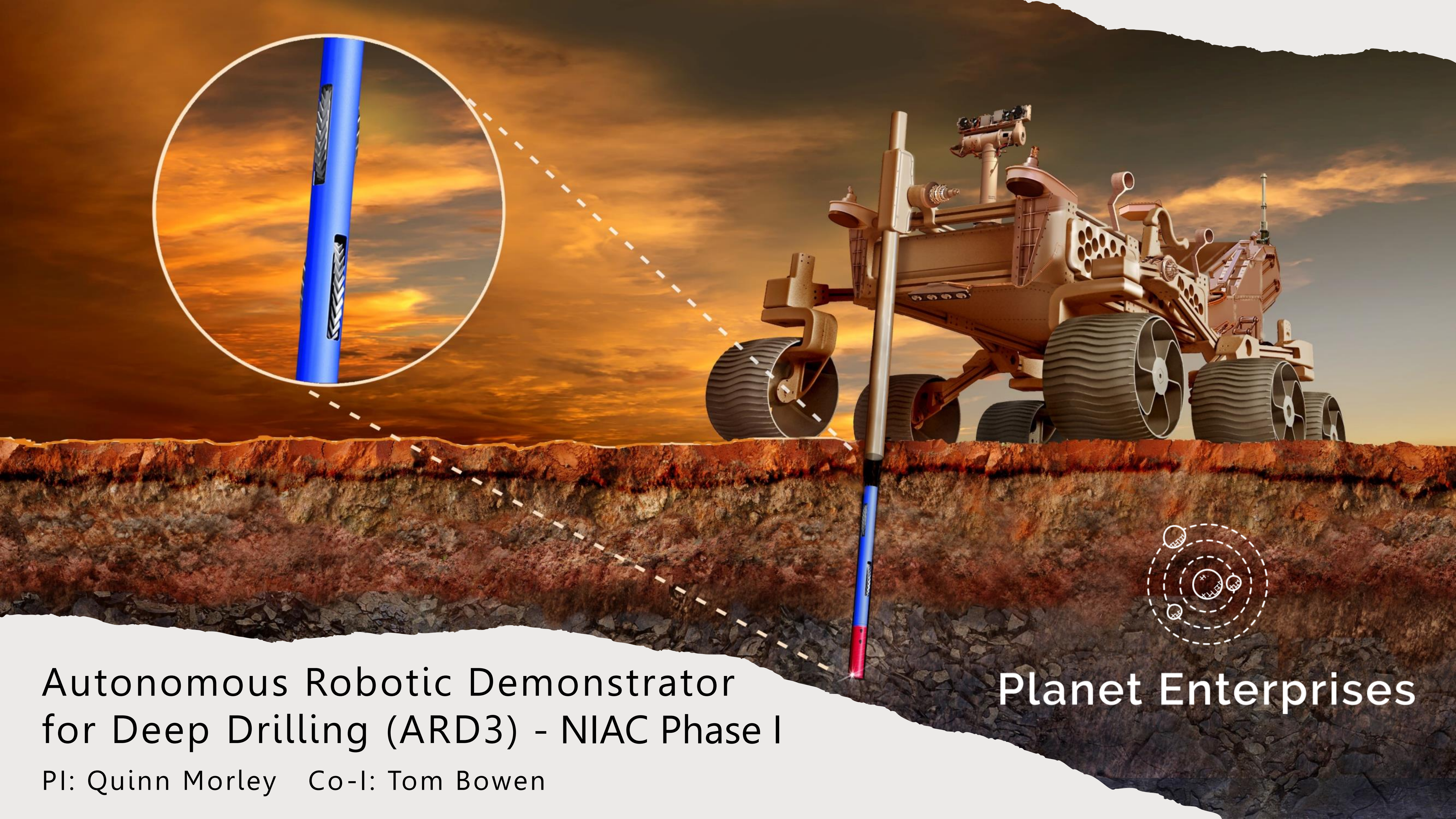


Autonomous Robotic Demonstrator for Deep Drilling (ARD3) - NIAC Phase I

PI: Quinn Morley   Co-I: Tom Bowen

Mission:

- Drill 50 m into the Mars South Polar Layered Deposits (SPLD)
- Analyze and cache ice cores

Extended Mission Goal:

- 1.5 km, subglacial lake access

Innovation:

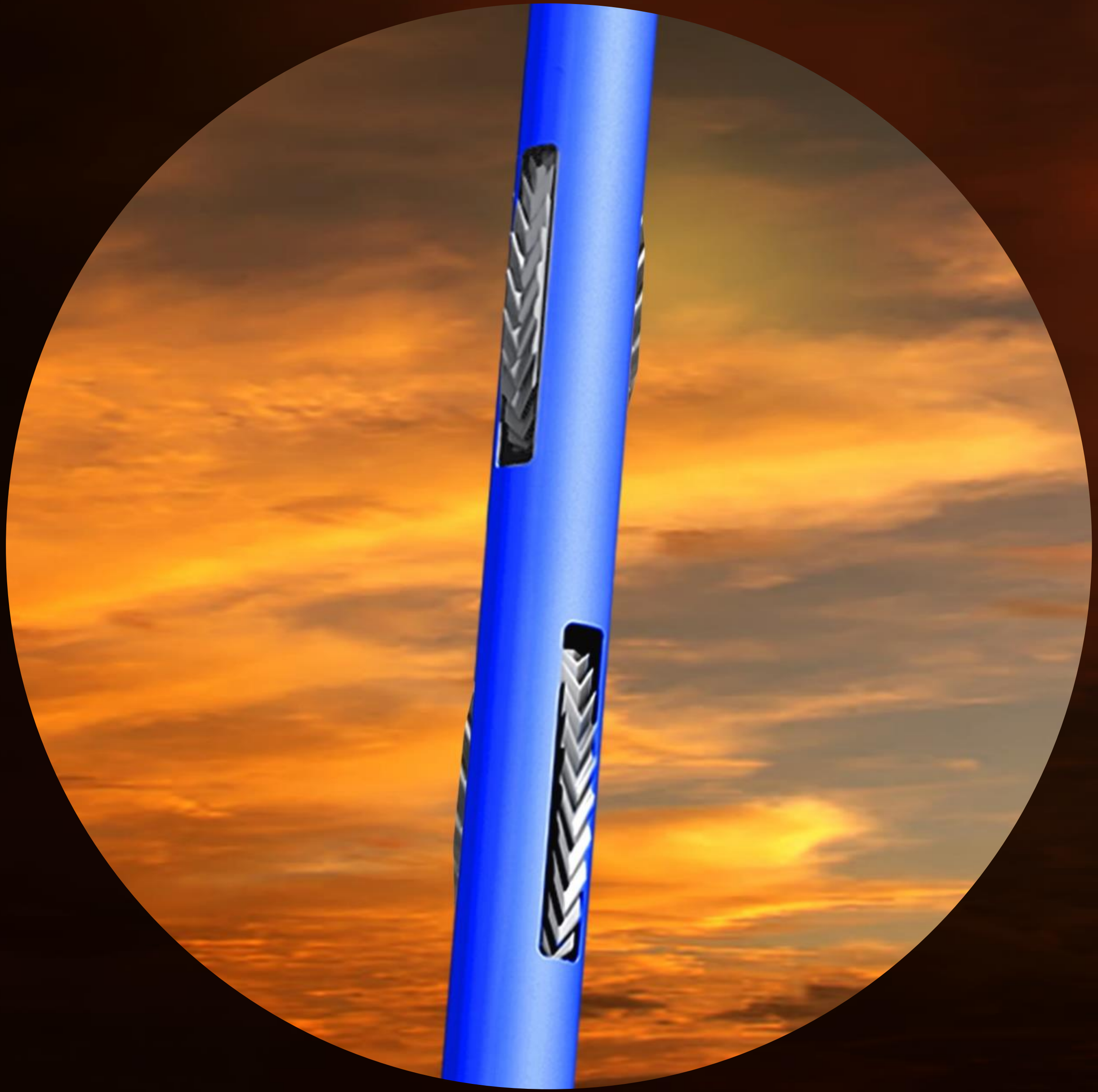
- Self-driving robots (borebots) “drive” up and down the borehole

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

PI: Quinn Morley Co-I: Tom Bowen

Planet Enterprises

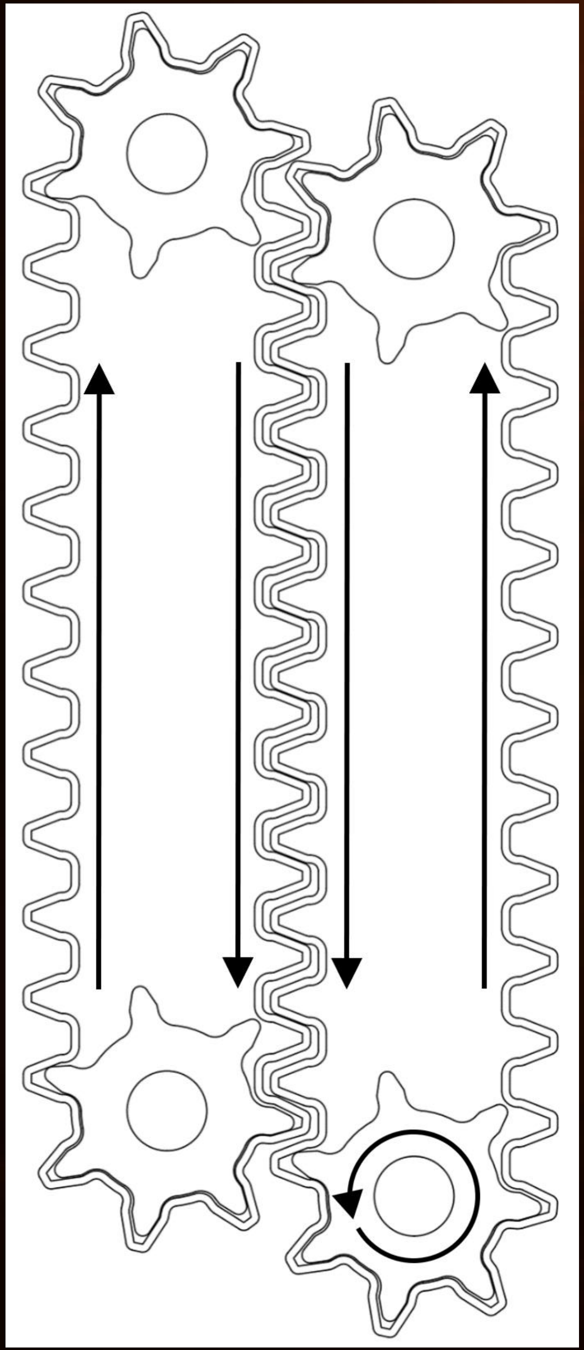
Borebot Drivetrain



- 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



Borebot Drivetrain   64 mm bore dia.

