Systems Architecture for Nuclear Distillation of Water Ore and Regolith Mining (SANDWORM)

Brad Blair
OrbChem LLC

6/9/22

Presented at the 2022 Space Resources Roundtable

Systems Architecture for Nuclear Distillation of Water Ore and Regolith Mining (SANDWORM) – *quad chart from a **failed** 2021 NIAC StepA*

innovation

- Continuous polar ice miner and nuclear thermoelectric autoseparator
- Leverages industrial combined heat & power (CHP) know-how to optimize thermal, electrical and chemical separation of lunar polar resources
- SANDWORMs crawl through lunar regolith, leaving piles of enriched and depleted material in their trail
- Later systems can selectively collect stored, enriched product streams (ore concentrate) as market demand evolves to meet supply
- Architecture is scalable (watt-level mini RTGs to KW and MW nuclear reactors) and modular (like a train with switchable caboose elements, enabling refinery upgrades)

technical approach

- Combine three worm "segments" or unit operations: granular material miner, volatile separator, water condenser / bricklayer
- Optimize thermal and pressure requirements across the front-end (low-T, low-P), the middle (high-T, high-P volatile separation and product refining), and the back-end (mid-T, mid-P condensation)
- Utilize the thermal properties of lunar polar soil to cool a nuclear reactor and condense products
- Harness the benefits of nuclear power for continuous polar operations
- Combines and balances the best features of mining and nuclear power

potential & benefits

Establish scientific baseline for lunar polar regions
- Front end captures forward looking pristine state measurements
- Provides a rich data set to lunar scientists and economic geologists

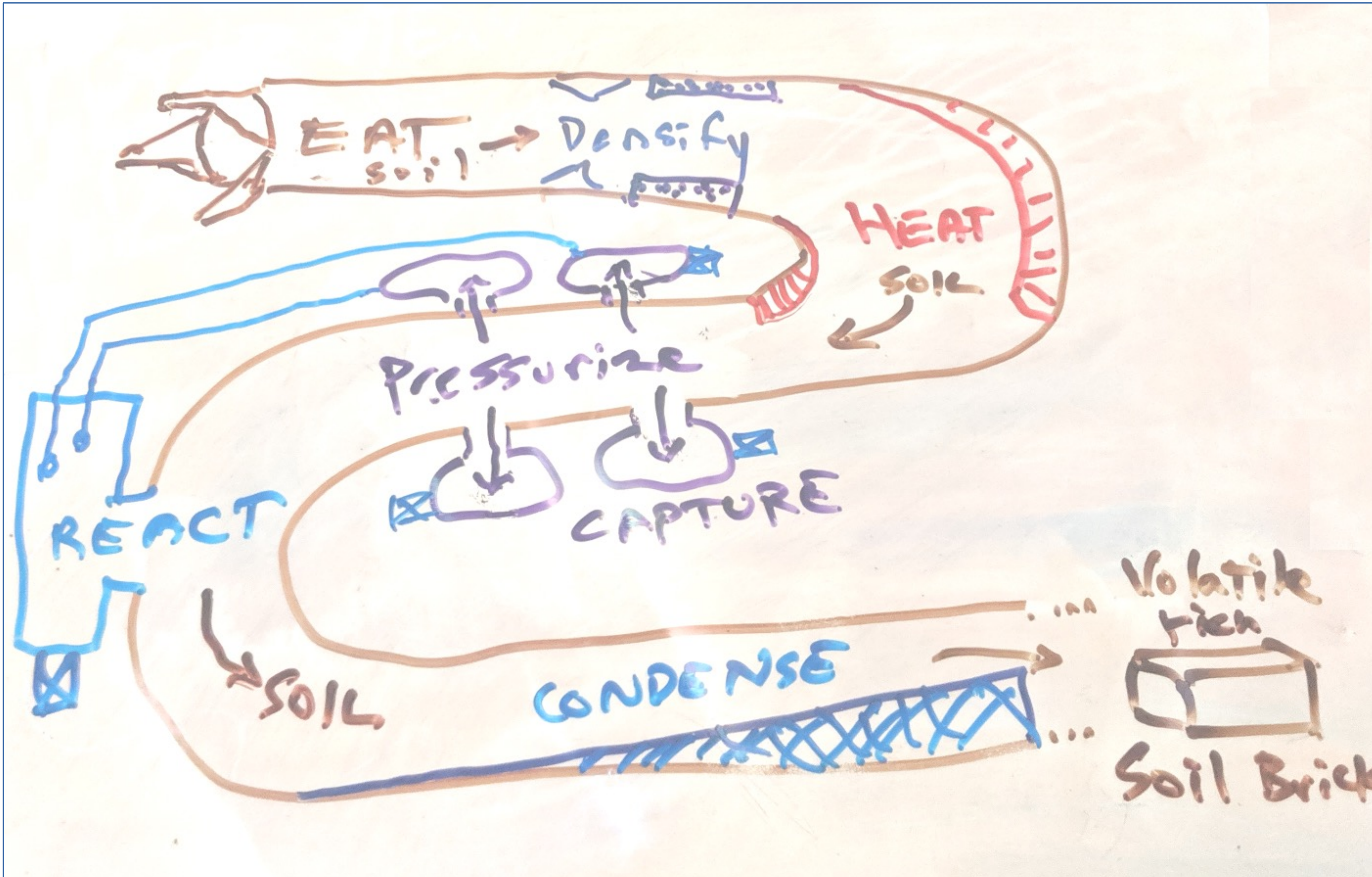
Product assay and verification is as easy as counting bricks

