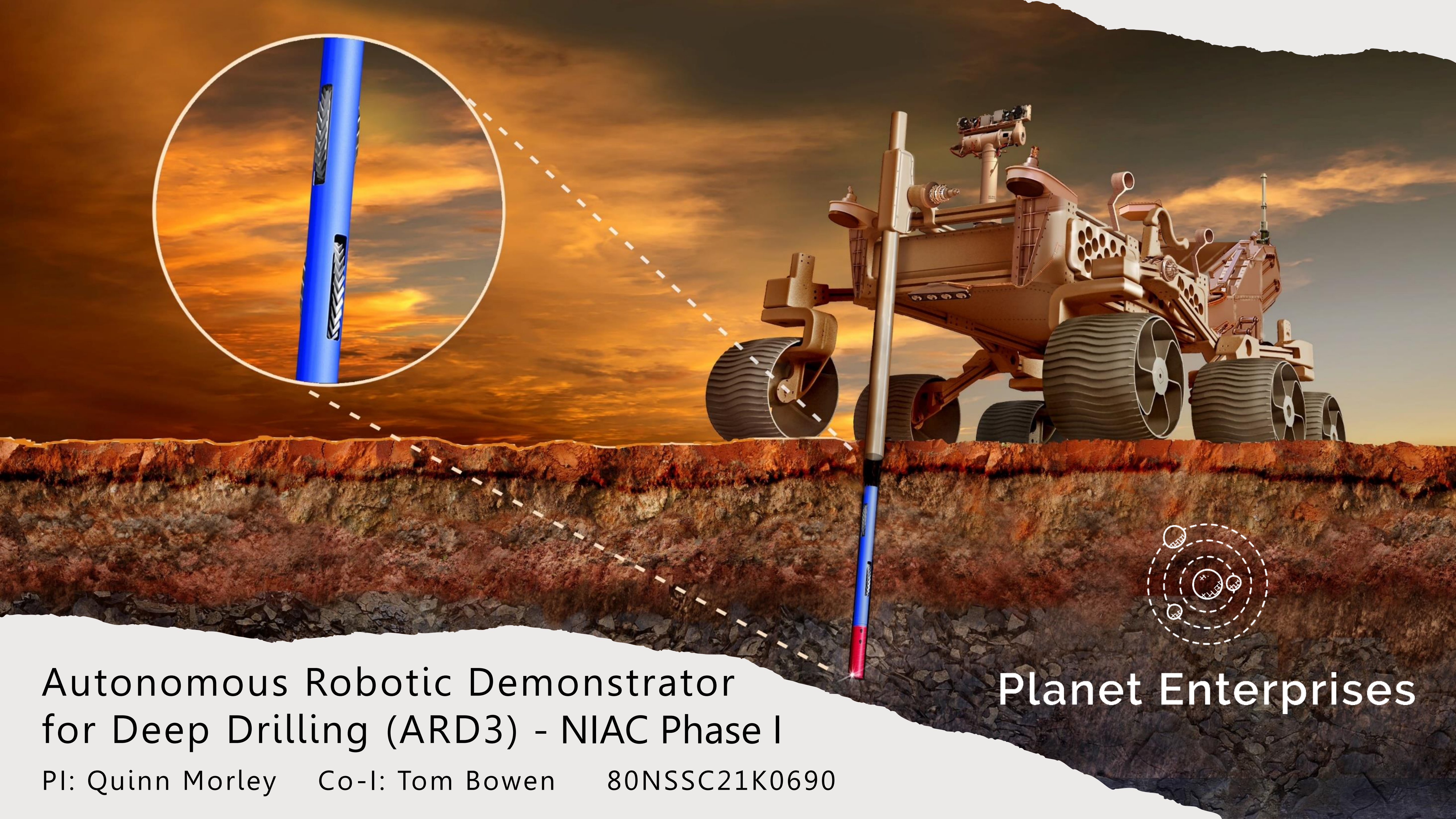

Autonomous Robotic Demonstrator for Deep Drilling (ARD3) - NIAC Phase I

PI: Quinn Morley   Co-I: Tom Bowen

80NSSC21K0690

Planet Enterprises

What are we trying to do?

- Drill into the South Polar Layered Deposits (SPLD), the southern ice cap of Mars
- Analyze and cache ice cores
- Extended Mission: drill 1.5 kilometers deep
- Self-driving robots (borebots) “drive” up and down the hole, and take turns drilling

Why is it important?

- Mars’ polar caps can help us learn about the past climate of Mars, as well as the history of the solar system (including Earth)
- There may be liquid water under the cap

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Planet Enterprises

SPLD Characterization Summary

- A review of Mars polar science in 2000 concluded that the densification model put forth by Arthern et al. (1999) agrees with orbital observations
  - This conclusion would only apply during periods of positive mass accumulation
  - Clifford, et al., (2000). "The State and Future of Mars Polar…" doi:10.1006/icar.1999.6290
  - Arthern et al., (1999). "Densification of Water Ice…" doi:10.1006/icar.1999.6308
- A thick ice-cemented sublimation lag layer (up to 30 m) is one possible explanation for the "fog" effect that SHARAD experiences in the SPLD
  - This indicates a period of negative mass balance that may still be occurring
  - Whitten & Campbell (2018). "Lateral Continuity of Layering…" doi:10.1029/2018JE005578
  - This layer was well known during Mars Polar Lander era, but the thickness was unknown. Vasavada et al., (2000). "Surface properties of…" doi:10.1029/1999JE001108

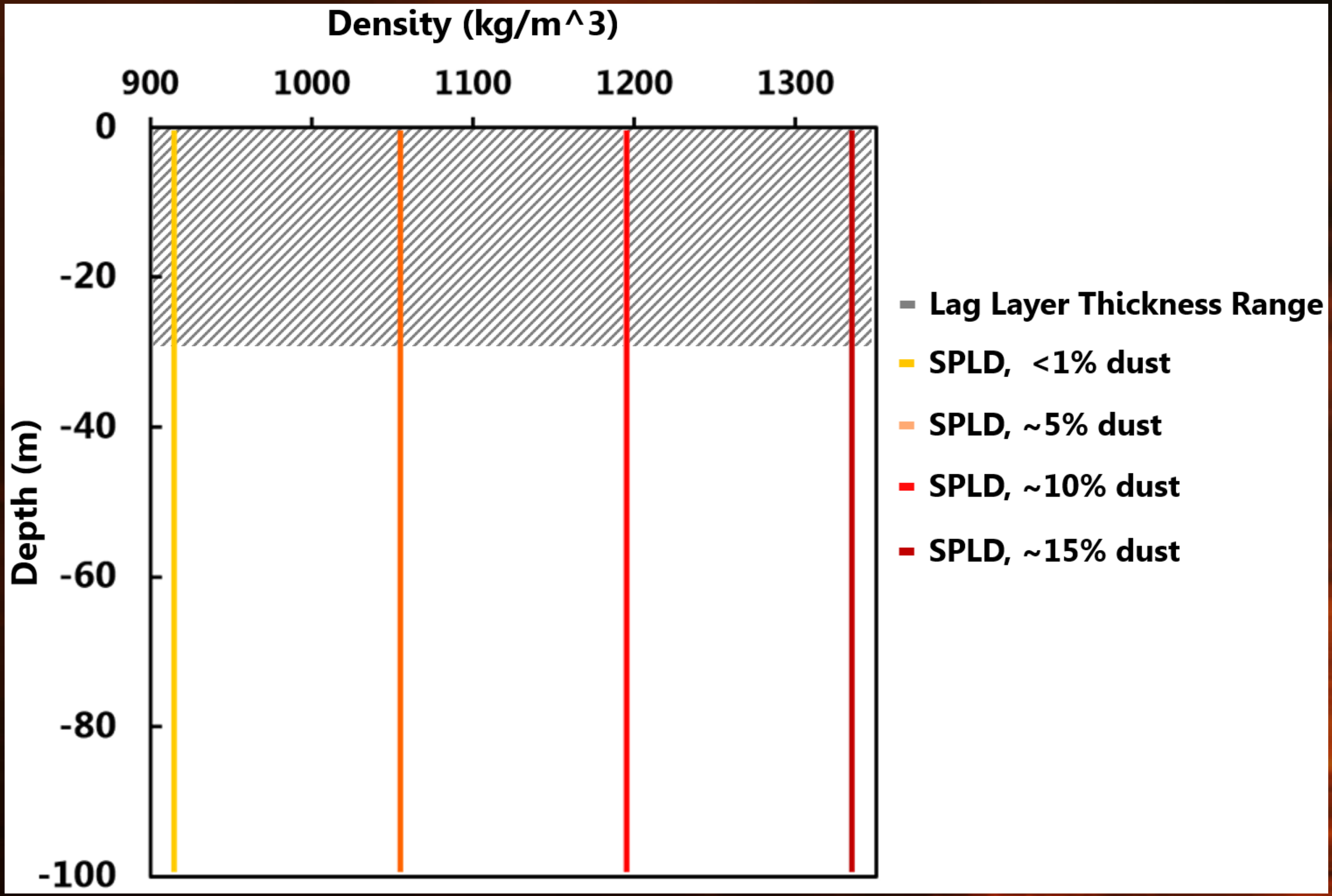
SPLD Characterization Summary

- Zuber et al. claim the SPLD are <u>"clean" water ice</u> with 15% dust. Li et al. showed that this is indeed the case, but that large density variations exist depending on the location (no claim is made as to the density of layers)
    - Zuber, M. et al., (2007). "Density of Mars [SPLD]" doi:10.1126/science.1146995
    - Li, J. et al., (2012). "Density variations within the [SPLD]…" doi:10.1029/2011JE003937
- No CO2 layers are expected in the stratigraphy below the top seasonal layer
    - Phillips, et al. (2011), Supplement to "Massive CO2 Ice…" doi:10.1126/science.1203091
    - Dr. Peter Buhler, Planetary Science Institute, personal communication, June 2021