- Pressure on the wall of the hole can be varied in design, but we only have a few options for changing this in-situ

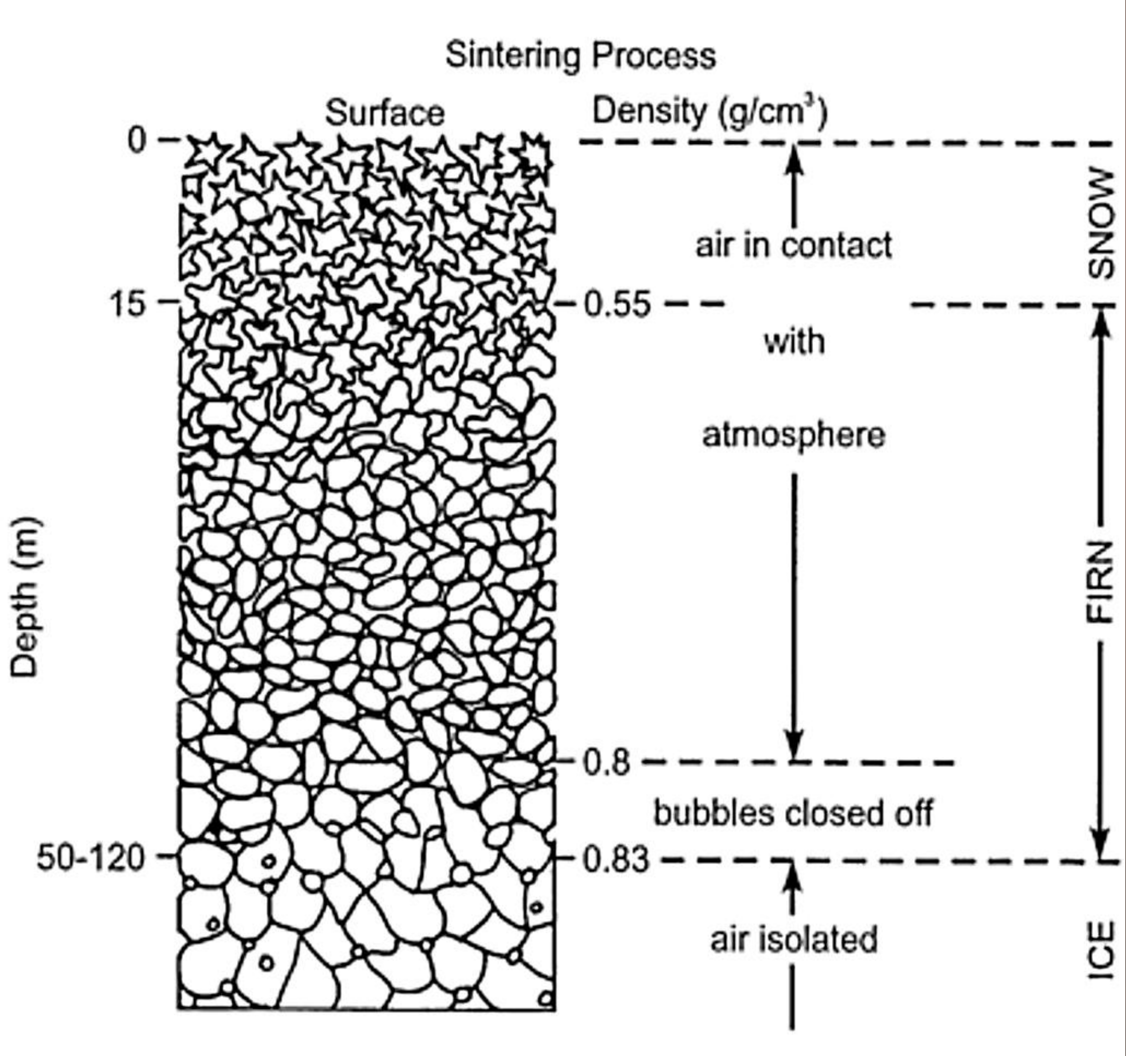
- Depending on the nature of the substrate, there is a potential for dramatic and quick erosion of the borehole wall
  - This is the main motivator for our characterization efforts