Volatile products like water ice, solid NH3 and O2 can be shaped into the form of stackable bricks for ease of later handling and collection

Enhances the polar environment for later development
- Leaves a clear track to follow by other equipment (auto roadbuilder mode with potential for conductive and fluid paths)
- Strengthens the roadway (can stabilize crater wall slope hazards)
- Surface and subsurface modes are possible (end of mission it could dive deep for unique scientific measurement opportunity)
- Downstream equipment could be configured to run through the same track twice, enhancing and simplifying refining options
- Surface enhancements could help recapture lander volatiles

evaluation notes

Patent Pending - PPA Drawing



“Thank You” ***Outer Space IP***

(Patent Agents with ISRU Specialization)

https://outerspaceip.com/

- OrbChem would like to shout out a big “high five” to OSIP (Flat Fee, Affordable Patent Services)
- Patenting your Lunar IP can be as easy as saying *“OSIP is our TABA* provider...”* and adding an allowable cost line item to your SBIR (or other NASA Grant) proposal…

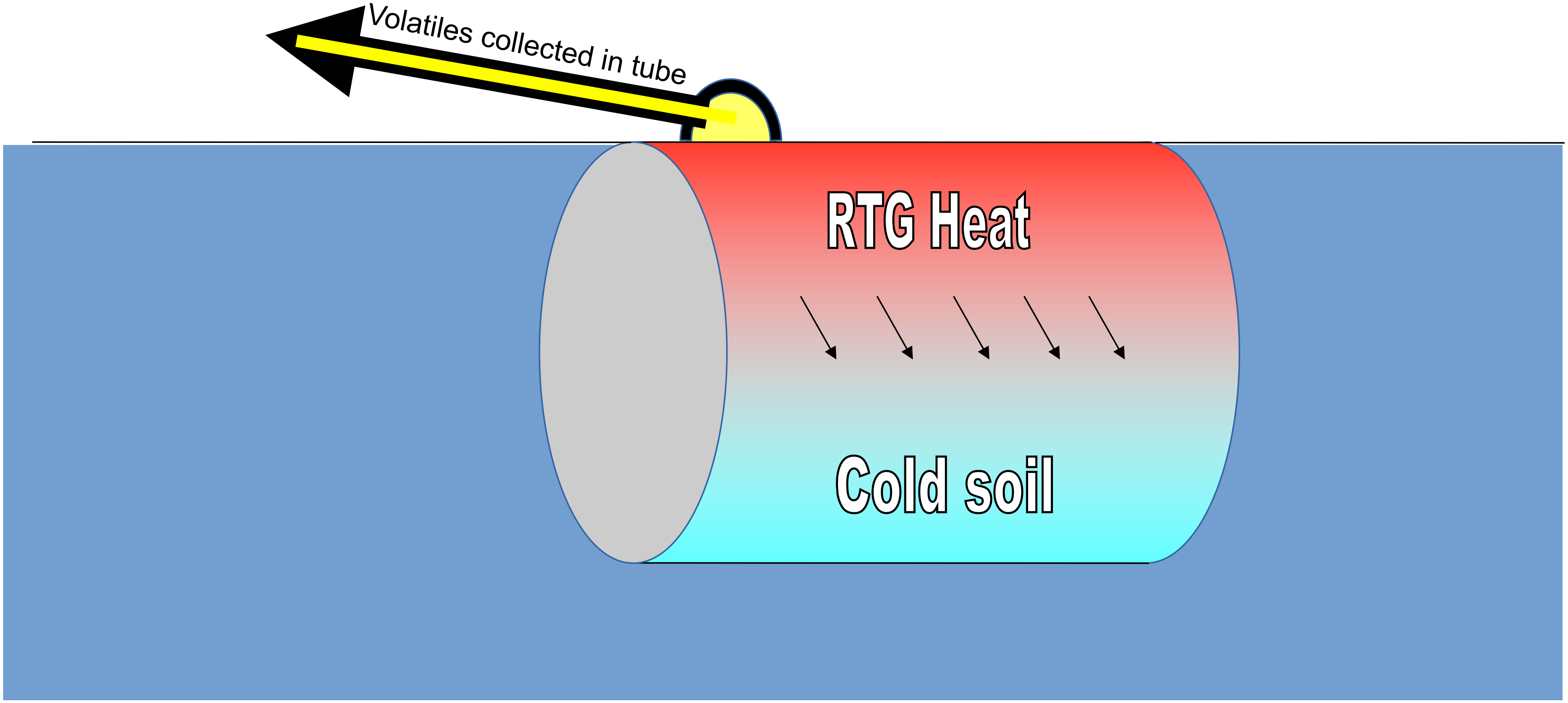
** TABA = Technical & Business Assistance - funding that is available to augment many NASA and DoD Grants*

SANDWORM Functional Decomposition

- What happens when you put a hot shape in a cold place?
- Key **architectural features** include:
  - Design radioisotopic heat & electricity level in nearly any shape
  - Entrain cold regolith as a heat & volatile sink at multiple segment inlets
  - Multi-stage pressure and temperature regions using jamming forces
  - Continuous release of polar volatiles + transport through tubes
  - Select custom isotopes to specify gamma or X emission frequencies for near field continuous sensing of mineral and volatile fluorescence
- Drag behind any independent mobile system, or use dragline-type gantry crane to operate from a fixed deck (e.g., lander) to enable multi pass extraction and volatile concentration
- Radioisotope heat could potentially generate thermal expansion + gas for propulsion, enabling mechanism free mobility
- The lander body could be outfitted with volatile refining / purification, processing and fuel distribution systems

Thermal Devolatization System
(3D printed nonlinear RTG in arbitrary shape)

Drives volatiles toward condensation onto or into cold soil
(extract and create a segmented brick of concentrate)



Note: Choice of cylinder is intended to simply convey the concept and is not implied as a design choice