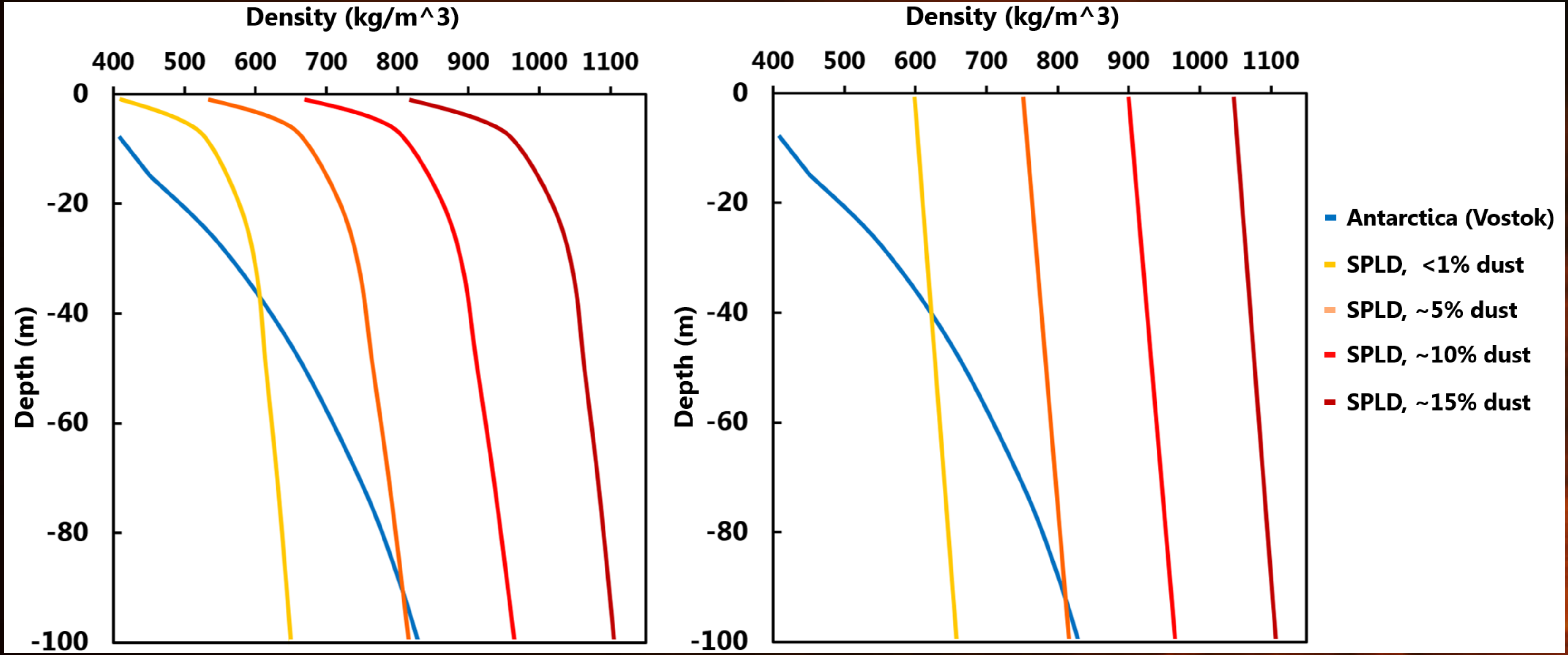
To Summarize: the surface is likely hard, consolidated ice-bound dust/regolith that transitions to a hard and dense water ice with 5-25% dust content, which varies by layer. This result is <u>very favorable</u> in our context.

Depth vs. Density: Upper Bounds

- Vertical lines show density of a “perfectly dense” substrate at various dust concentrations (for context)
- Hatched area represents the predicted thickness range of a sublimation lag layer
  - A discontinuous jump in density is likely in areas where a lag layer is present
  - Predictions for the thickness of a sublimation lag layer range from 5 mm to 100 m, although a range of 1 m to 50 m is the most likely



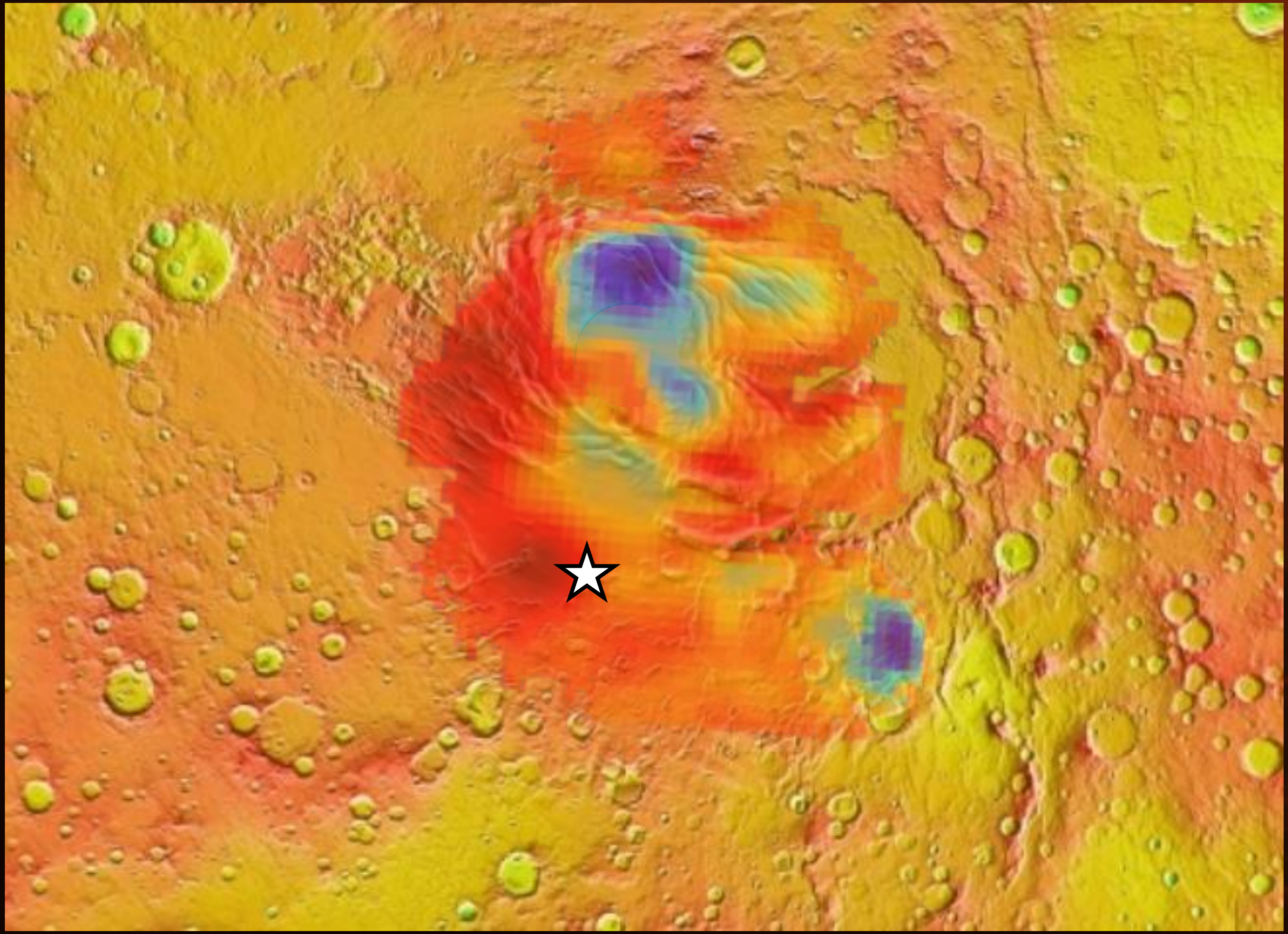
Depth vs. Density: Lower Bounds



PI’s estimated lower bounds for a positive mass balance (left) and negative mass balance (right)

SPLD curves inferred from Arthern et al. (1999). Figures / Vostok curve based on Fig. 2-3, “The Physics of Glaciers,” Cuffey. The “<1% dust” (yellow) curve on the left-hand plot approximates Arthern’s Figure 3 for the top 100 m.

