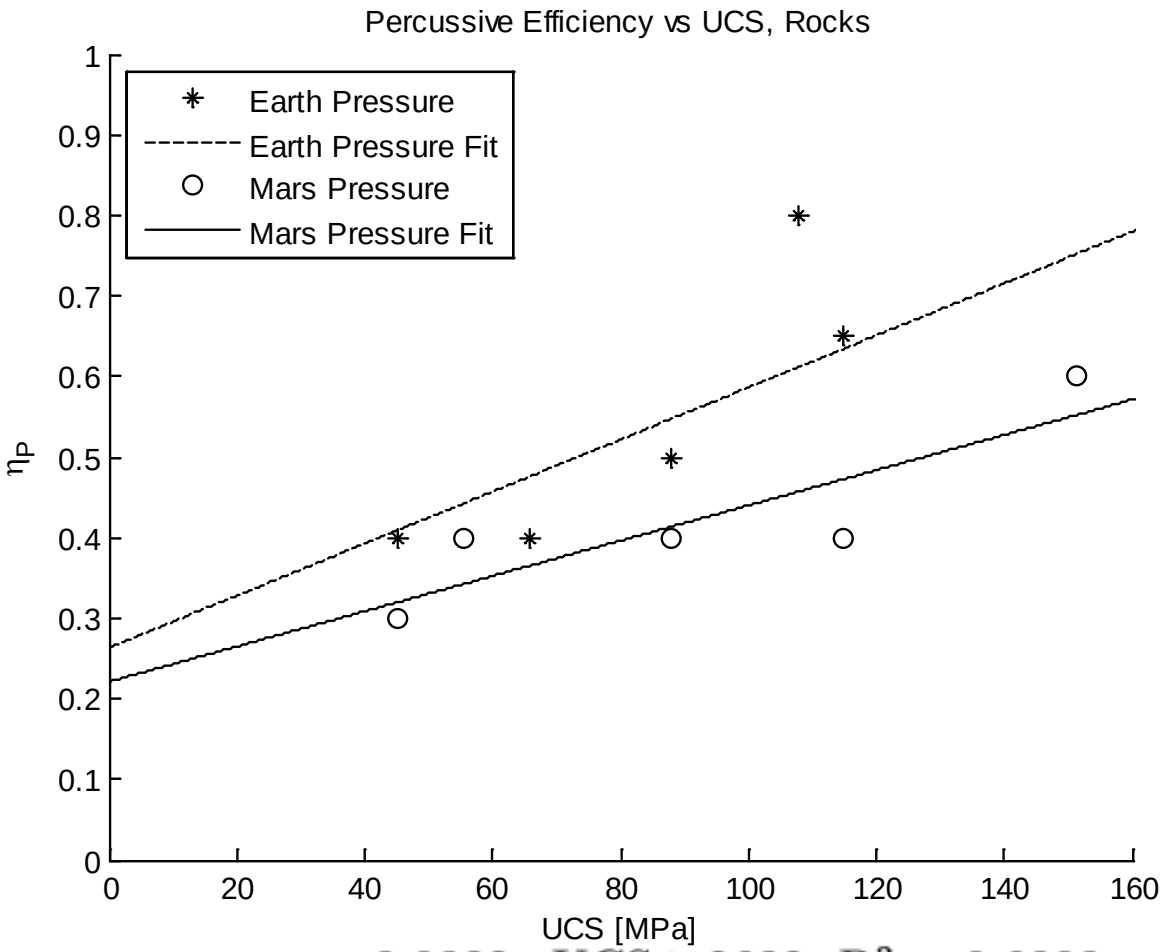
How does atmospheric pressure affect efficiency?



Earth Pressure: $\eta = 0.0032 \times \mathrm{UCS} + .2632,\ \mathrm{R}^2 = 0.6808.$

Mars Pressure: $\eta = 0.0022 \times \mathrm{UCS} + .2209,\ \mathrm{R}^2 = 0.7616$

- η is dependent on pressure: Zacny and Cooper, 2007 shows friction drops 10-15% at Mars pressure

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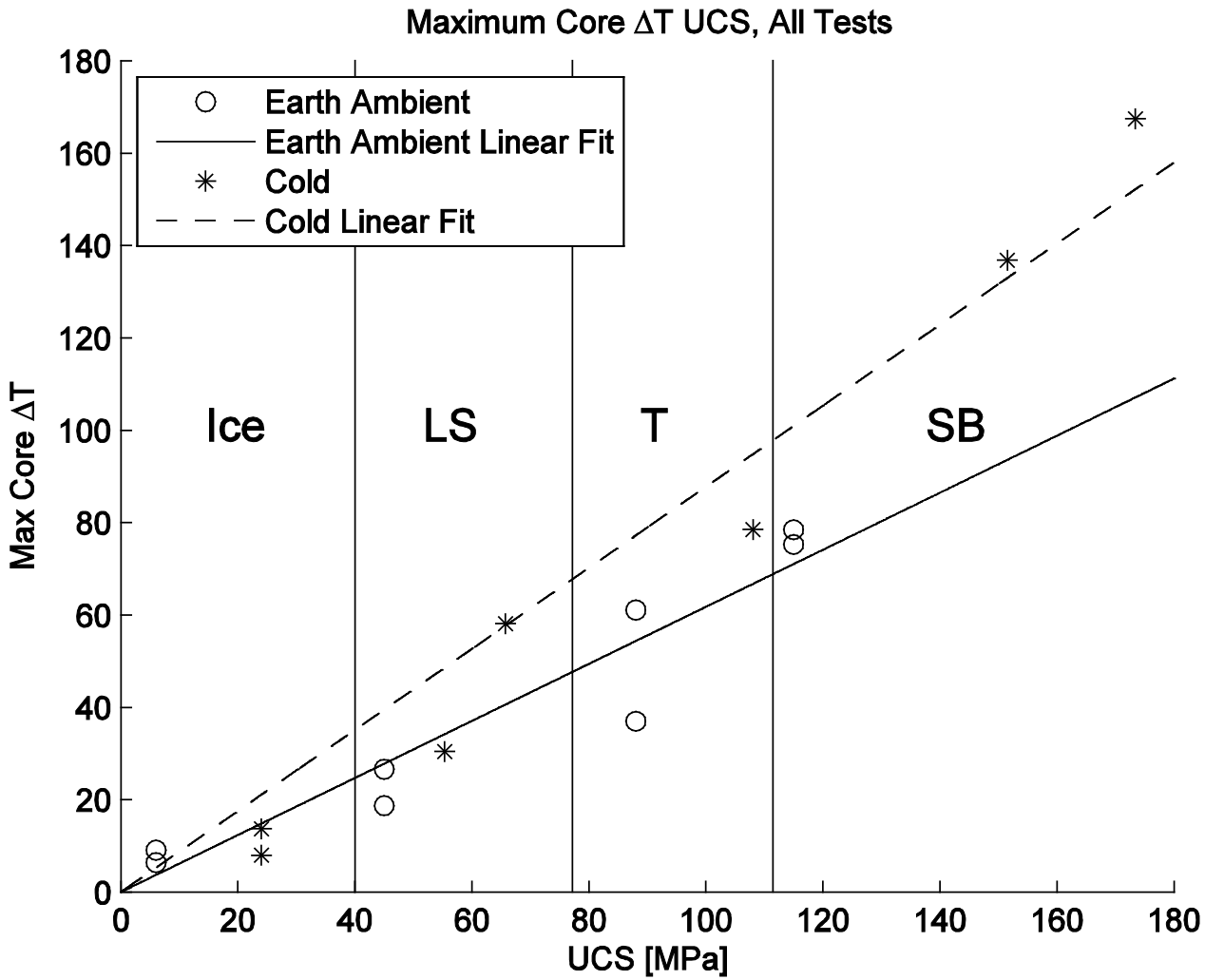
How does rock temperature affect core temp increase?