Key Features of SANDWORMs

https://www.istockphoto.com/photos/sand-worm

- Scalability is enabled by RTG / CAB power architecture up to full nuclear reactors
- Small versions can be 'launched' early to test and prove the technology
- Adjustable size front orifice
- Engineered sources of heat and radiation band
- Ingestable cold volatile and heat sink
- Volatile capture, separation and chemical processing options
- Extrusion channel reinforcement and emplacement of conductive lines

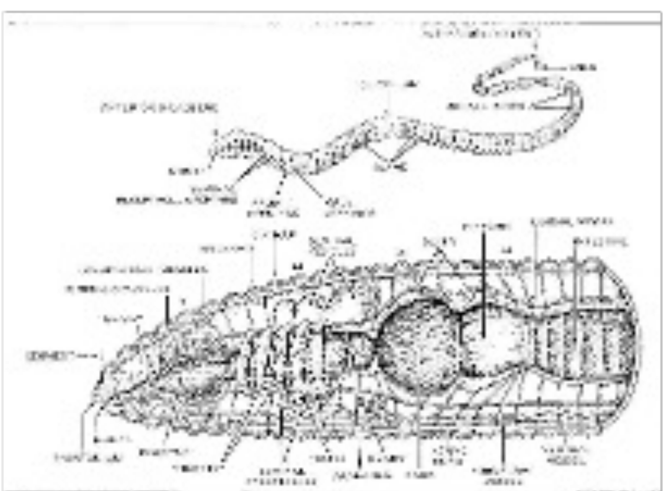
Segment Differentiation

https://scribblenauts.fandom.com/wiki/Sand_worm

https://i.redd.it/s338nvf2idq51.jpg

- Multiple “train car” segments can add functionality
- Add “buoyant” segments that enable system to self-excavate if buried in crater wall avalanche
- Propulsion segments could steer or vector ‘waste’ volatiles combined with thermal expansion