Potential Landing Site: -81.00° 193.00°

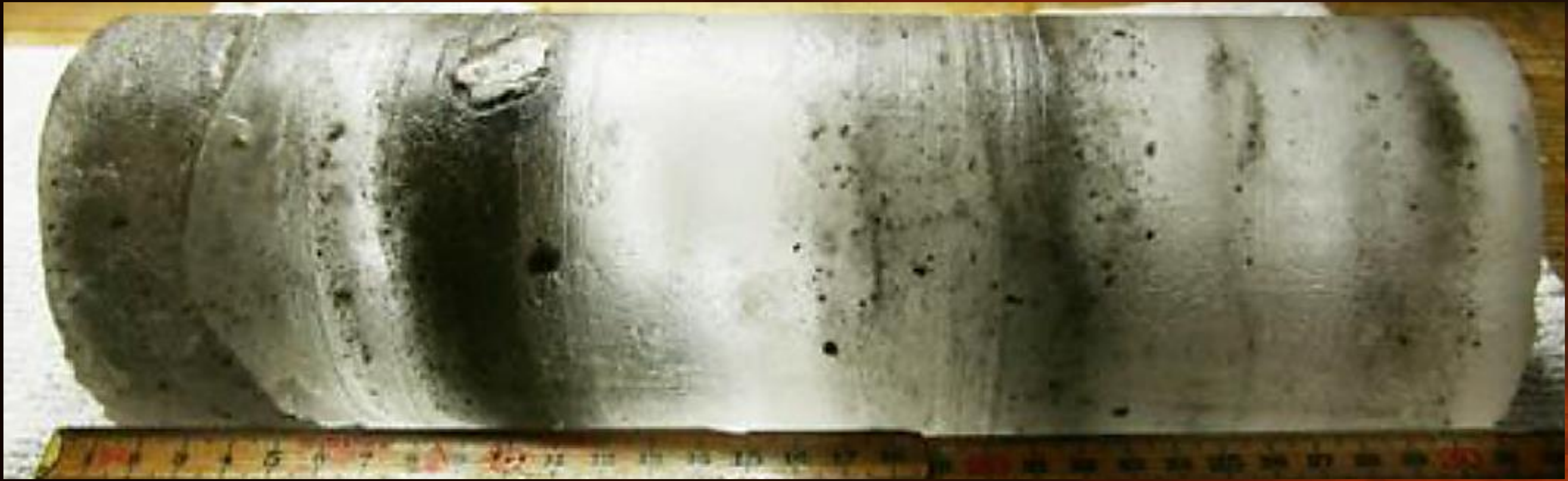


Density at potential landing site: 1200 kg/m^3 $\pm$ 100 kg/m^3

(Density overlay is figure 6-d, Li et al. 2012)

uahirise.org/ESP_066074_0990

SPLD Ice Core Analog

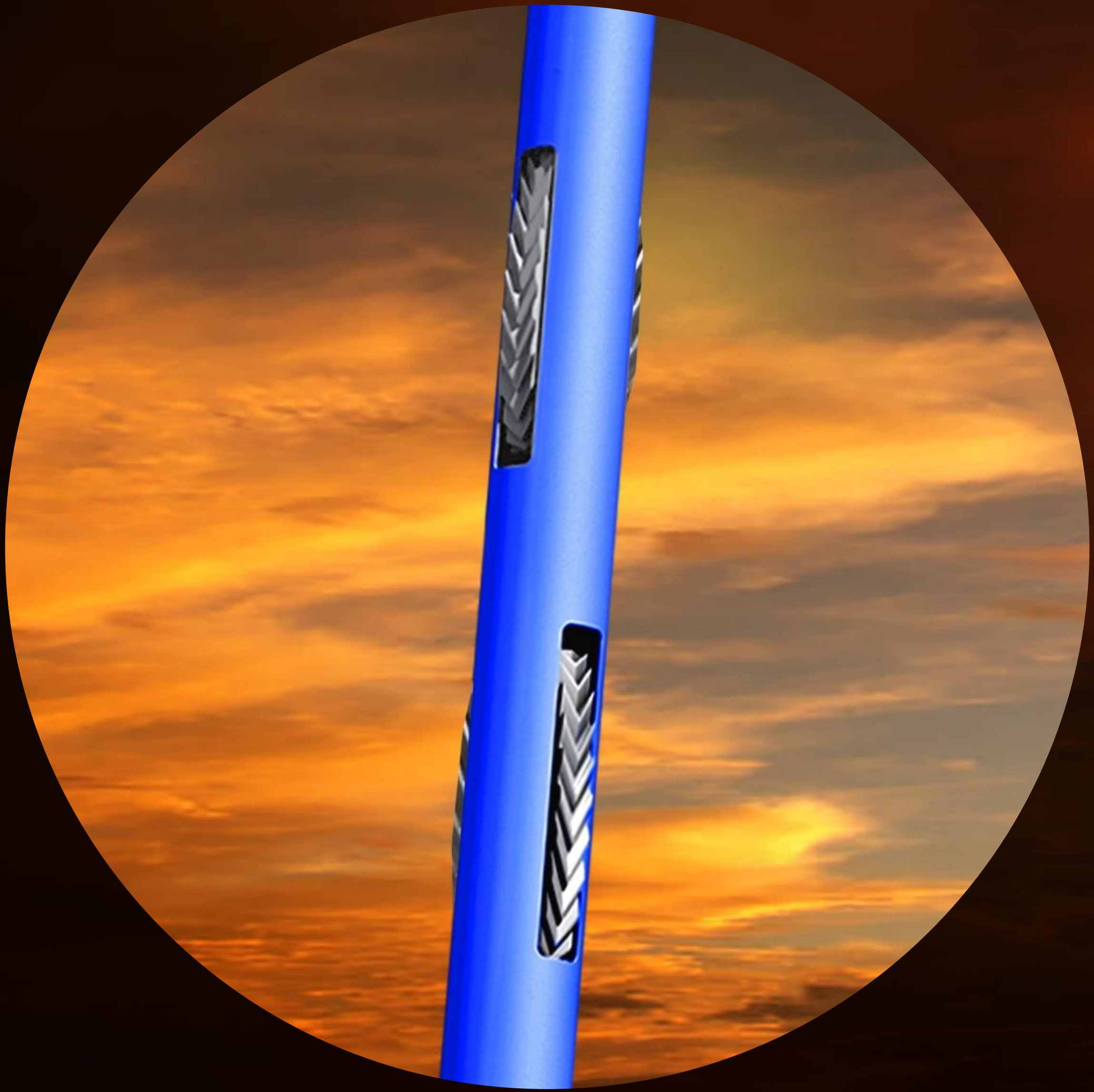


Ice core taken from the bottom of the NEEM borehole in Greenland

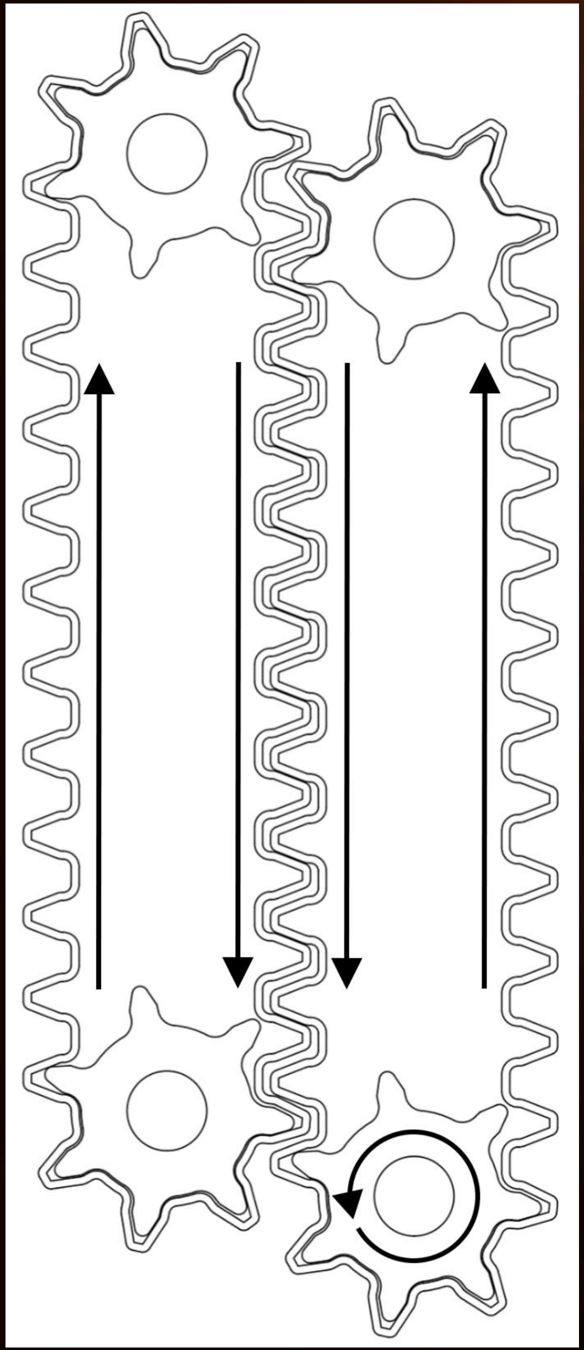
SPLD cores may be very similar (with more admixed dust) and are very likely to come up in pieces as seen here.