Room Temp: $\Delta T_{max} = 0.6177 \times \mathrm{UCS},\ R^2 = 0.9084$

Cooled: $\Delta T_{max} = 0.8776 \times \mathrm{UCS},\ R^2 = 0.9531$

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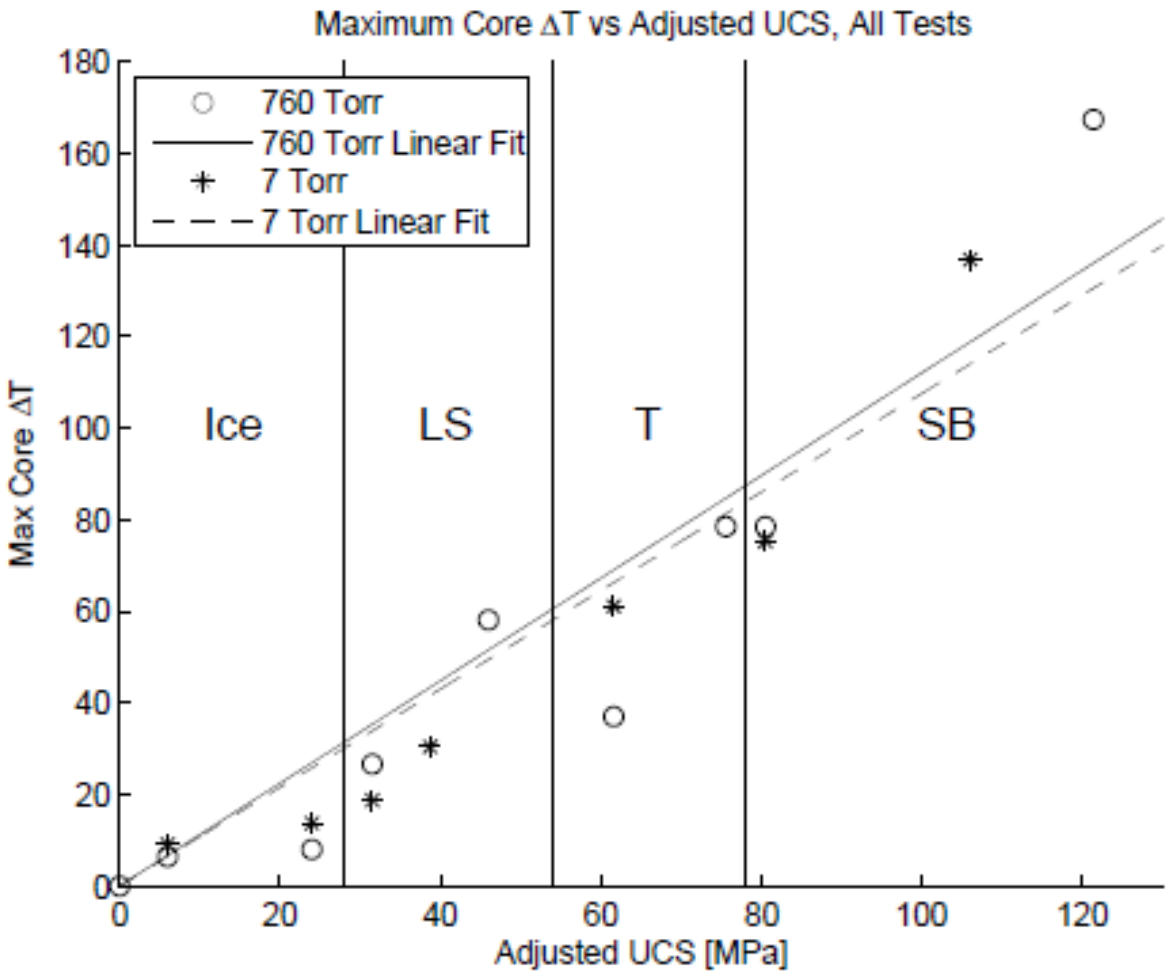
How does pressure affect core temp?



760 Torr: $\Delta T_{max} = 0.7902 \times \mathrm{UCS},\ R^2 = 0.8750$

7 Torr: $\Delta T_{max} = 0.7591 \times \mathrm{UCS},\ R^2 = 0.9159$

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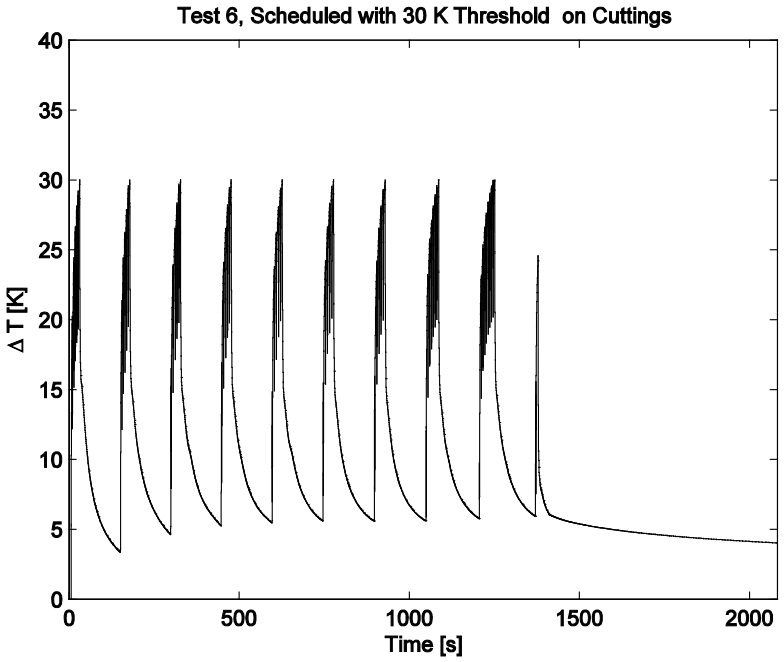
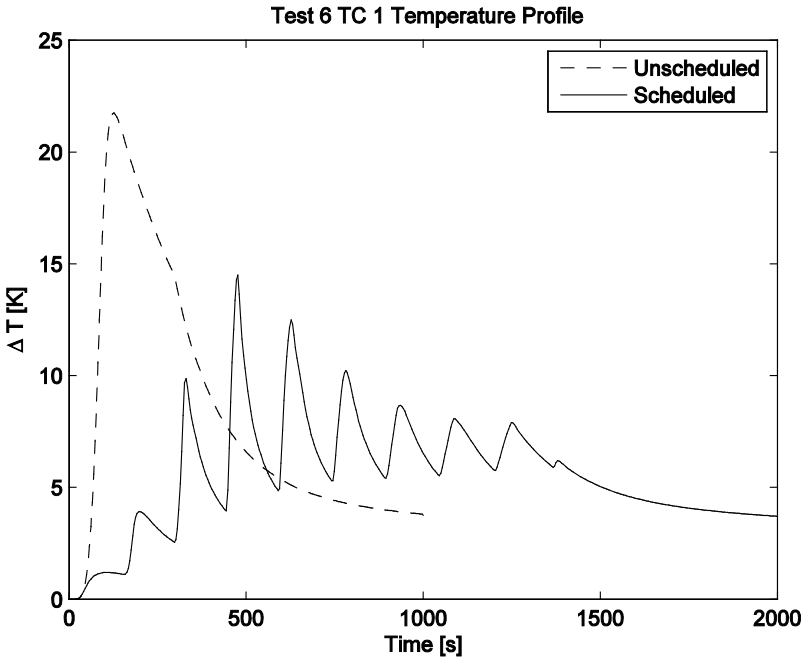
Acquisition Scheduling

- Limestone sample
  - 55 mm depth
  - ΔT in rock no more than 30 ˚C, 2 min pause if hit