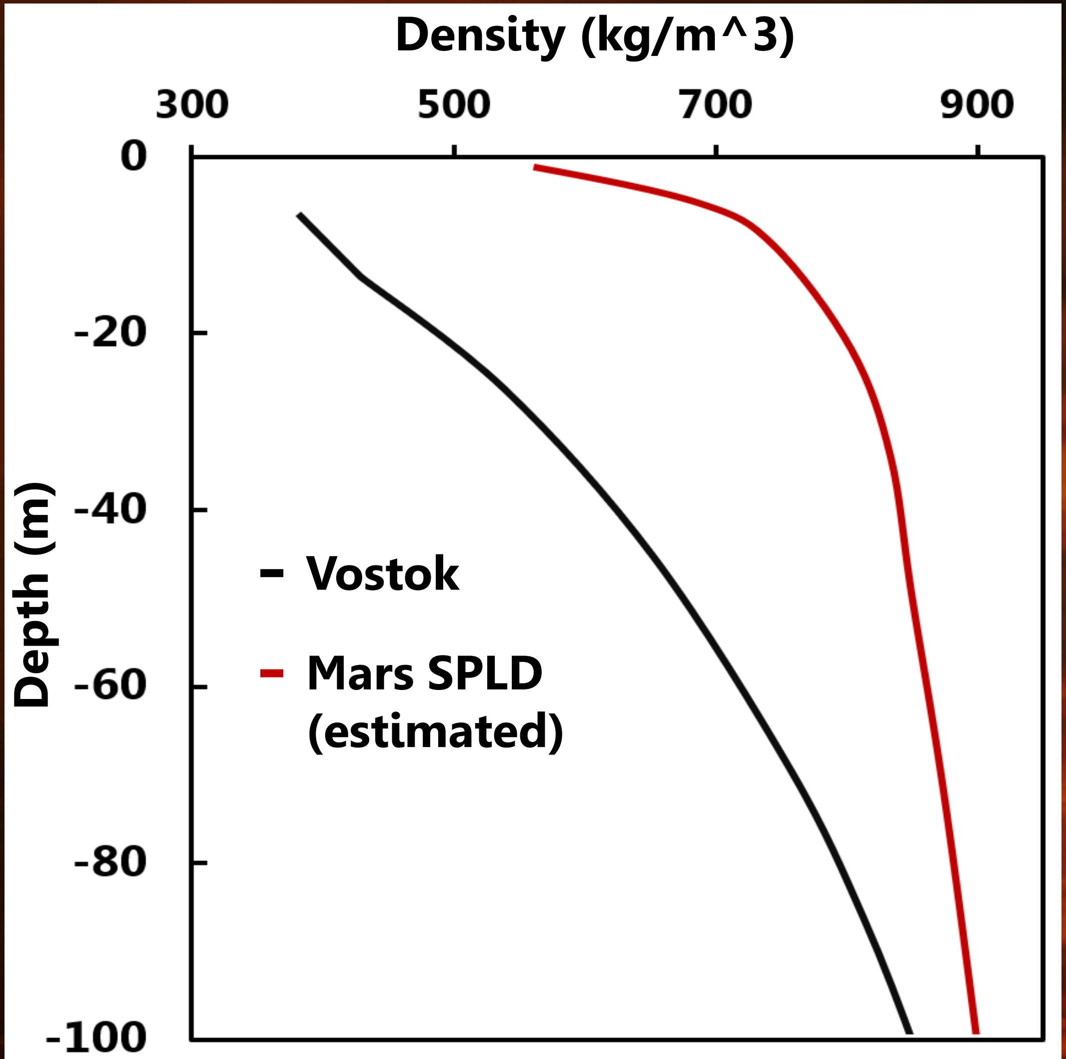
- Drilling challenges relating to the substrate are also significant, but are easier to mitigate

SPLD Characterization Summary

- Bar-Cohen, Y. and Zacny, K. (2020), *Advances in Extraterrestrial Drilling* claim "Ice on Mars, Europa, and Enceladus is very cold, while the gravity in all cases is low. Both of these aspects create an extremely stable borehole that would remain open for years." (p. 178)
- Arthern et. al (1999) "Densification of Water Ice…" is very influential. They claim that vapor-exchange processes dominate during formation, as opposed to sintering, doi.org/10.1006/icar.1999.6308
  - Work on the Mars Polar Lander landing site selection noted that the Arthern model agreed with remote sensing data, and the sintering vs. depth models did not
    - Vasavada, et. al (2000), "Surface properties of Mars' polar layered deposits and polar landing sites"
  - Sintering may be a driver at depth, ref. Molaro et. al, (2018), doi.org/10.1029/2018JE005773
- Zuber, M. et. al, (2007) claim SPLD is "clean" water ice with 15% dust, however the unit is examined as a whole (on average), doi:10.1126/science.1146995
- Li, J. et. al (2012) claim that there is a large variation in density in the SPLD; low density is caused by porosity; high density by included dust, doi.org/10.1029/2011JE003937