From: Smith, I. et al., “The Holy Grail: A road map for unlocking the climate record stored within the Mars [PLD]”

Borebot Drivetrain



- Tank tracks shown are actually flexible ring gears
- As prototyped, the entire drive system is made of flexible components: small chunks of ice or rock could pass through without causing binding or failure
- This NIAC study is mainly focused on the feasibility of self-driving drilling robots *in the context of* SPLD deep drilling from a rover



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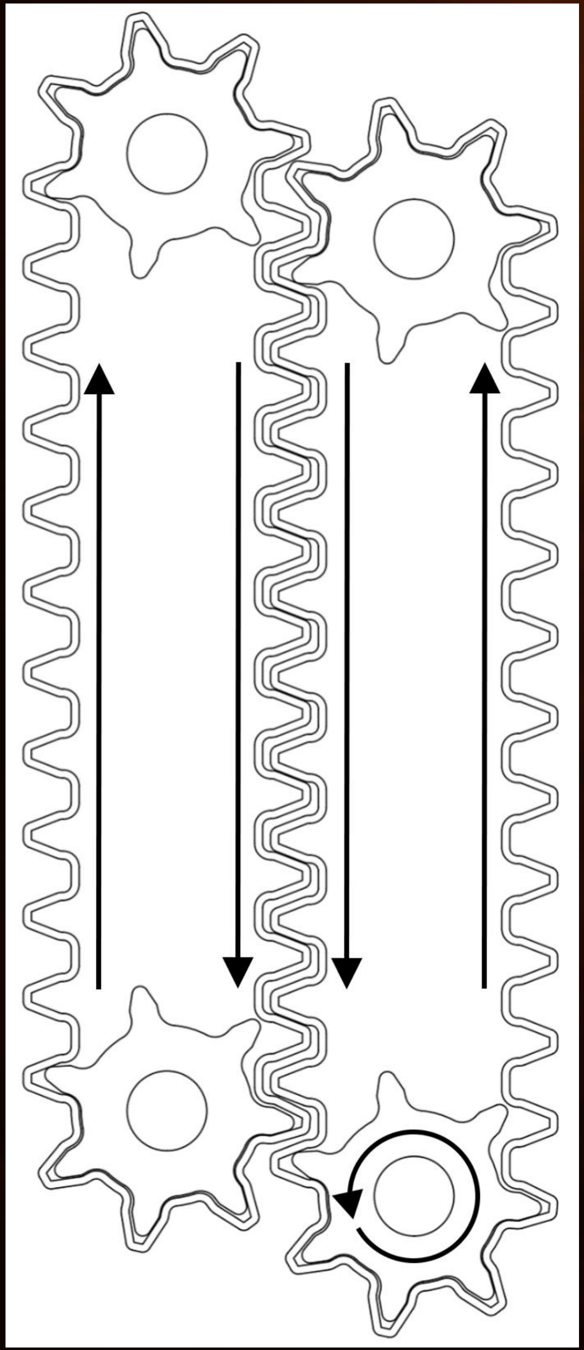

mp4 video https://git.io/JBbJ1

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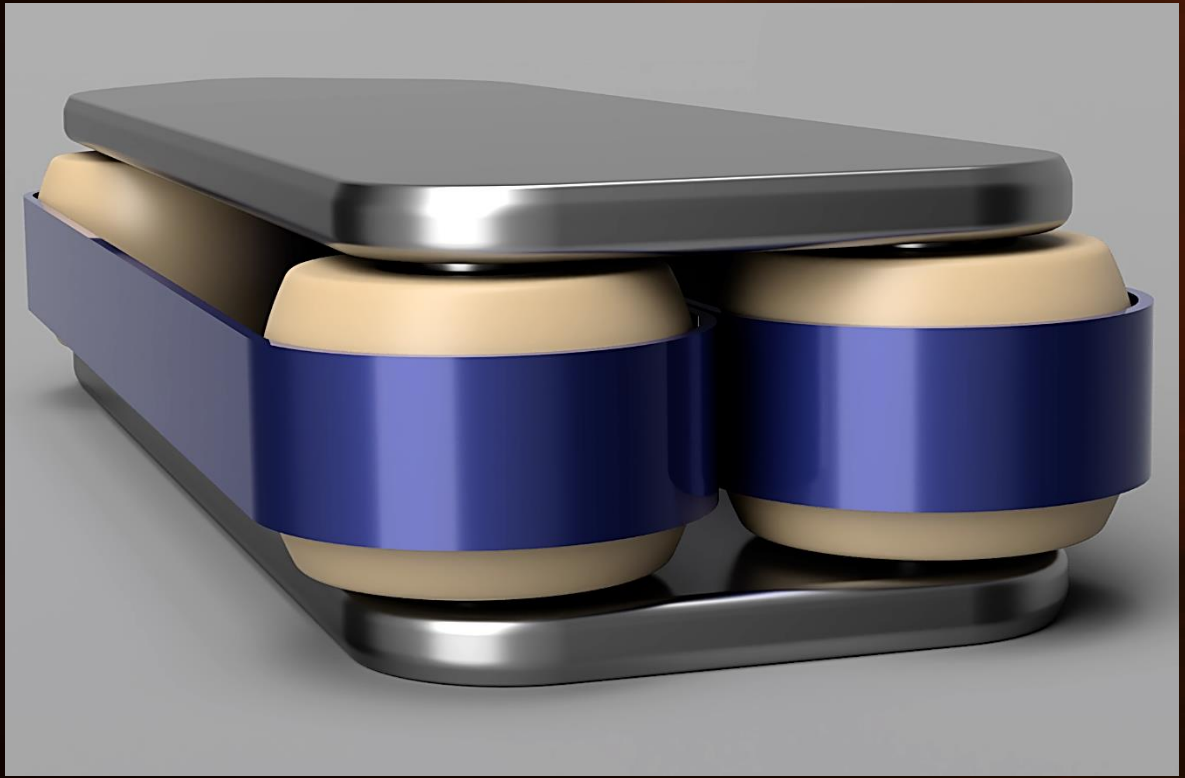
Borebot Drivetrain: Flat Belt Options



- We are also looking at drivetrain layouts that use flat belts, both with and without crowned pulleys

- Generally, the tolerances on a flat belt system have to be tighter, and the interface between the belts is less reliable, meaning independent track control may be a requirement

- The potential to have lower friction / rolling resistance may make it worth the challenges

Borebot Drivetrain: Directional Drilling

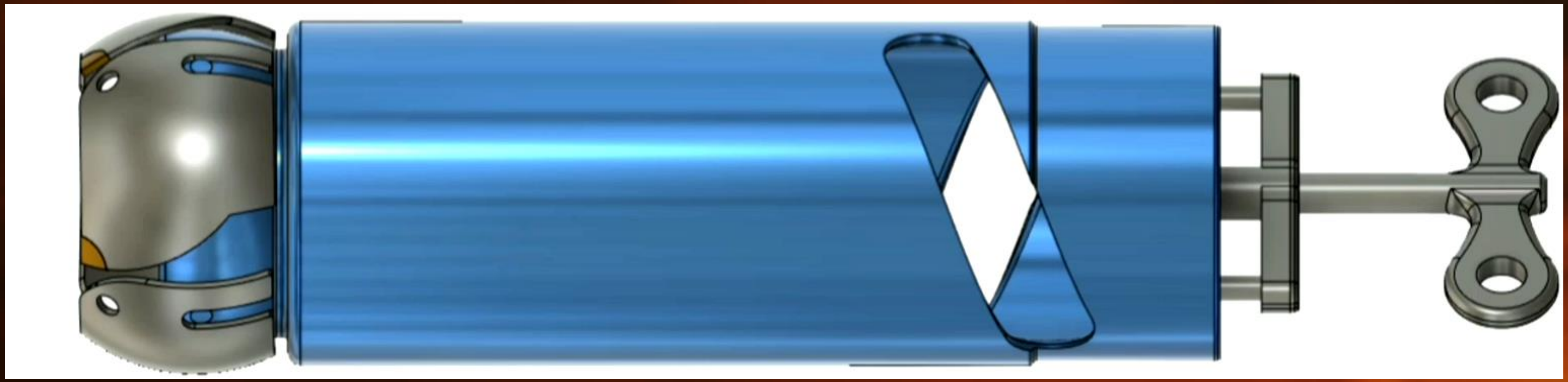
- Two borebot drivetrains could be joined together with an articulated joint, and use jackscrews for adjustment
- This concept could enable reliable, frequent branch borehole use and may have terrestrial applications, i.e., Earth science deep drilling in Antarctica
- On Mars, this could be used to mitigate a stuck borebot by creating a branch bore in order to bypass the blocked part of the bore