Sampling time increases 5x for this case

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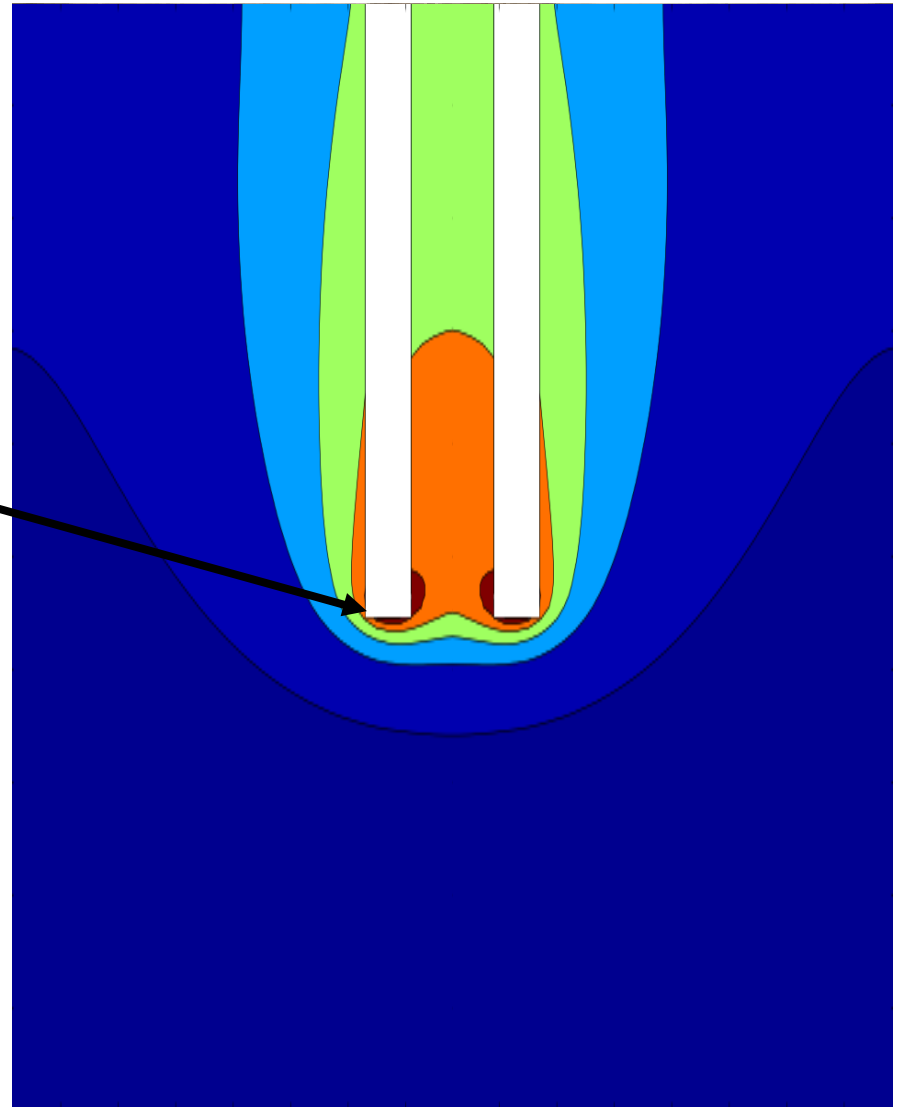
Suggestions for Future Work

- Fine-scale analysis at bit/rock boundary
  - Currently mm-scale model and measuring ability
  - Grain scale or smaller is desired
- Study icy-soil mixtures: relevant to Mars subsurface



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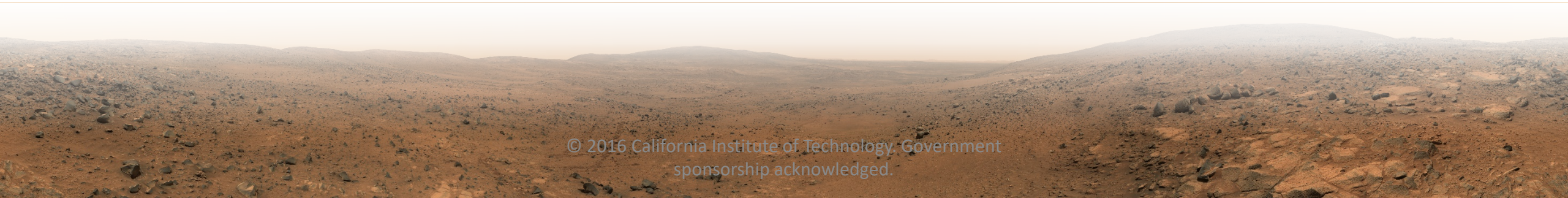
Work at JPL: Mars 2020 Sampling & Caching Subsystem



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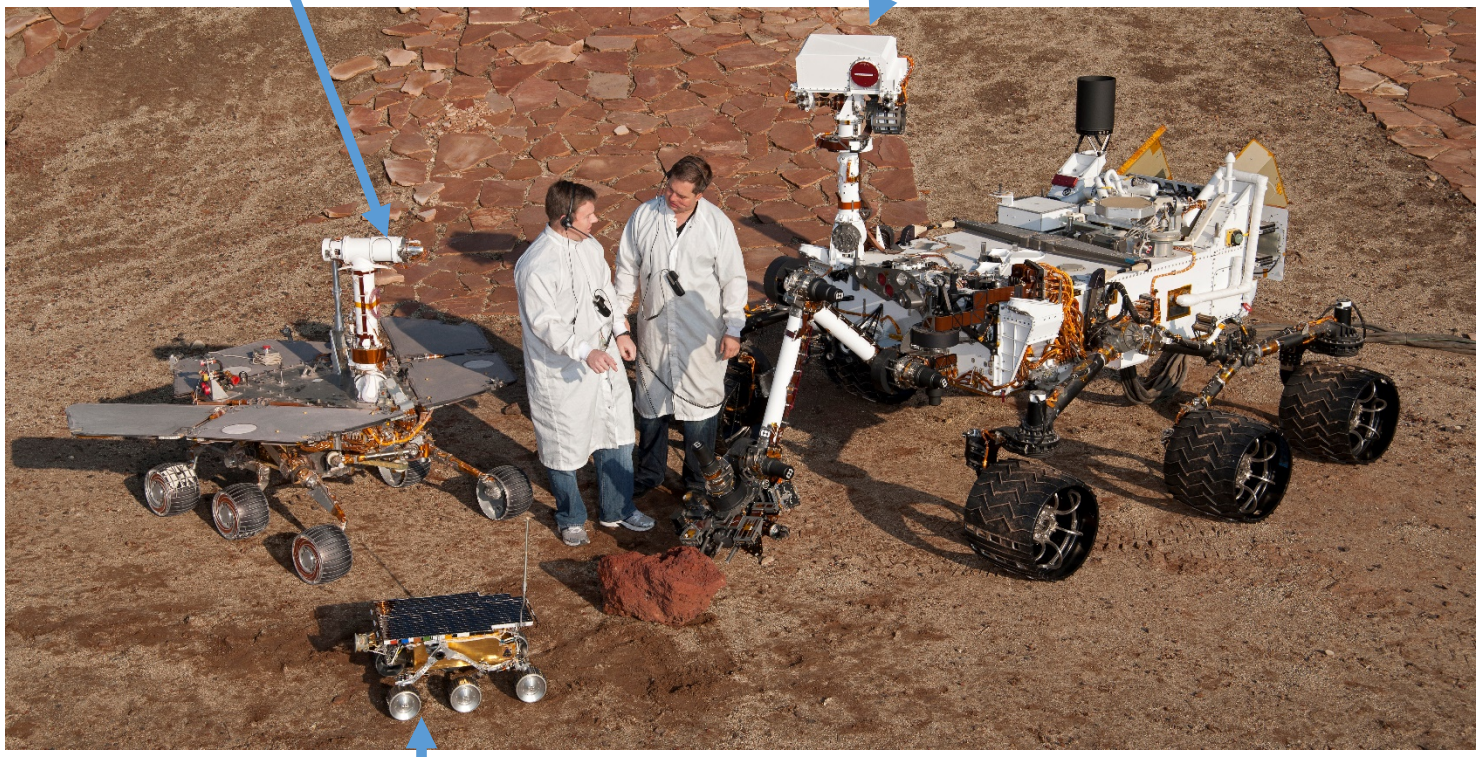
Spirit & **Opportunity**, 2003