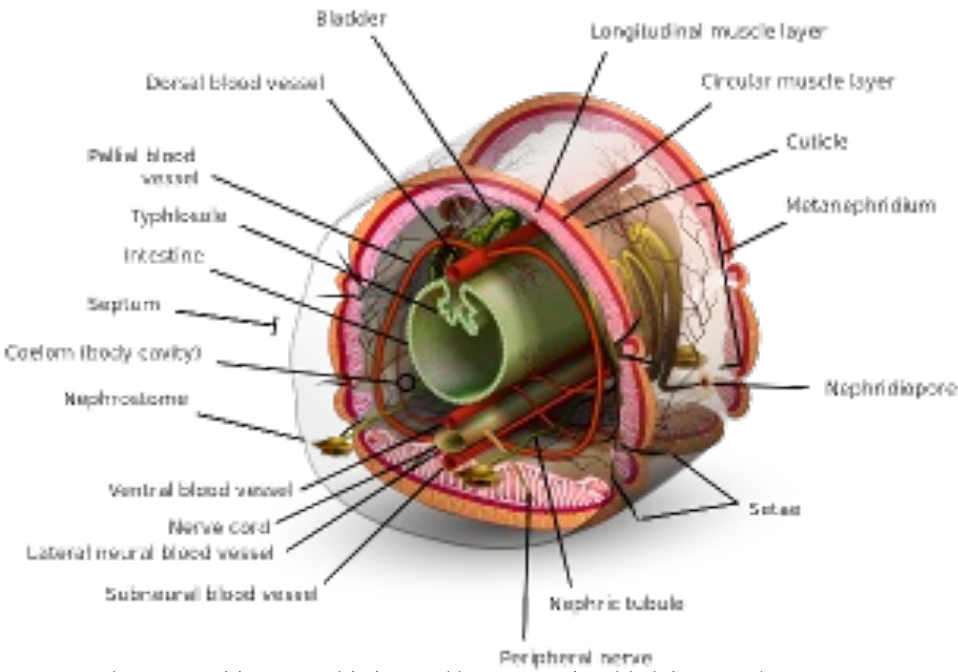
Lessons from Nature



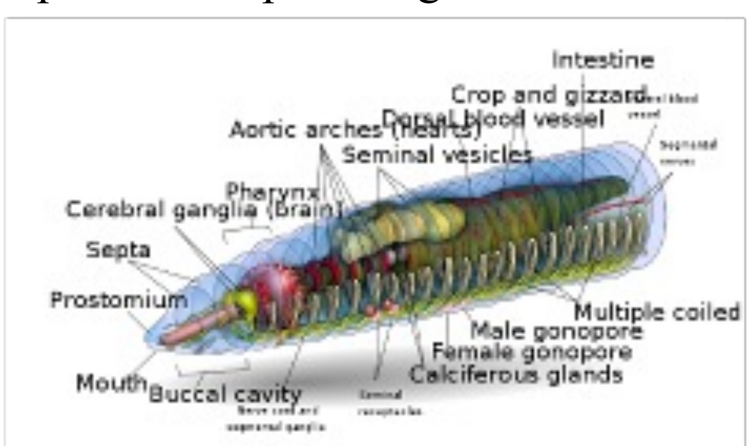
- System morphology can adopt features from the natural world, including options for mobility, chemical reaction chambers, ingestion and waste management
- Droppings or tailings can be 'enhanced' with sequestered byproduct volatiles, enabling long-term value creation

http://pages.erau.edu/~andrewsa/sci_fi_projects_spring_2015/Project_2/Finn_John/Dune%20project%20(2)/Dune%20project/Dune.html

Annelid Morphology



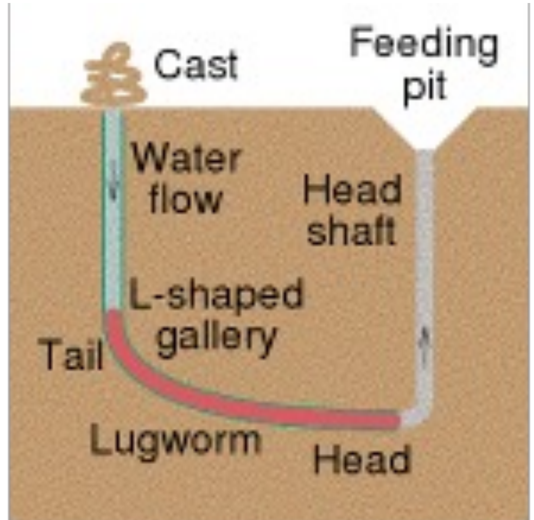
https://en.wikipedia.org/wiki/Earthworm



- Resource flow through sandworm will have many of the same functions as an earthworm
- Biology-inspired engineering systems design can identify opportunities and missing elements

Worm Castings (aka 'Ore Concentrate')