Mitigating Drilling Challenges – Crumbly Ice

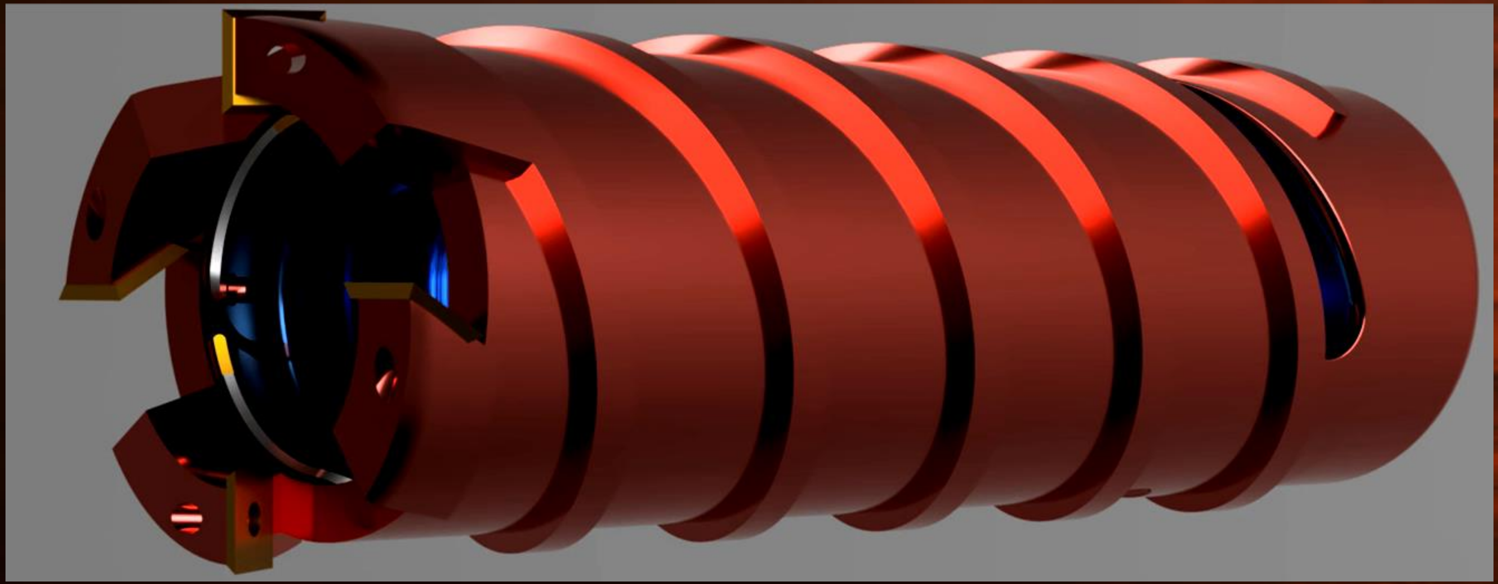
- This innovation enables reliable capture of crumbly/non-cohesive ice cores
- Carbide teeth are brazed onto a steel-bladed spherical iris
  - Low annular profile, can take a 40 mm dia. core
  - Larger diameter after throat (room for chips)
- The main drill motor is used to actuate the iris via a clever pin-puller strategy
  - Full drilling torque available to close iris
- A ratchet mechanism could hold the aperture while rotating the drill in order to cut hard/consolidated cores

Mitigating Drilling Challenges – Crumbly Ice

Use URLs to download .mp4 animations if viewing a PDF



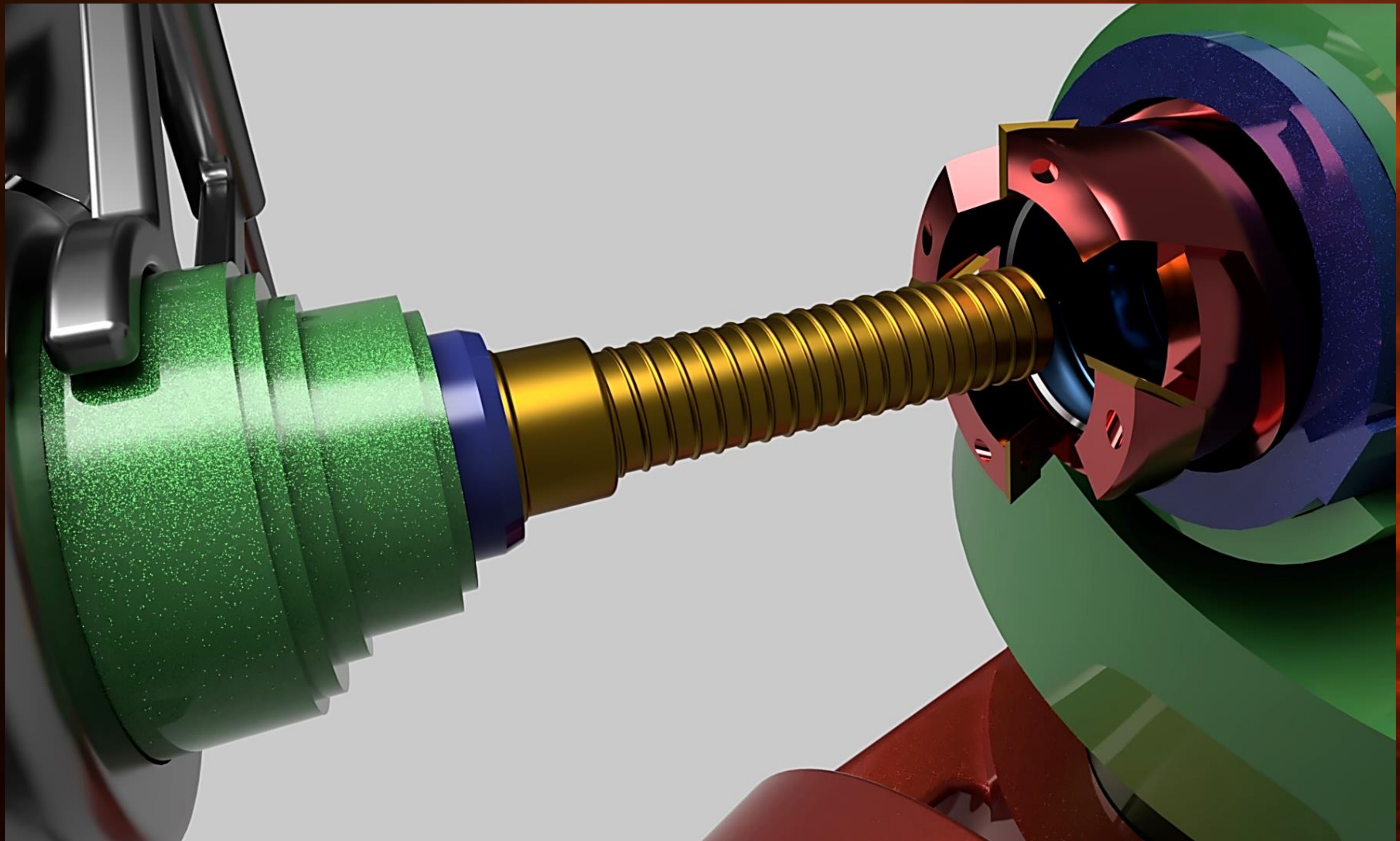
https://git.io/JsPov



https://git.io/JsKah

Caching / Analysis of Ice Cores

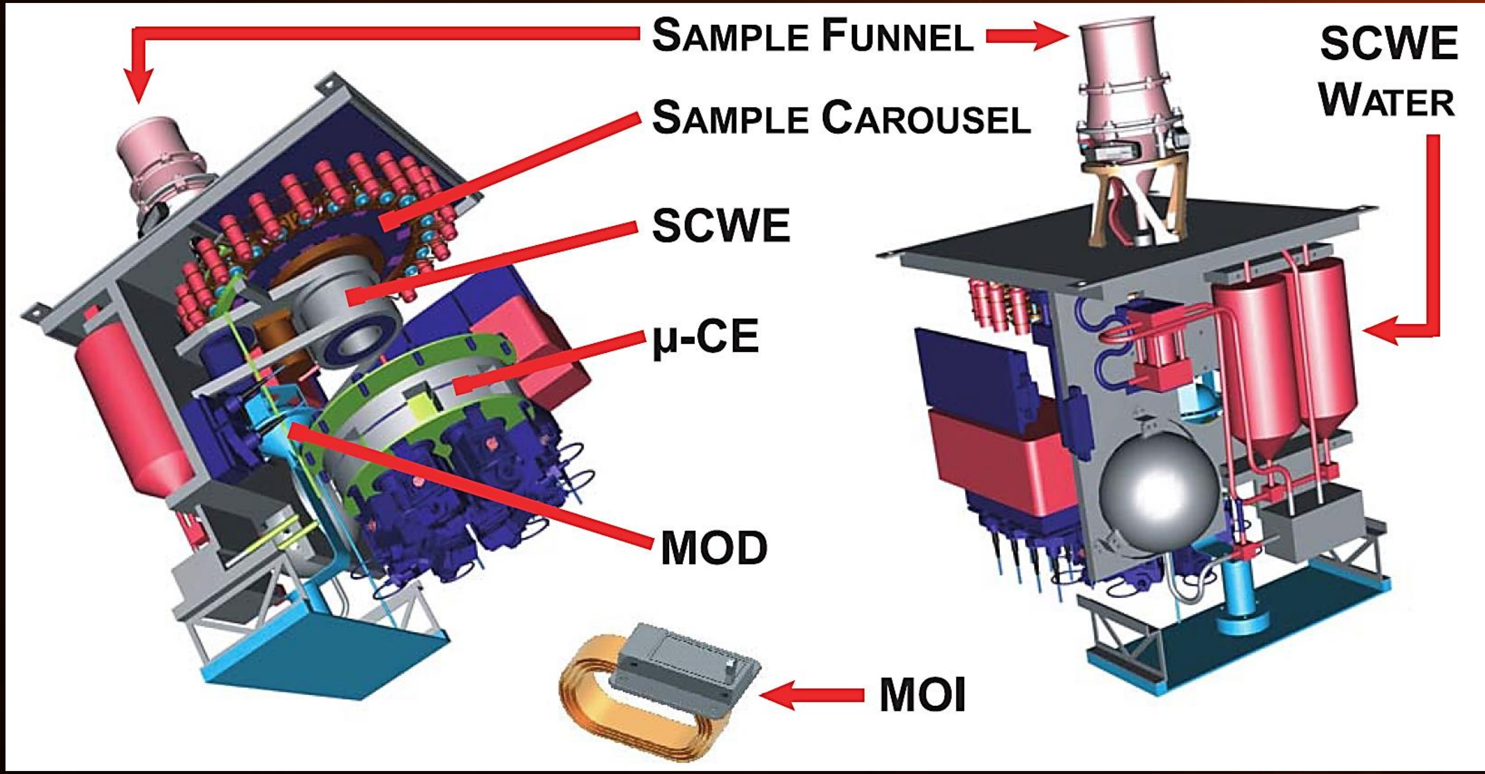
- The Perseverance Adaptive Caching Assembly (ACA) is used
- Sub-sampling: drill chuck actually fits on the end of the borebot
- Or, re-coring: turret corer (or chuck holder) can be moved to the rover deck, to re-core the larger ice cores and extract a pristine core center