Mars Science Laboratory a.k.a. Curiosity, 2011



Sojourner, 1996

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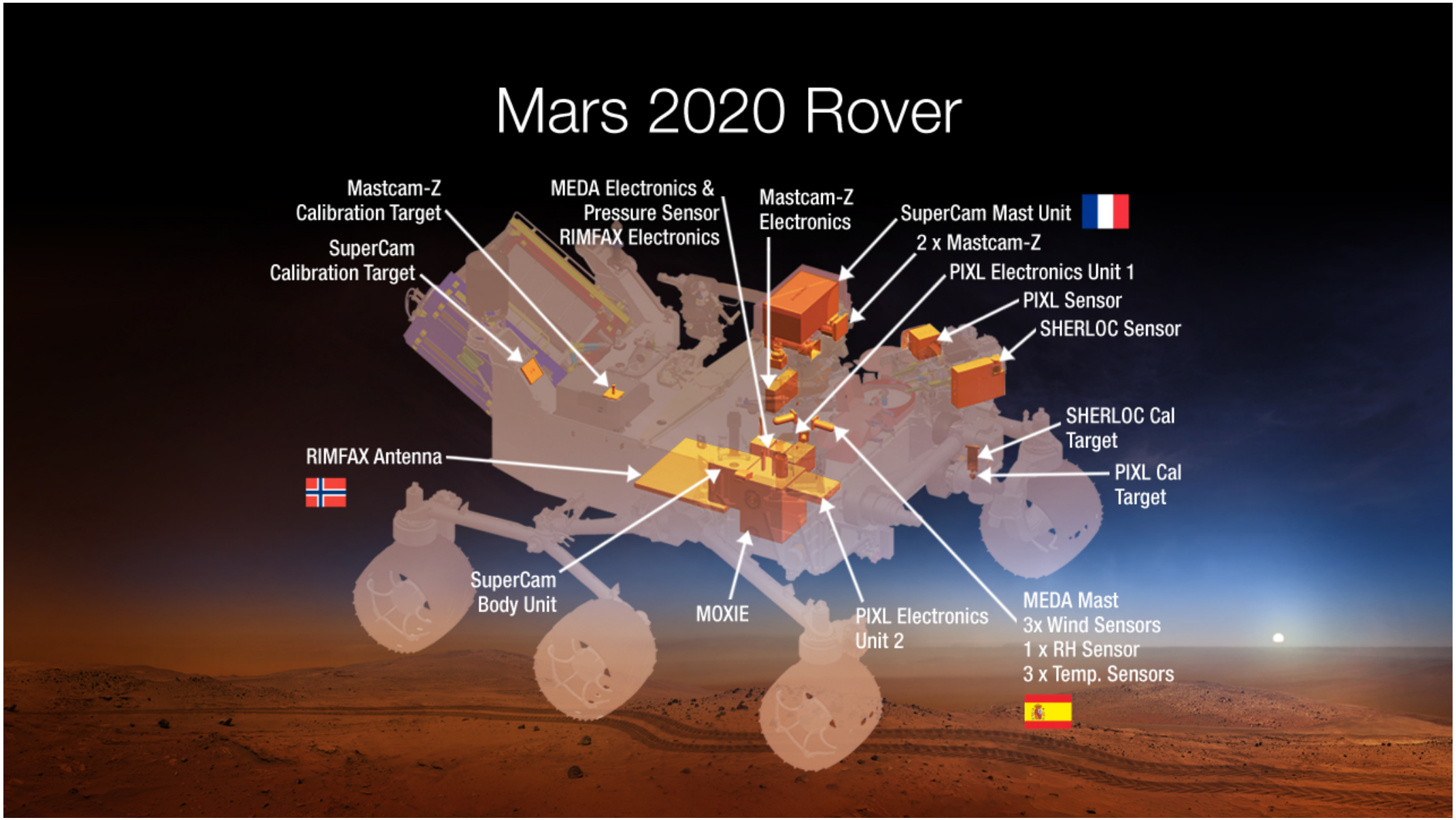

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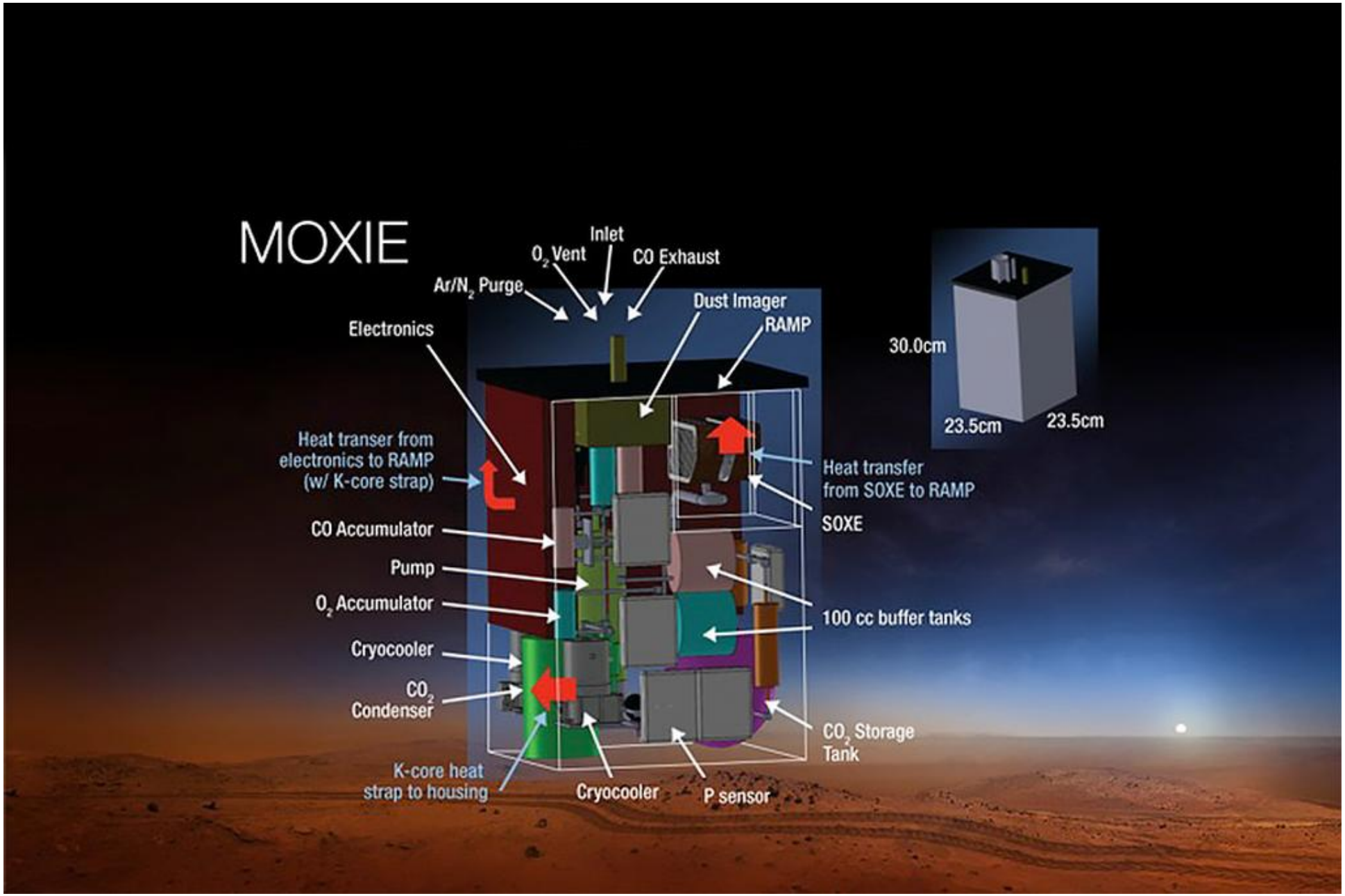

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Science Objectives	How Objectives Addressed
A. Geology • Characterize the processes that formed and modified the local geologic record	Cameras, ground-penetrating radar, x-ray fluorescence, Raman spectroscopy, weather sensing
B. Astrobiology • Perform investigations of habitability, biosignatures, and potential evidence of past life	Cameras, ground-penetrating radar, x-ray fluorescence, Raman spectroscopy, weather sensing
C. Sample Caching • Assemble a returnable cache of samples for possible future return to Earth • Ensure compliance with future needs in the areas of planetary protection and engineering	**Coring drill, caching subsystem**
D. Human Exploration • Contribute to the preparation for human exploration of Mars	Oxygen production, mineralogy

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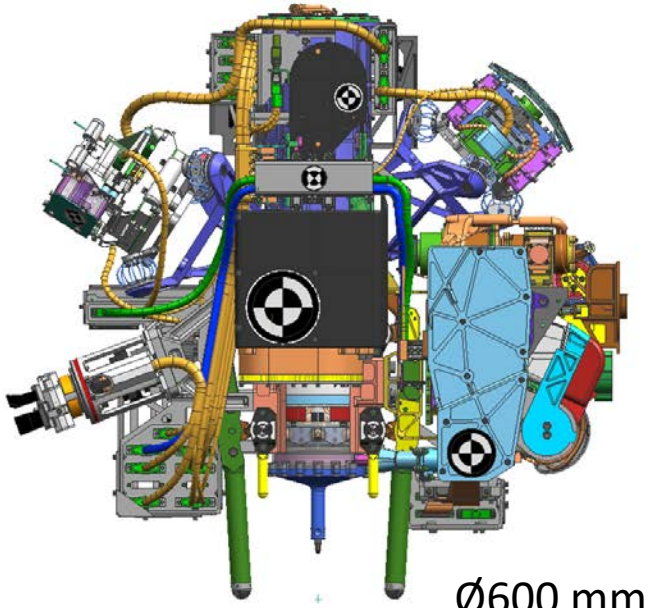
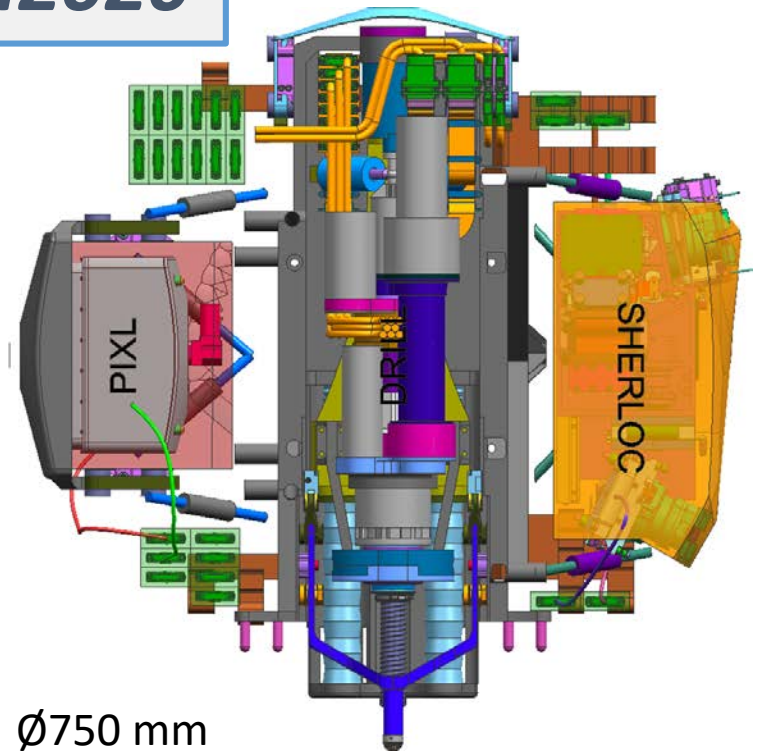
MSL