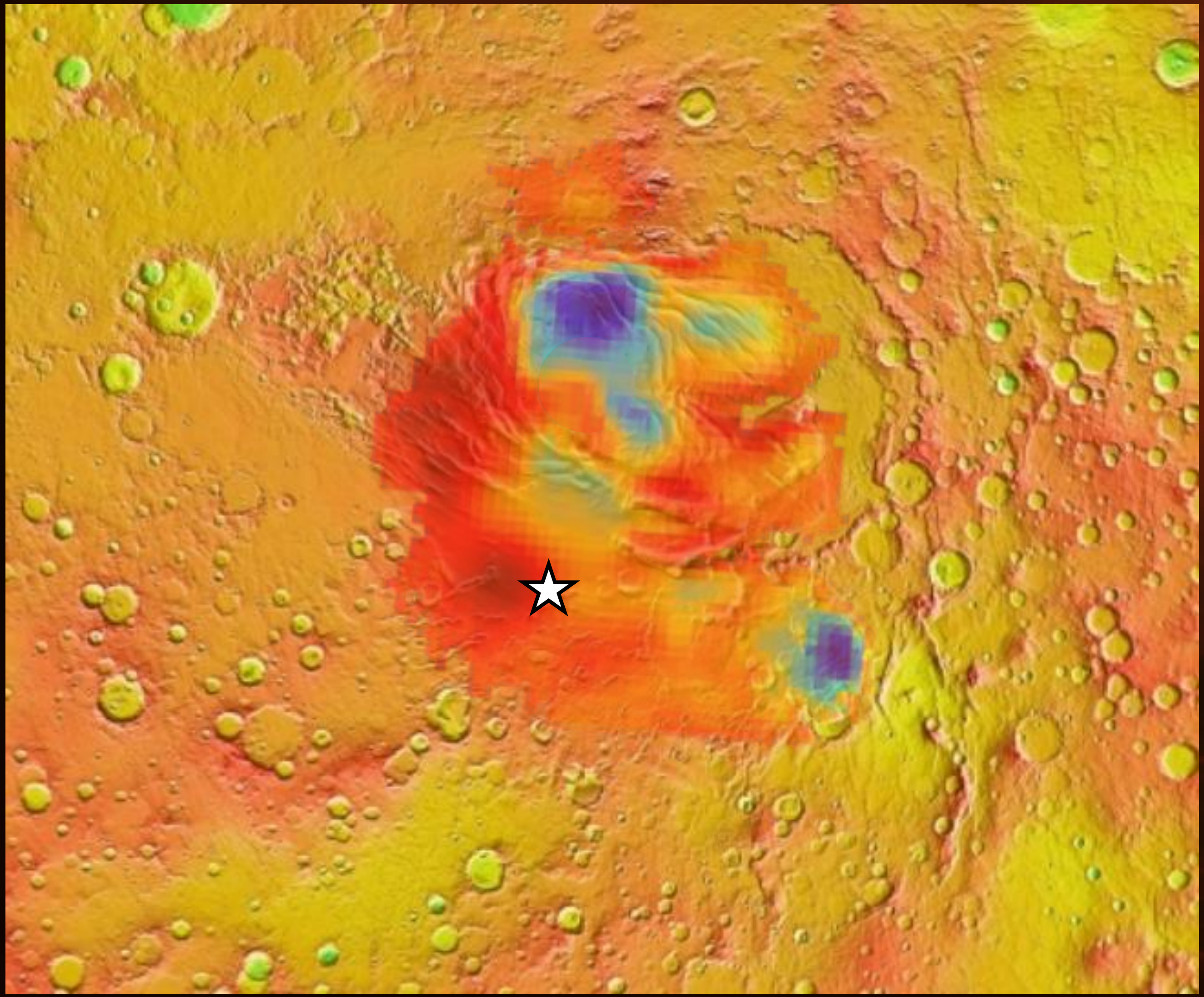
SPLD Characterization Summary





Left: Glacier formation (Earth). "Ice structures, patterns, and processes," Bartels-Rausch et. al, 2012.
Right: PI's notion of density vs. depth, modified from Figure 2-3, "The Physics of Glaciers," Cuffey.

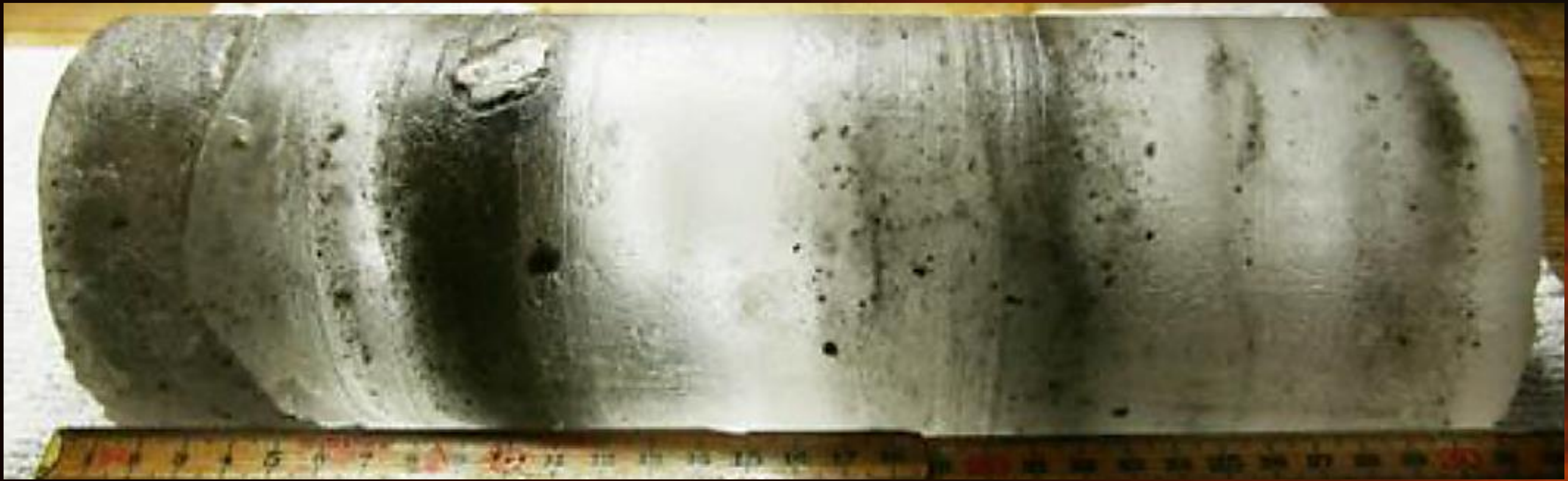
Potential Landing Site: -80.835° 190.652°