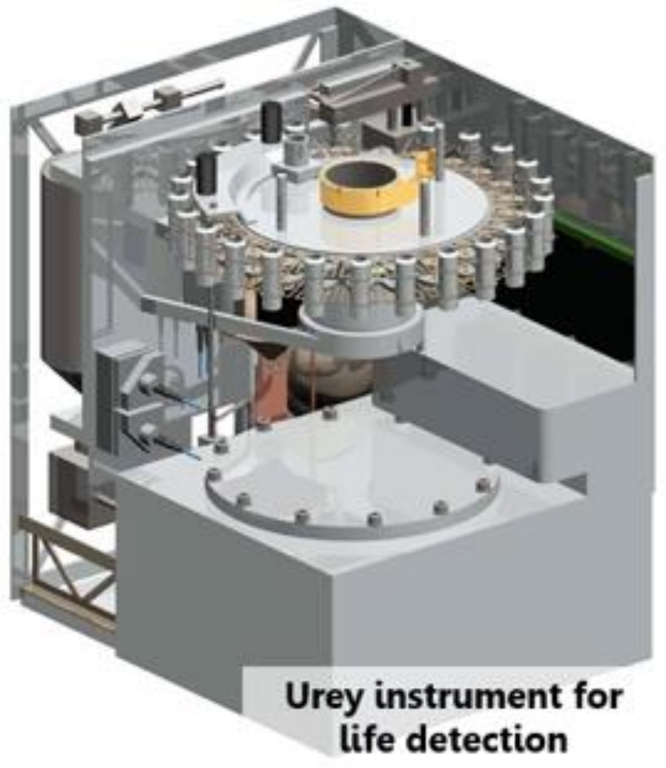


Science Instruments

Rover Instruments

- Urey life detection instrument (in the space used by MOXIE on Perseverance)
- Raman UV Spectrometer (added to ACA vision station, or external [SHERLOC])
- Ice core melting station, with mass spectrometer analysis of released gasses





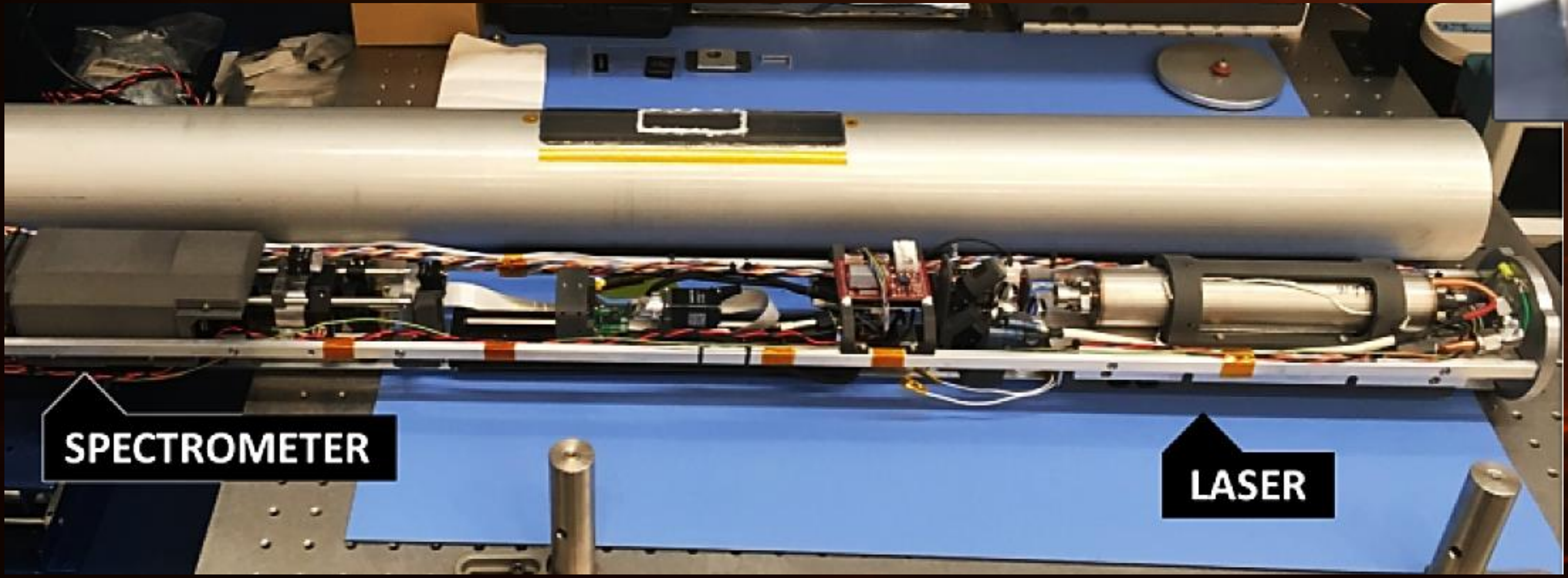
Aubrey, A., et. al. (2008). “The Urey Instrument: An Advanced In Situ Organic and Oxidant Detector for Mars Exploration.” doi:10.1089/ast.2007.0169

Science Instruments

Downhole Instruments

- Microscopic imager (white and UV light), seen right
- WATSON Deep UV Raman Spectrometer, seen below
- Ice conductivity measurement
- D/H hydrogen ratio measurement
- Sonar for ice thickness and density

Zacny, K. et. al, 2016.
doi:10.1061/9780784479971.027

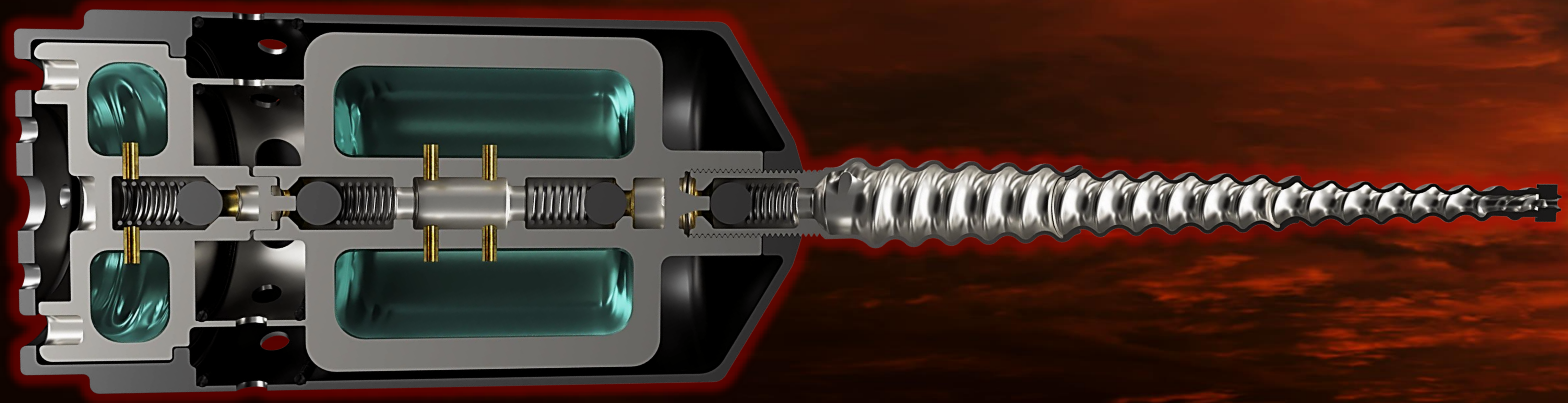


Eshelman, M. et. al, 2019.
doi:10.1089/ast.2018.1925

Sampling Liquid Water on Another World

"Breakthrough" is a notorious phase of subglacial lake access, and is a major challenge for our extended mission goal.

As a mitigation measure, we calculated the thickness required of an ice "plug" in order to prevent breakthrough (see next slide) and developed a penetrator probe instrument to perform the final subglacial access and extract a liquid water sample. The required ice thickness to prevent breakthrough is about 4 cm.



Sampling Liquid Water on Another World

Ref. Arnold, N.S. et. al (2019), "Modeled Subglacial Water Flow …" Methods section for $\kappa = 1$.

Ref. K.F. Voitkovskii (1960), "Mechanical Properties of Ice," for shear strength estimate.