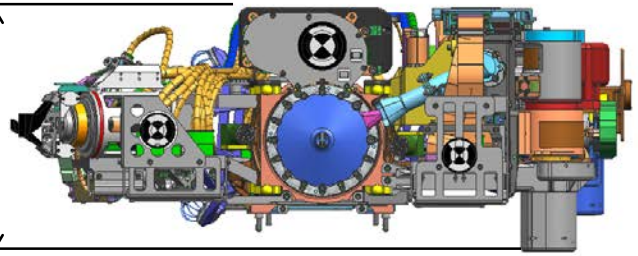
Ø600 mm

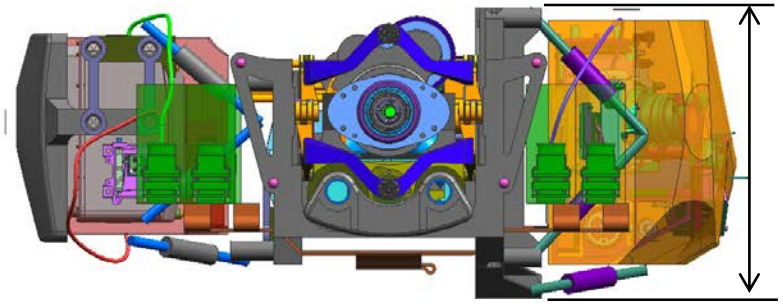
M2020



Ø750 mm

240 mm





280 mm

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We made the news! 3:30

https://youtu.be/OjQz3STH19w?t=198

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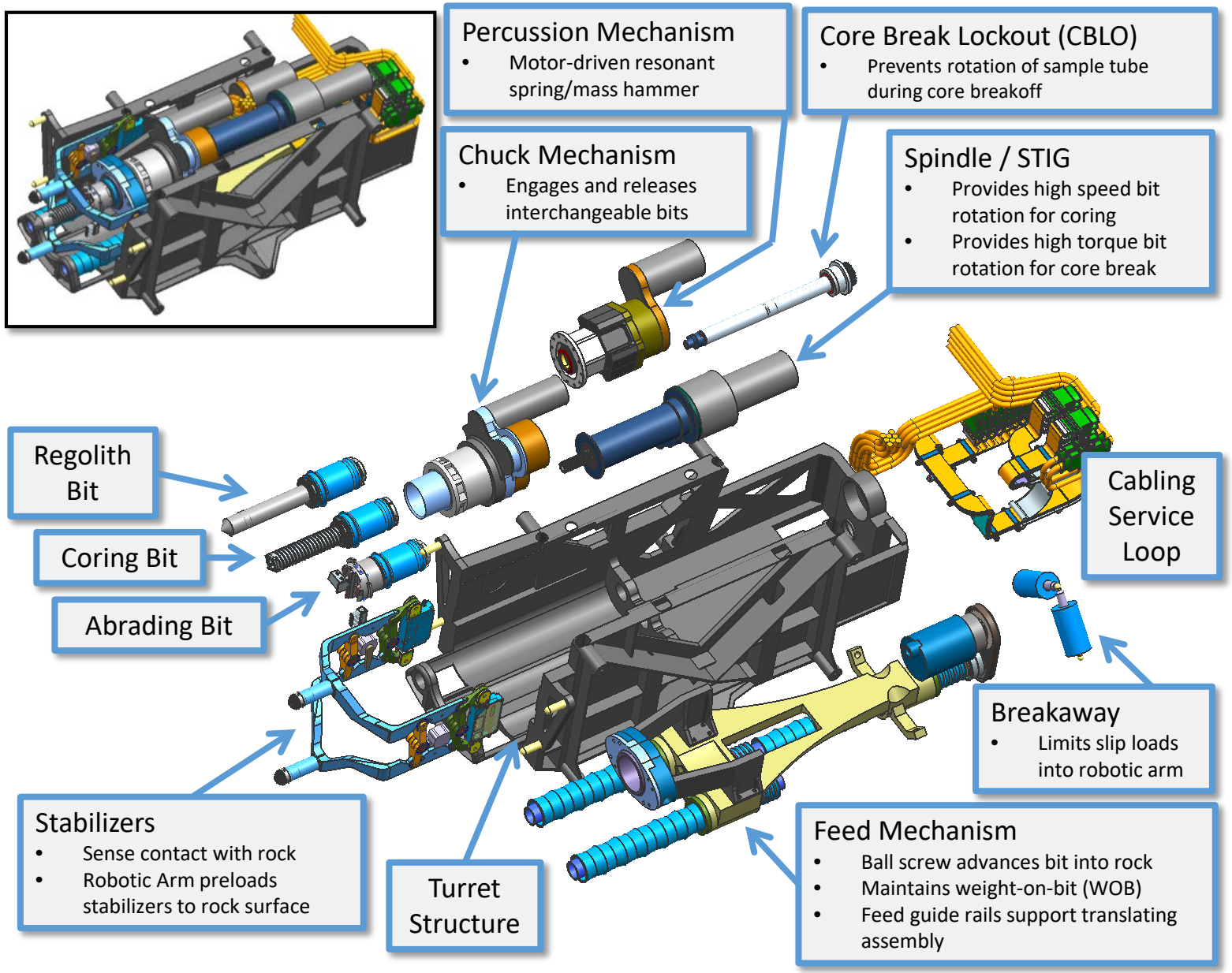