Density at Potential Landing Site: 1200 $kg/m^3 \pm 100$ kg/m^3

uahirise.org/ESP_067367_0990

SPLD Characterization Summary

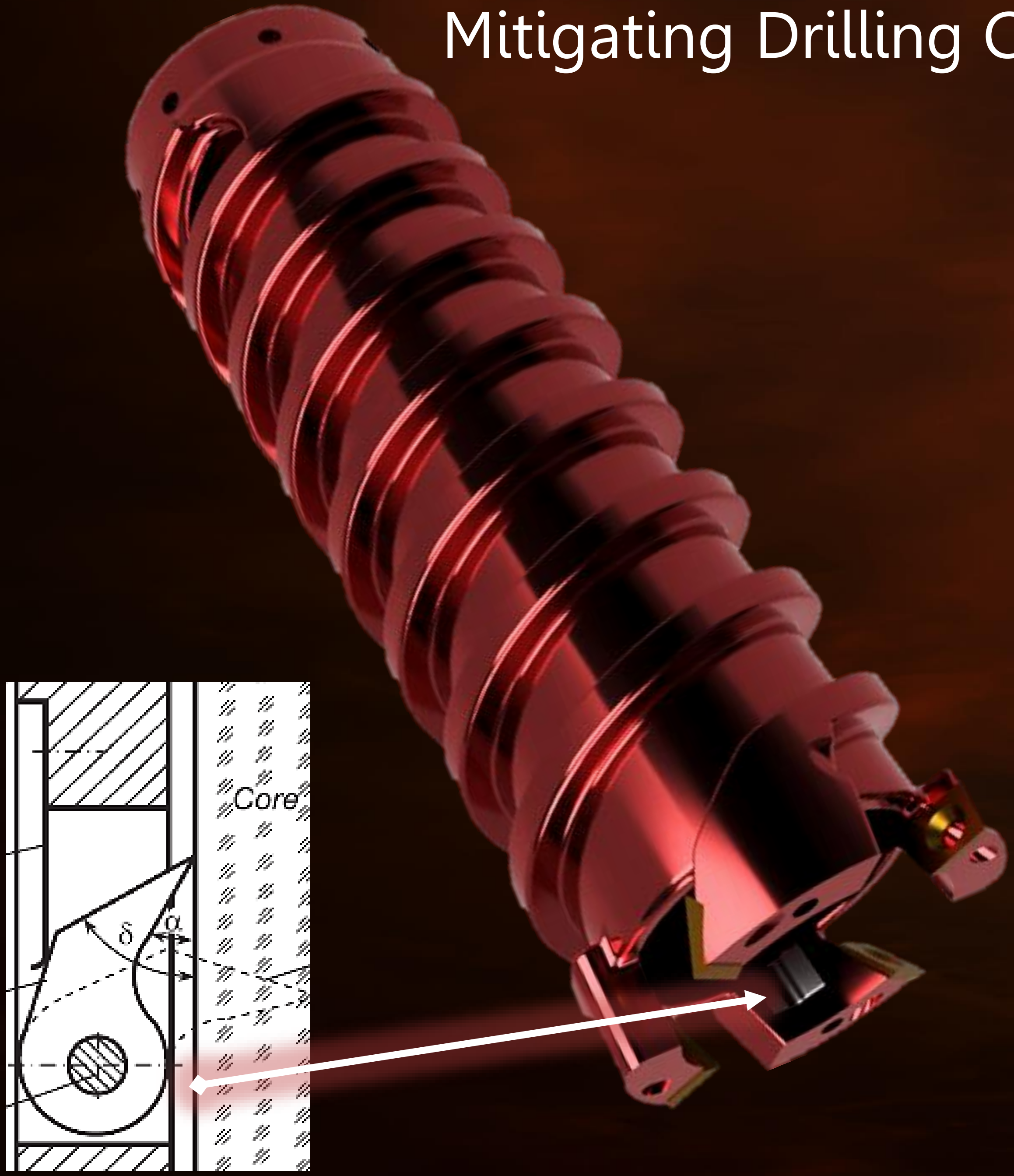


Ice core taken from the bottom of the NEEM borehole in Greenland

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]”

Mitigating Drilling Challenges – Hard, Clean Ice



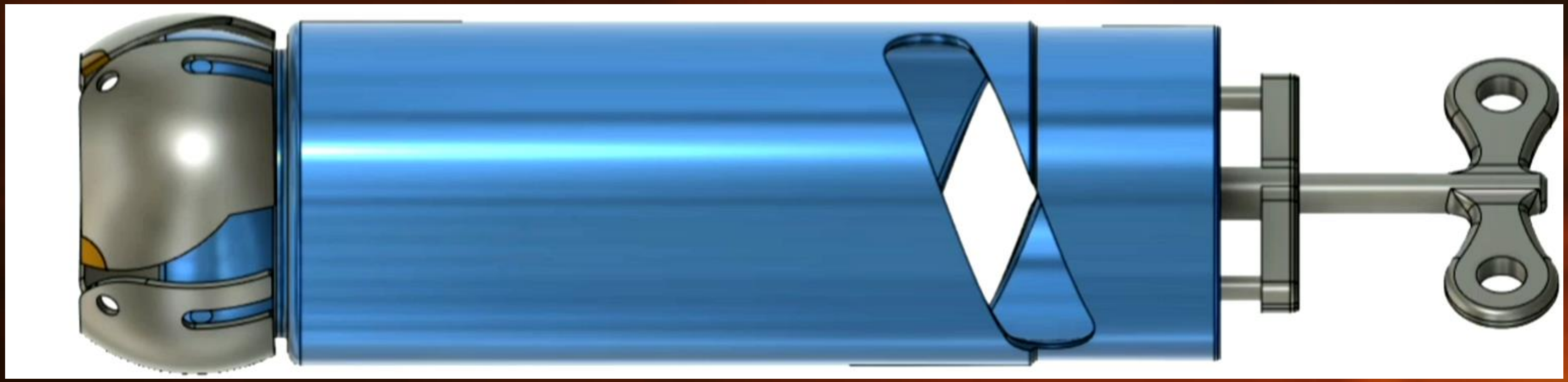
- Drilling hard, very cold, clean ice is mainly an exercise in chip clearing
- Increased system reliability overall
- Mechanically simpler drill head
- Cores can easily be broken off with a variety of “core dogs,” which cause the core to fracture at the desired location, and retain it for transport
- This would provide us with a slightly larger core, lower power consumption, more room for chip clearing