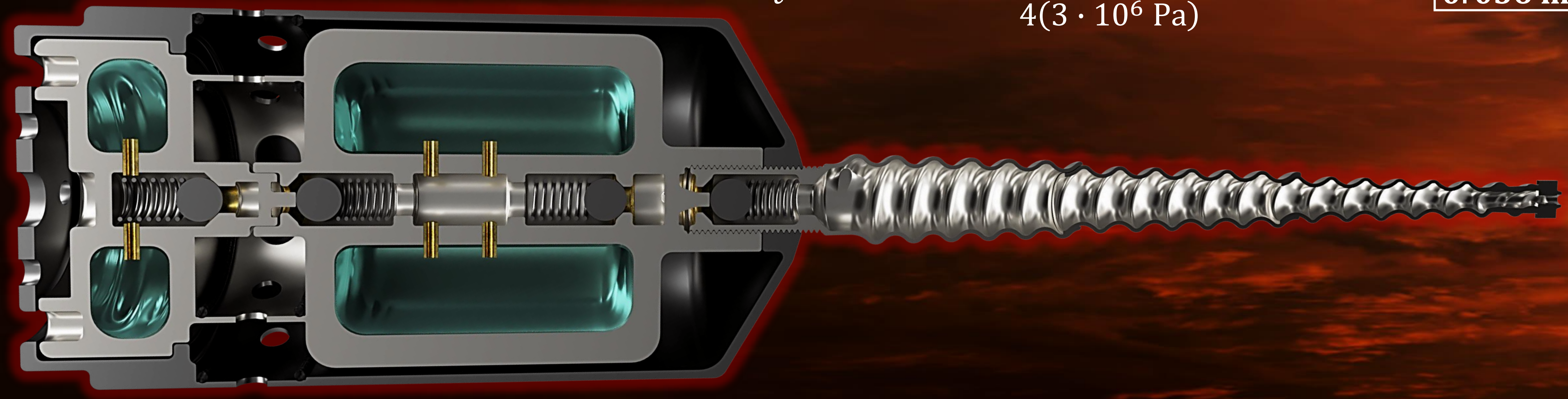
$$\Delta P = P_{H_2O} - P_{atm} \quad \rightarrow \quad \Delta P \approx P_{H_2O}$$

Shear strength S for water ice at 200 K: **3.0 MPa** (conservative)

$F = L \cdot t \cdot S$ (Punching force equation), L is perimeter of shape

$$t = \frac{F}{LS} = \frac{P_{H_2O} \cdot A}{\pi \cdot D \cdot S} = \frac{P_{H_2O} \cdot \frac{\pi}{4} D^2}{\pi \cdot D \cdot S} = \frac{P_{H_2O} D}{4S} = \frac{\kappa \rho_{ice} g h D}{4S} = \boldsymbol{\frac{\rho_{ice} g h D}{4S}}$$

$$t = \frac{\left(1200 \frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 3.71 \frac{\mathrm{m}}{\mathrm{s}^2} \cdot 1{,}500\ \mathrm{m}\right)(0.064\ \mathrm{m})}{4(3 \cdot 10^6\ \mathrm{Pa})} = \boxed{\mathbf{0.036\ m}}$$



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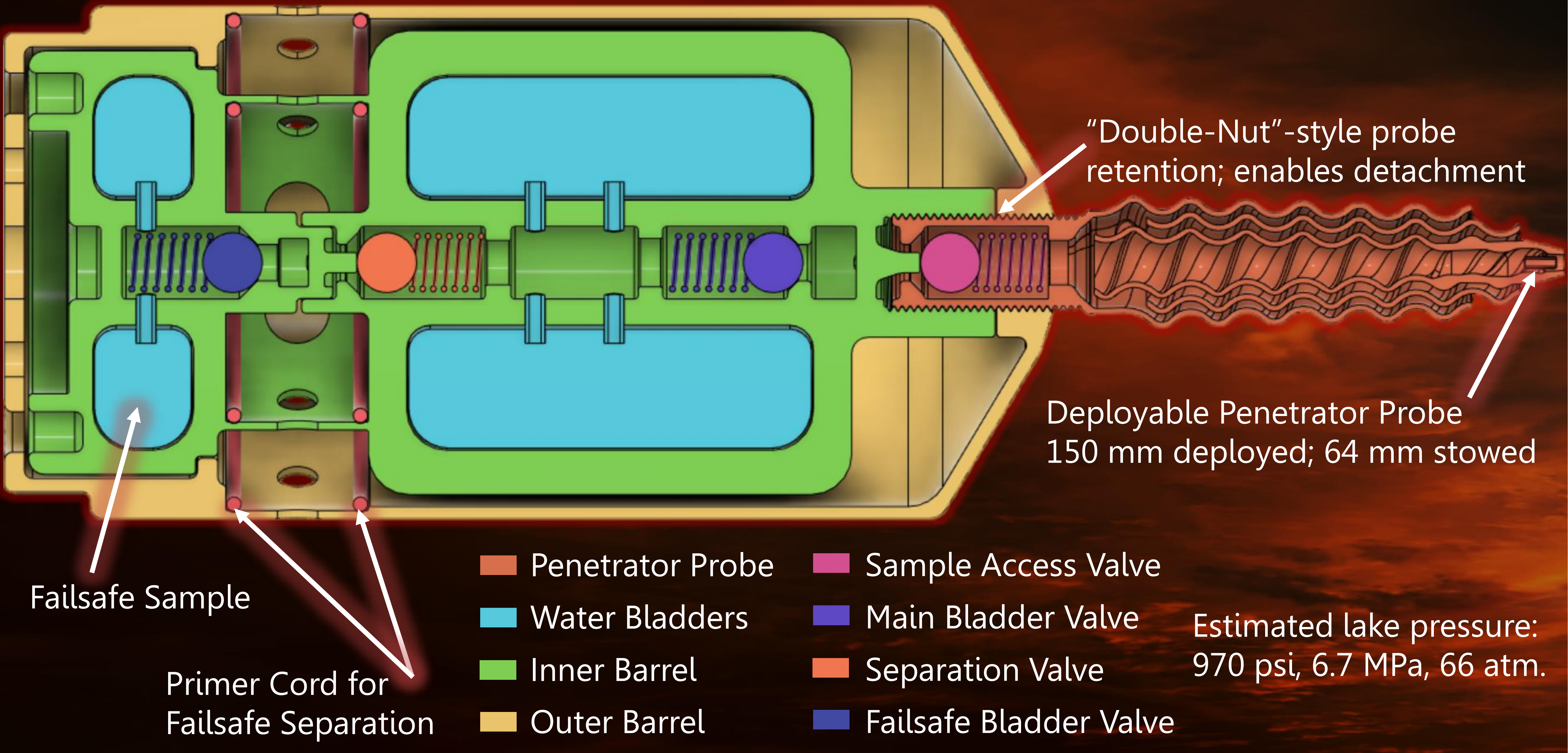
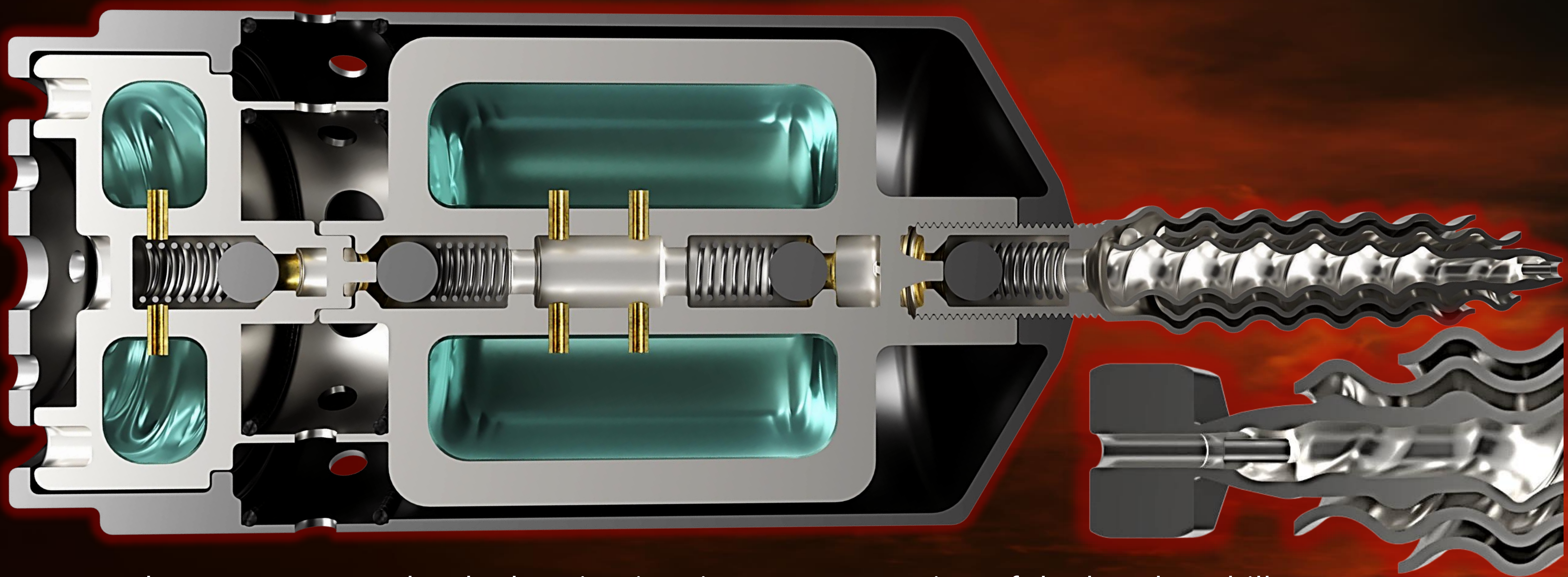


Estimated lake pressure: 970 psi, 6.7 MPa, 66 atm.