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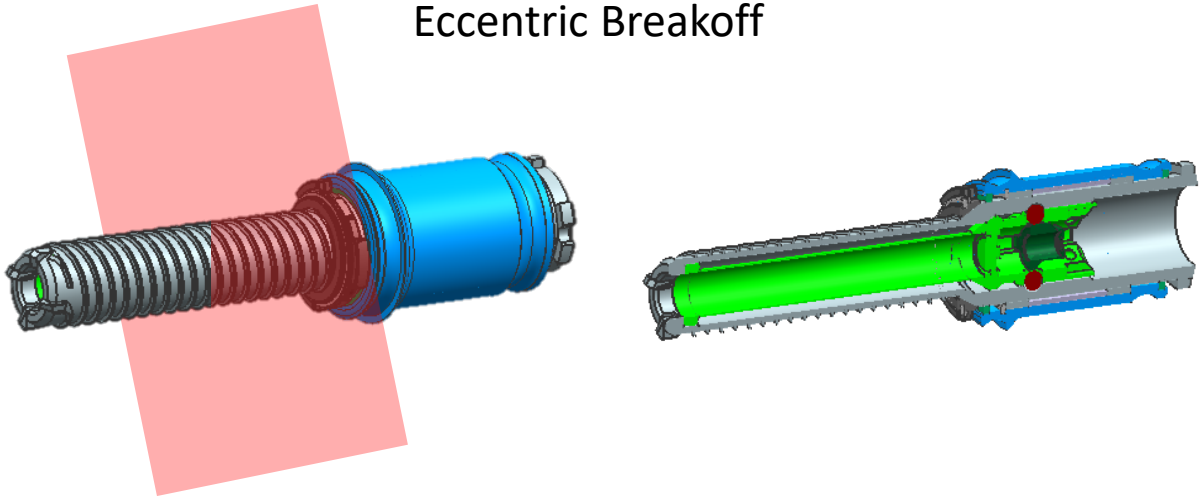
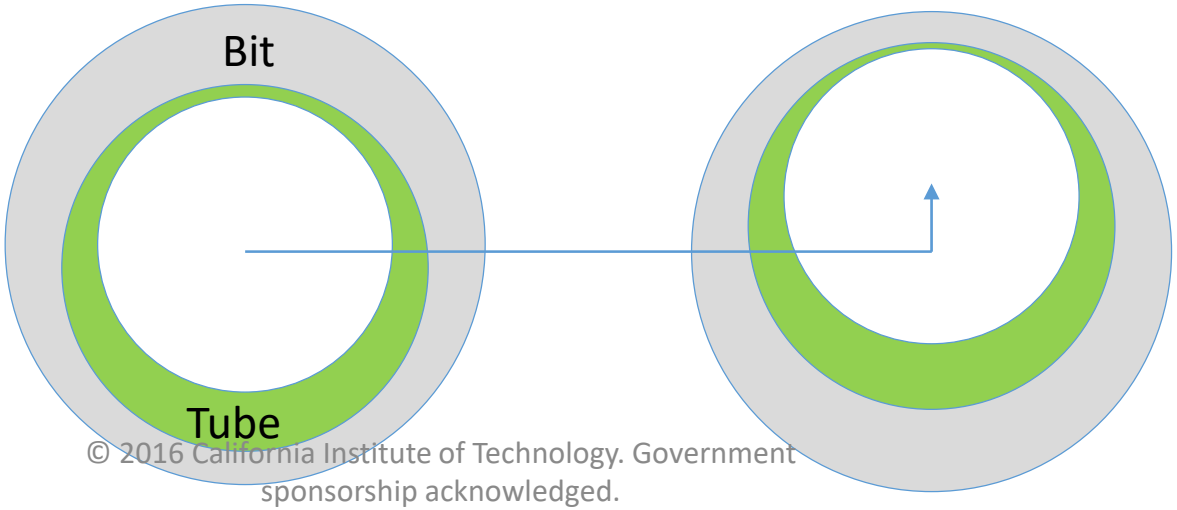
Corer Mechanisms: Bits

Eccentric Breakoff





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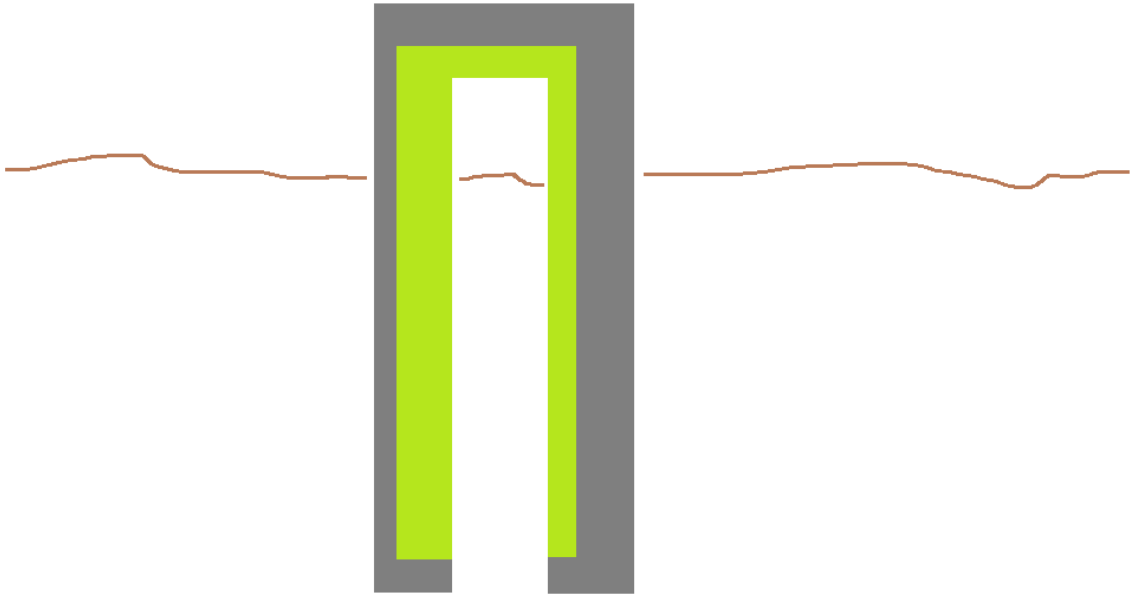

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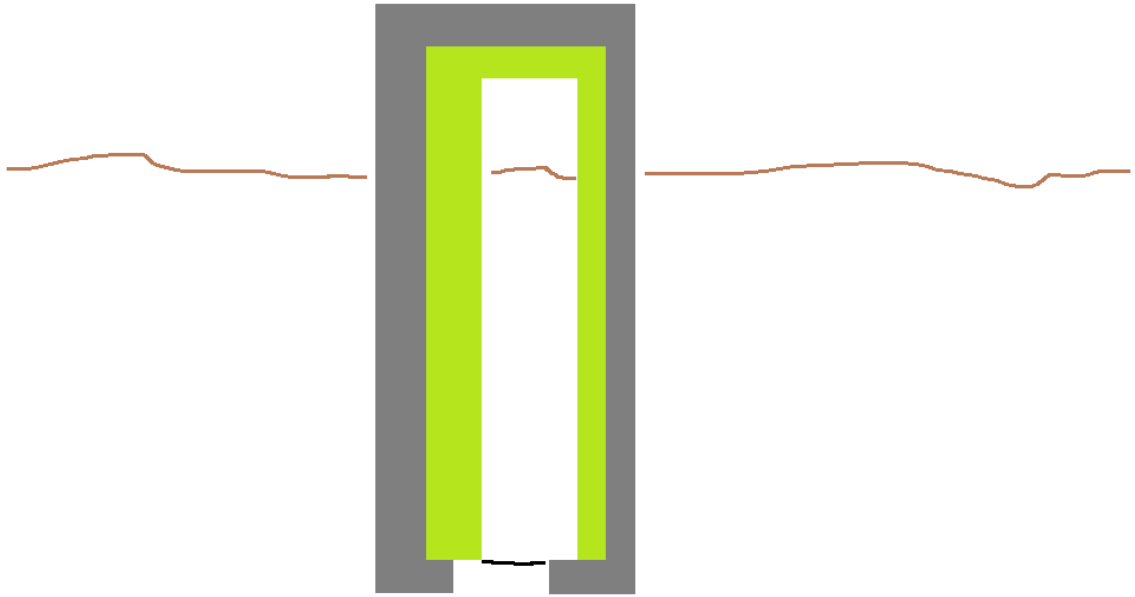

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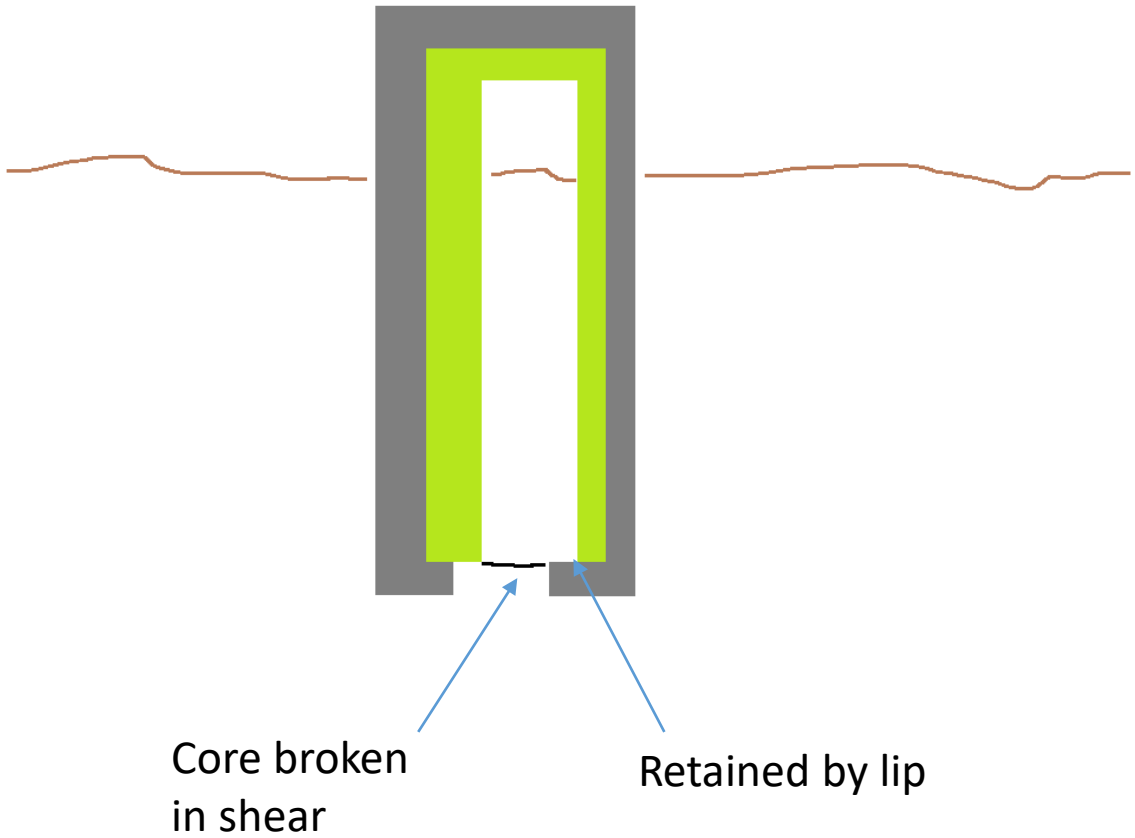