Mitigating Drilling Challenges – Crumbly Ice

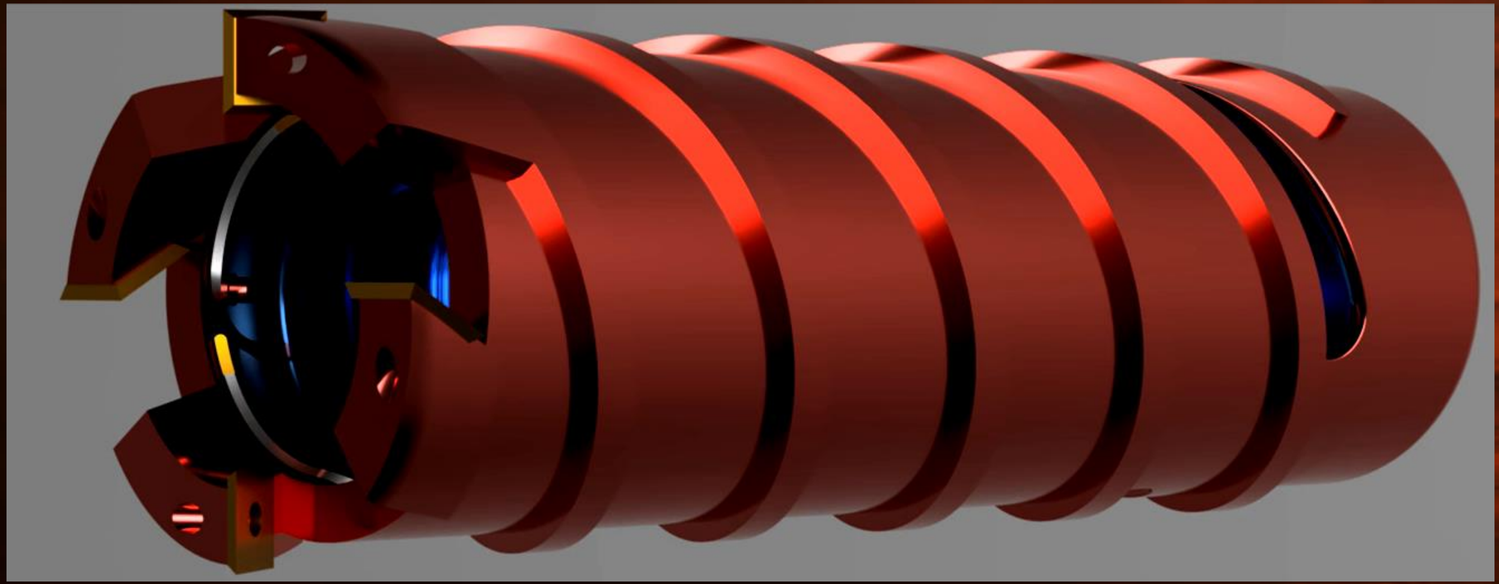
- This innovation enables reliable capture of crumbly/non-cohesive ice cores
- Carbide teeth are brazed onto a steel-bladed spherical iris
  - Low annular profile, can take a 40 mm dia. core
  - Larger diameter after throat (room for chips)
- The main drill motor is used to actuate the iris via a clever 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
- Two video animations on next slide

Mitigating Drilling Challenges – Iris Closure Animation

Use URLs to download .mp4 files if viewing a PDF



https://git.io/JsPov



https://git.io/JsKah

Mitigating Drilling Challenges – Automation

Continuous autonomous core drilling with a dozen robots operating sequentially completely changes the trade space:

- Time for core/chip removal, drill cleaning, and servicing is low-impact and can take place in dedicated bays
- Removal rates are less important, efficiency more so
  - Penetration rates as low as 15 cm/hr, targeted power < 15 W
- Chip carrying is "free" – ticket paid by the core
  - Tripping to the surface is a science goal, not an inconvenience
- Total trip time at max depth, including drilling: 3.5 hrs
  - This low speed still allows for a 4-year nominal extended mission, culminating in subglacial lake access (1.5 km depth)
  - Target component lifespans to support 10,000 cycles / 10 years
  - Driving speed range still under preliminary review

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 for an ice "plug" in order to prevent breakthrough (see below), and developed a penetrator probe instrument to perform the final subglacial access and extract a liquid water sample.

Required ice thickness to prevent breakthrough:

$\Delta P = P_{H_2O} - P_{atm} \quad \rightarrow \quad \Delta P \approx P_{H_2O}$ on Mars for dry drilling