Sampling Liquid Water on Another World



- The Penetrator Probe deploys in-situ via counter-rotation of the borebot drill motor
- 10 mm shear-nut ensures proper torque for deployment and “setting” of the telescoping sections of the probe (this friction fit is critical), the nut breaks off when torque is reached
- A “nut pocket” on the rover’s arm/chassis can hold the nut during deployment

A Few Engineering Challenges

Presented by Tom Bowen

- Brains
- Navigation
- Power Requirements
- Thermal Requirements
- Downhole Instrumentation

Brains

Low End

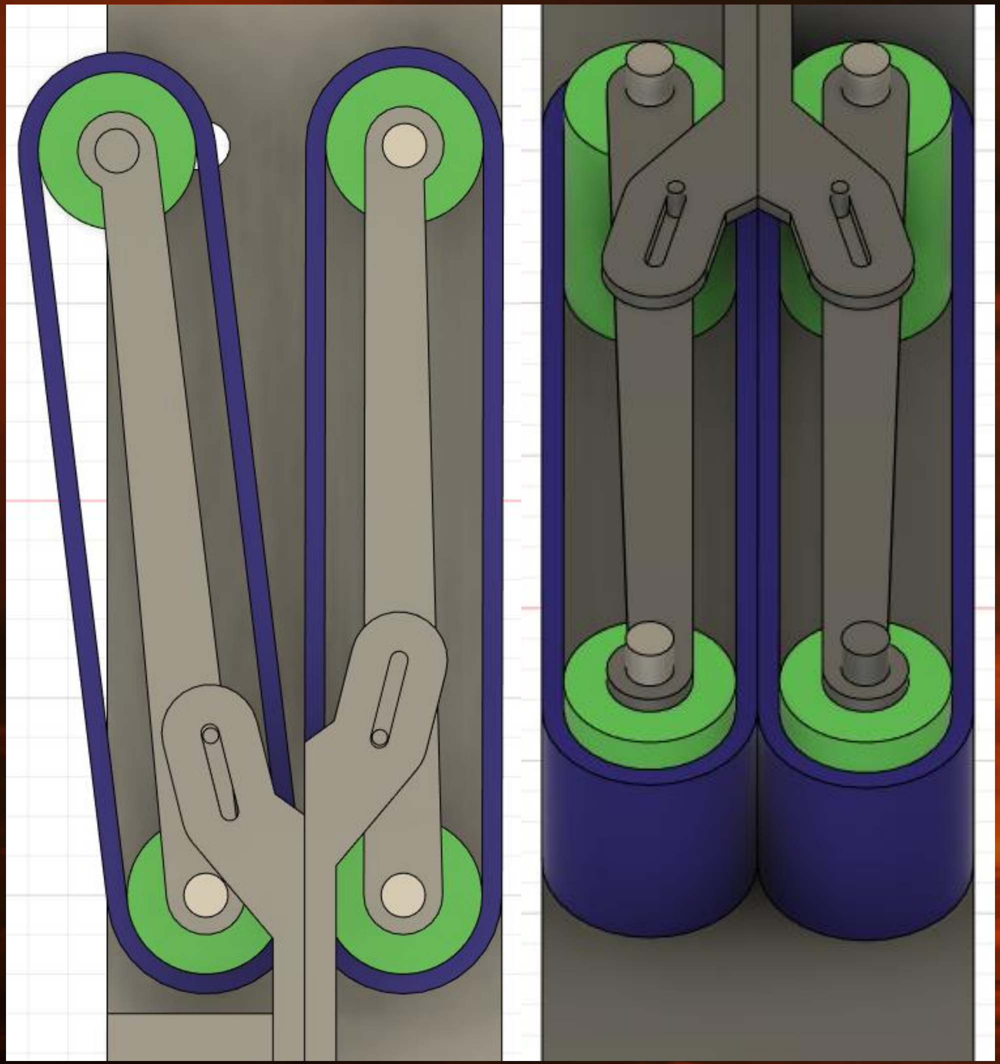
- Commercial Microcontroller
- Moderate speed
- Moderate capacity
- Easy to program, open source
- SD card storage
- Extra computation farmed out to peripheral instruments if needed

High End

- SoC; MCU + FPGA
- High speed
- High capacity
- Harder to program, proprietary
- SD card storage
- More centralized computation
- Higher power requirements

Navigation

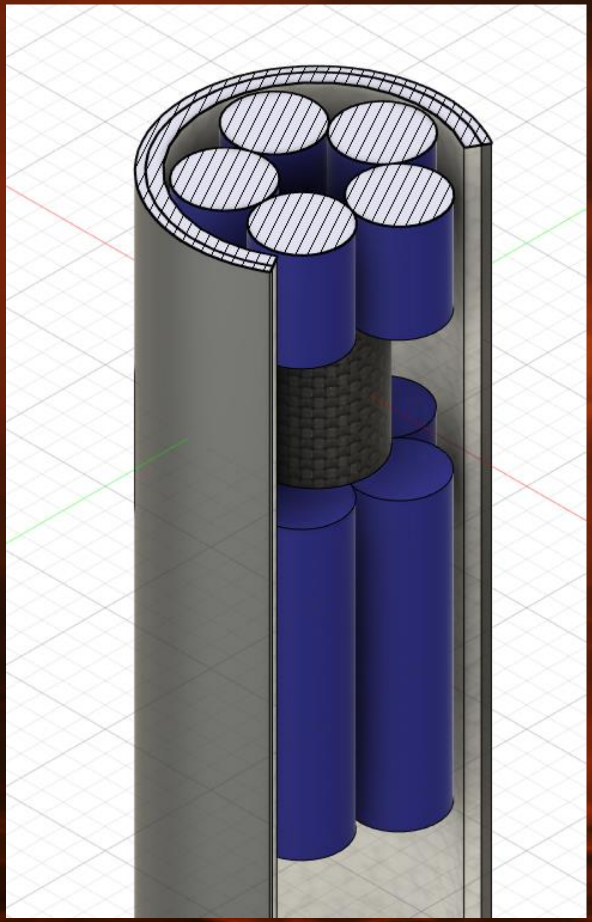
- Commercial sensor options available
- Autonomous drilling navigation well understood[1]
- Directional drilling using variable pressure drive
- Kicking one end of a tread out can angle (on the order of 1 deg.) the bot for changing the direction of the drilling operation
- Branch holes for additional science or obstacle avoidance



1. Kowalski J. et al. (2015). "Navigation technology for exploration of glacier ice with maneuverable melting probes." https://doi.org/10.1016/j.coldregions.2015.11.006

Power Requirements

- Need high density, reliability, cycle life
- Drive efficiency is a big deal – regenerative braking would be great
- Hotel loads offer slow death
- Nominal capacity is reduced to improve cycle life ~40%
- The noble 18650 cell.
- Typical chemistries do not like the cold.
- Lithium Titanate would be great but has a low energy density



Possible battery arrangement with Radioisotope Heater Unit (RHU)

Thermal Requirements

- Staying above 0C for batteries
- Minimal convection
- Radiation appears to dominate
- Conduction is a risk down hole
- Electric heating, RHU, waste heat from components
- Structure design for warmth
- Phase change materials

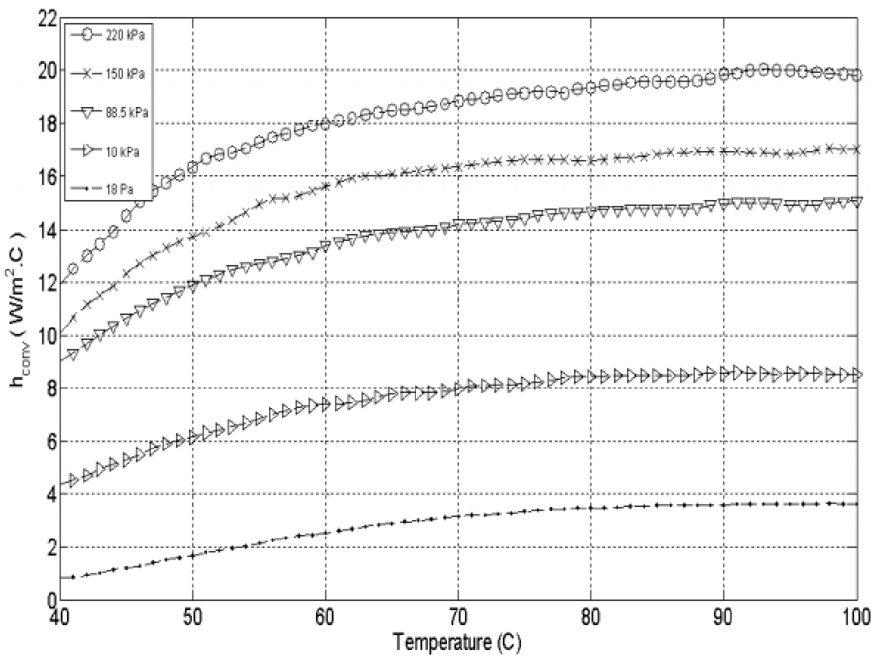


Fig. 4 Convection heat transfer coefficient with temperature at different pressures

Graph: Saidi, Maysam & Hosseini, R.. (2010). Air Pressure Dependence of Natural-Convection Heat Transfer. Lecture Notes in Engineering and Computer Science. 2.

Downhole Instrumentation

- Low power/size is a plus
- Best case: Science from stuff we have on board already
- Temperature, pressure, magnetometry, and gravimetry free from IMU
- Drill power draw
- Drill thermocouples
- Gas sensing for substrate off-gassing/sublimation
- Seismic information
- Tomography data between lander/downhole instruments
- Electrical/thermal resistance
- Microscopic imager[2]
- Color camera/Spectrometry

2. Zacny, K. et al. (2016). “Development of a Planetary Deep Drill.” doi:10.1061/9780784479971.027

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