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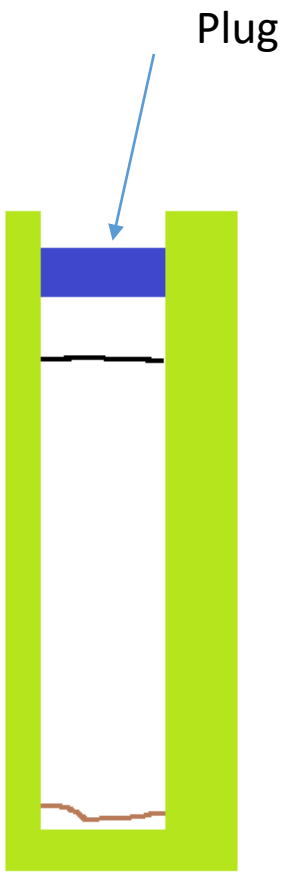
Approximately to scale



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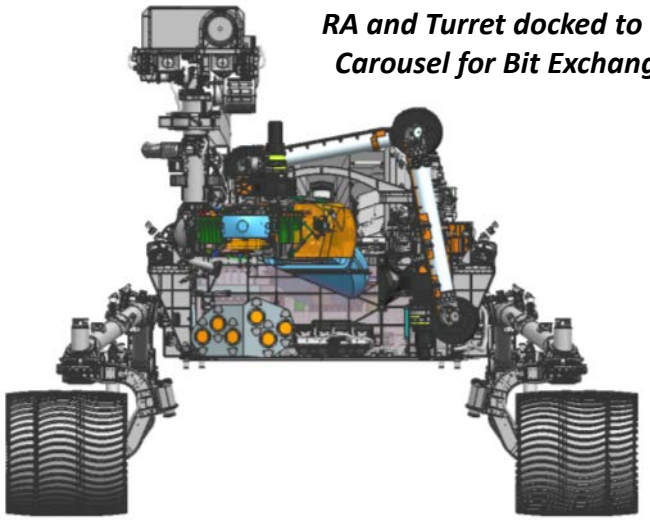
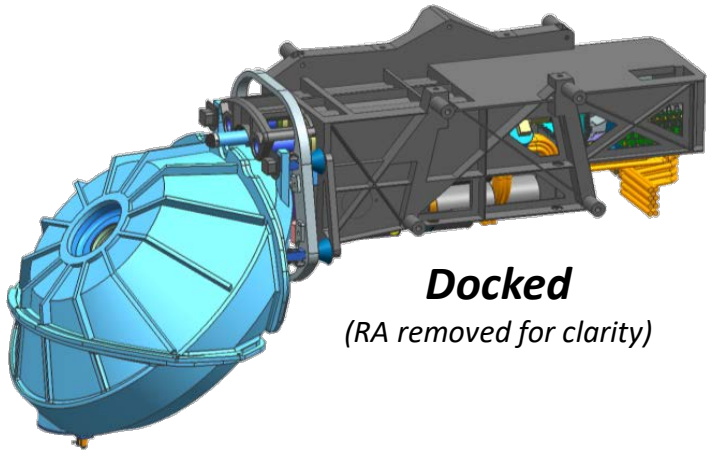
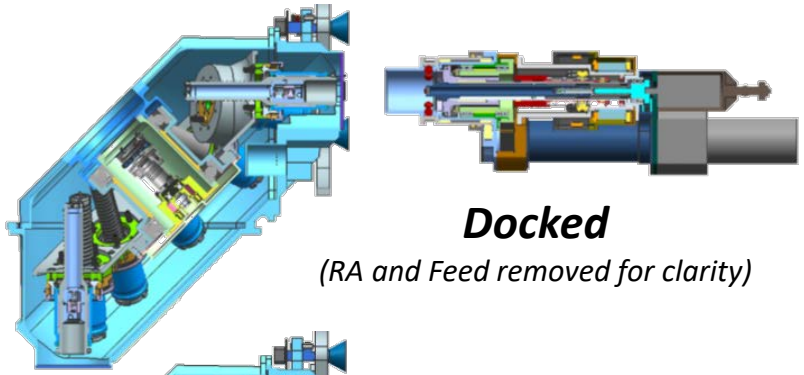


RA and Turret docked to Bit Carousel for Bit Exchange



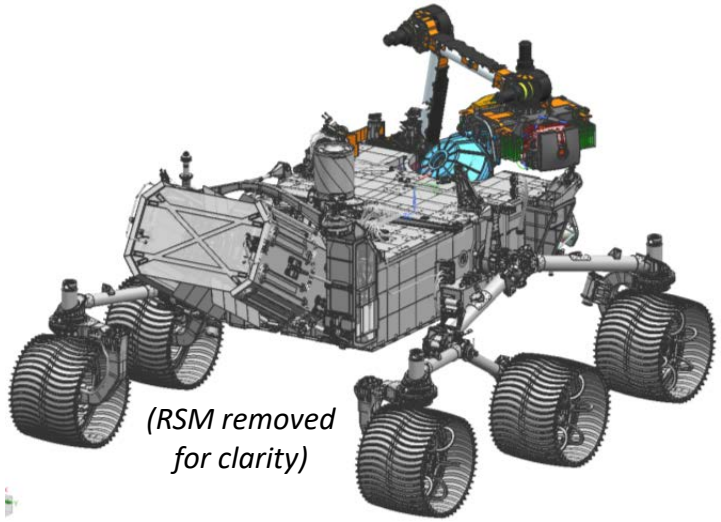
Docked

(RA removed for clarity)



Docked

(RA and Feed removed for clarity)



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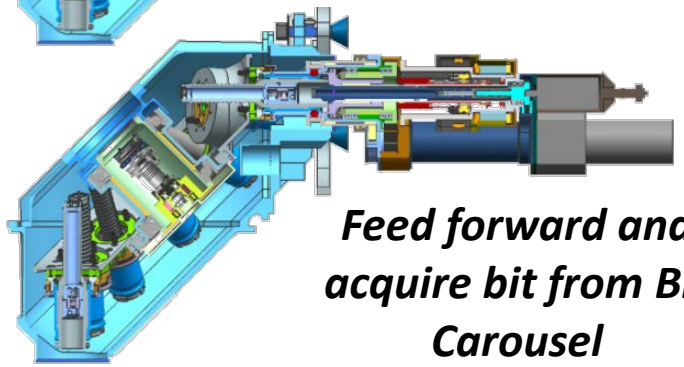