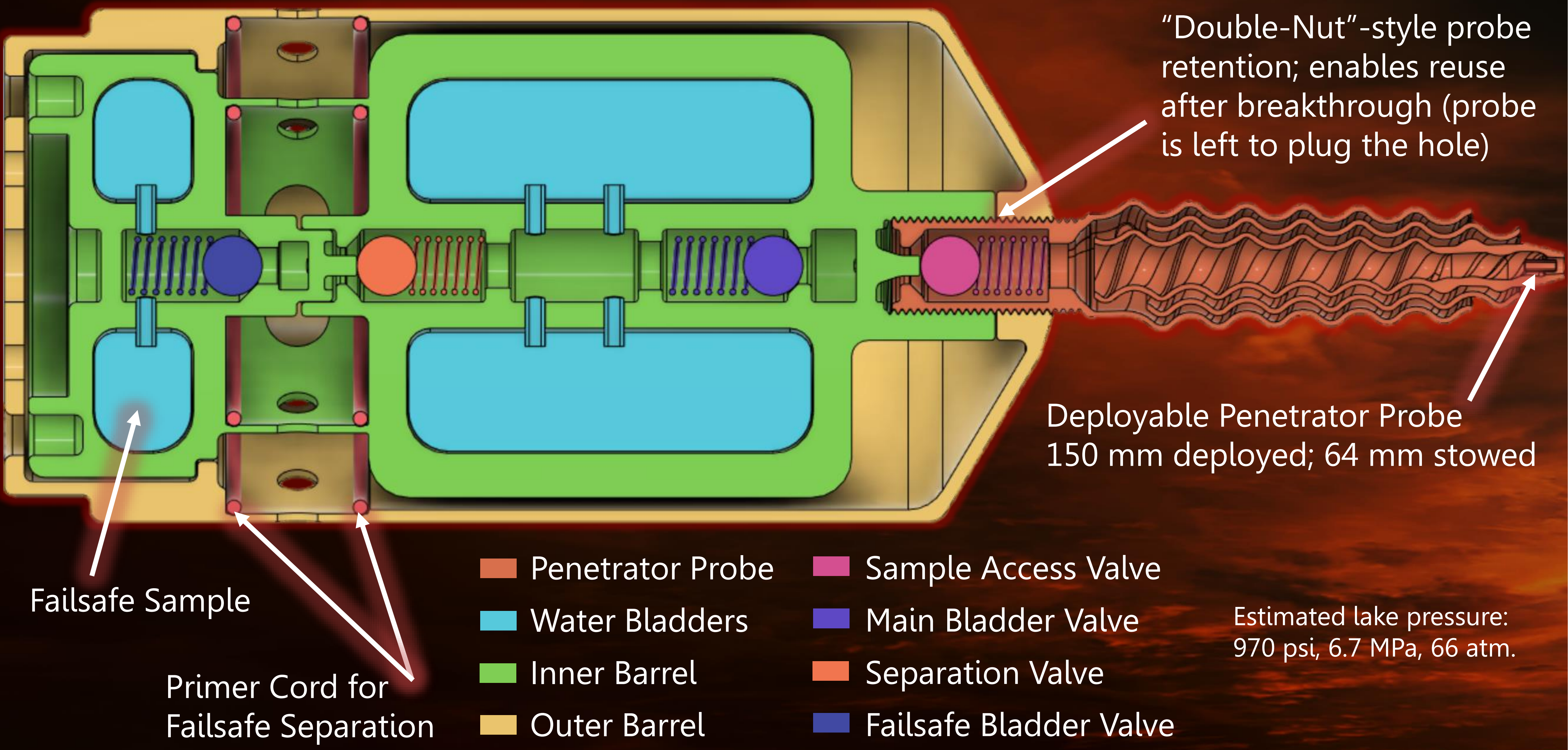
Shear Strength S for water ice at 100 K: $\mathbf{3.0\ MPa}$ (conservative)

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

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

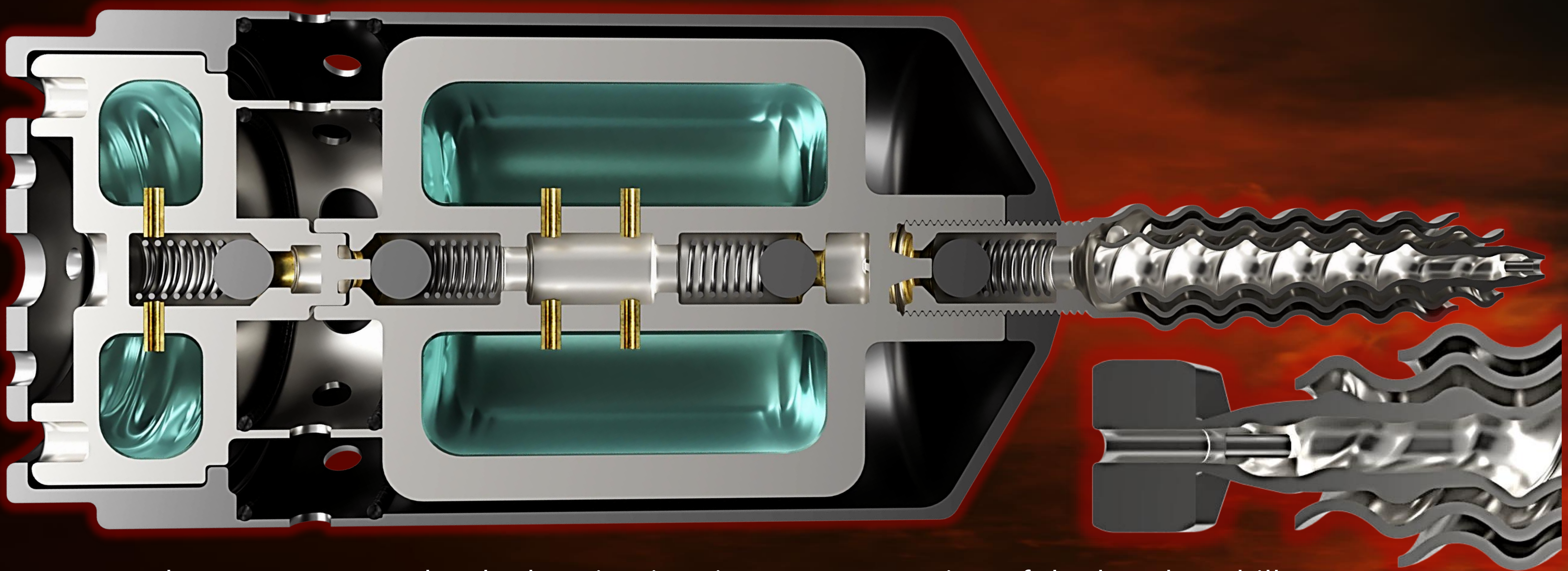
$$t = \frac{\left(1200 \frac{kg}{m^3} \cdot 3.71 \frac{m}{s^2} \cdot 1{,}500\ m\right)(0.064\ m)}{4(3 \cdot 10^6\ Pa)} = \boxed{\mathbf{0.036\ m}}$$

Sampling Liquid Water on Another World



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

Please Contact Us!

- We are still looking for feedback on the SPLD stratigraphy
- We are aware that future SPLD characterization efforts are already in development, but these may not be focusing on the sort of qualitative traits we need to understand in order to support deep drilling activities
- Humans are unlikely to operate in polar regions, so autonomous deep drilling is the most logical path forward for SPLD ground operations
- Our 8-page NIAC white paper from is available at https://git.io/Js2bu

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