Feed forward and acquire bit from Bit Carousel

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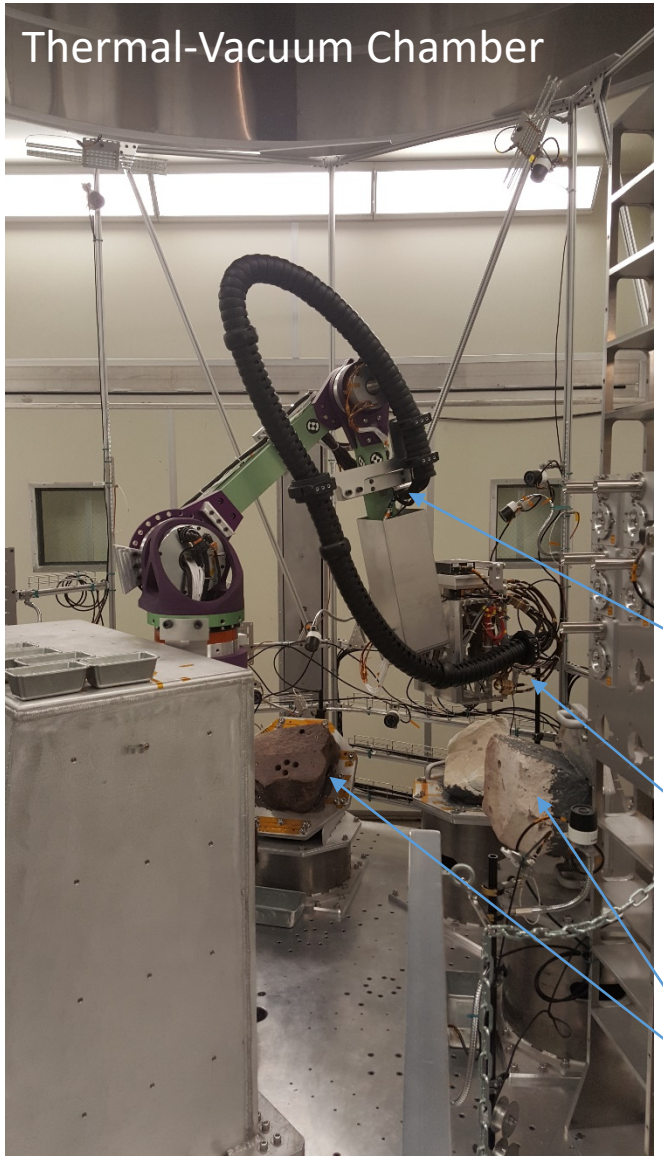

2 m class robotic arm

Drill

Mars analog rocks

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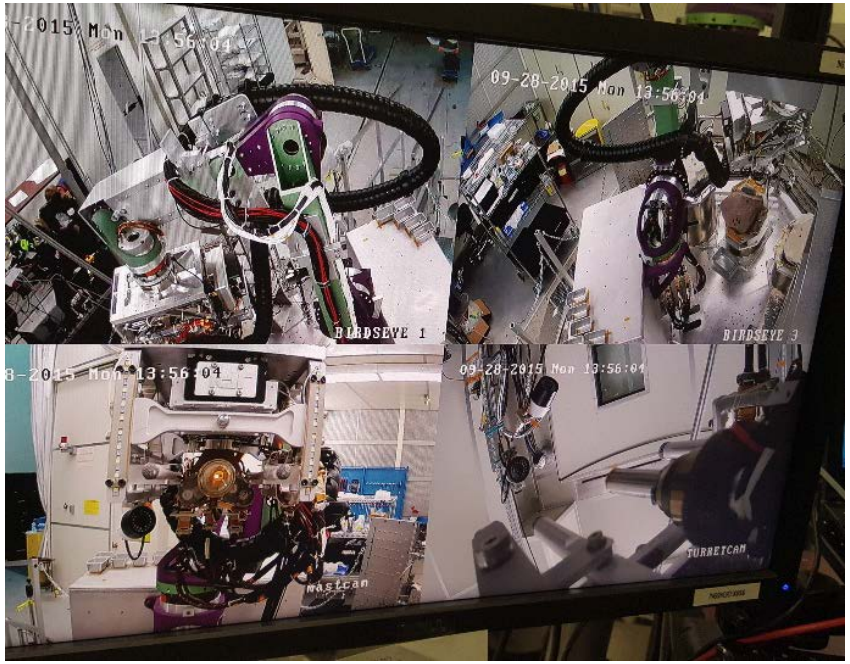
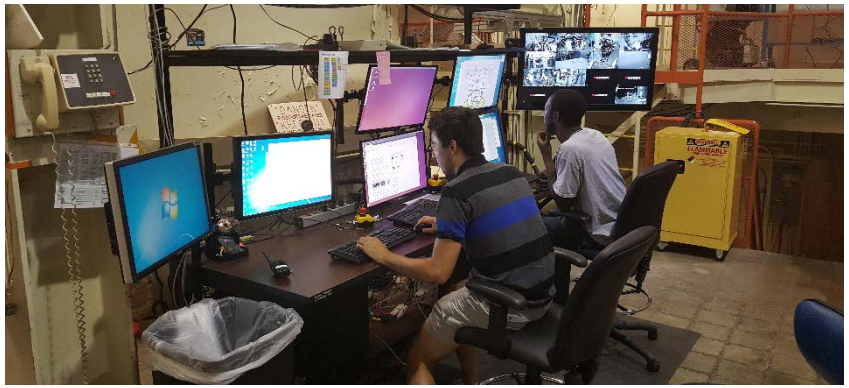
For added mission realism…





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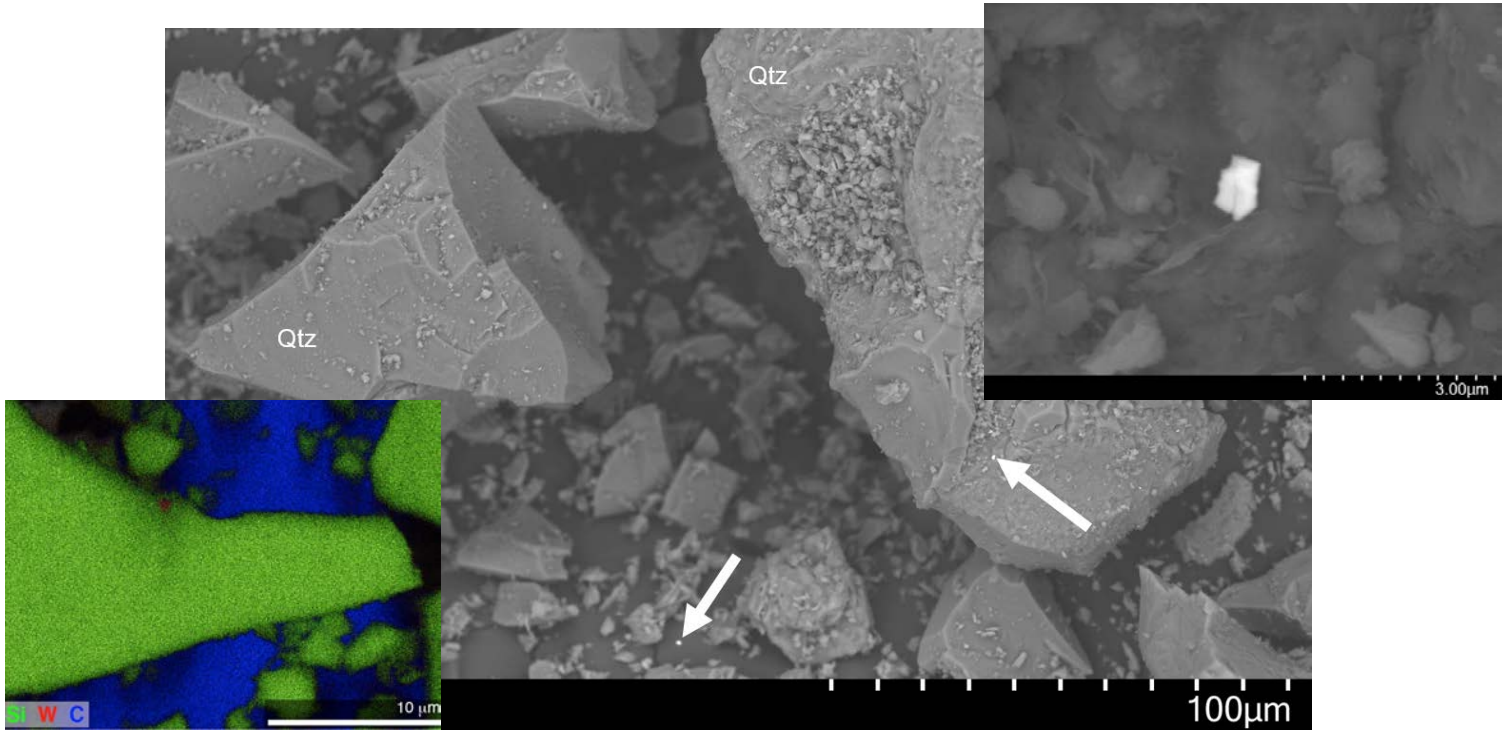
- Testing geometry and materials
  - Does the bit succeed in cutting rock and removing powder from the hole?
    - Excessive heating of sample, excessive power consumption?

  - Do we contaminate samples with bit tooth material (tungsten carbide)?



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Questions?

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