https://www.marinespecies.org/aphia.php?p=image&tid=129868&pic=427

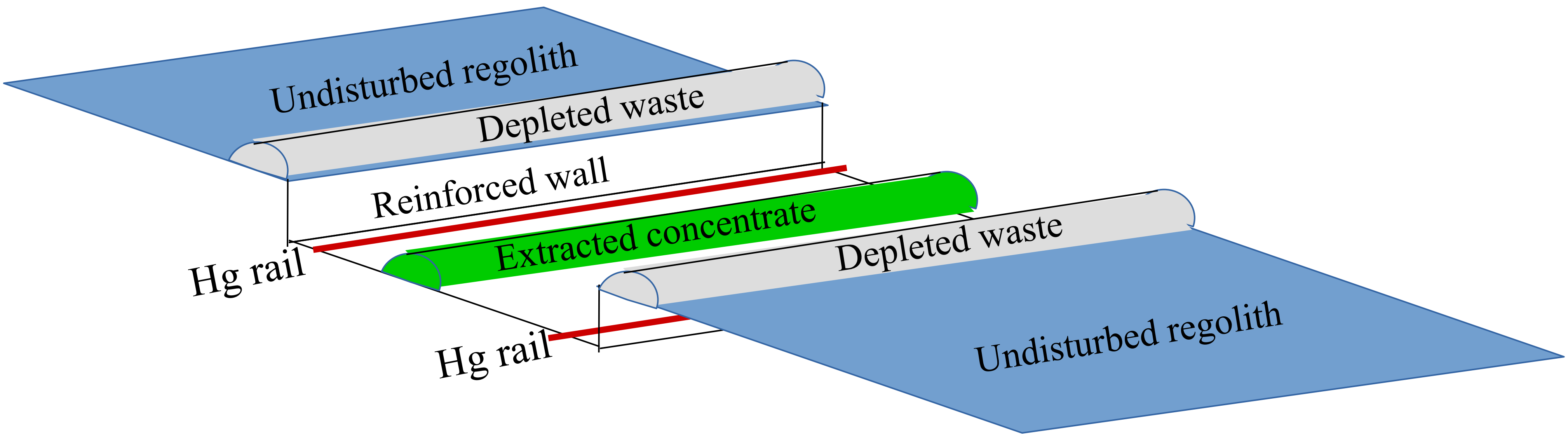


https://en.wikipedia.org/wiki/Lugworm

https://www.dreamstime.com/photos-images/lugworm-worm.html

- The Bow Lugworm (aka 'sandworm') leaves a visible trail of 'processed tailings' along many sandy coastlines
- Earthworm castings are considered *highly valuable* for agriculture
- Worm castings concentrate nutrients in an encasement, enhancing 'agricultural value' compared to the depleted soil they travel through
- This is a good analogy for a lunar SANDWORM – extracting & concentrating volatile ore that can be stored for later use

Channel Features can Store Value
(think of this as a reinforced roadway)



Science Applications of SANDWORM

- Continuous trench sampling of volatiles and other key minerals is possible with the SANDWORM architecture by design of a “ripper” blade with “heated” tip and variable depth
- Generates thermal output (devolatilization) as well as creating a volatile escape channel for continuous measurement of volatile inventory in selected polar regions
- Multiple custom radioisotopes can be specified for near field continuous geophysical exploration (*terms and conditions apply, including placement and type of sensors)
- The lessons learned by adding a trenching capability to a polar exploration rover would directly inform a future commercial SANDWORM design

https://www.ebay.com/itm/180933463051

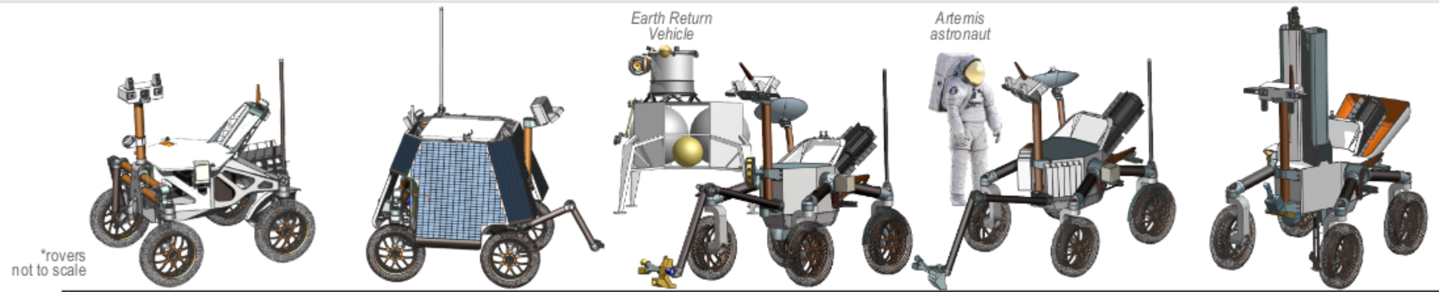
https://www.monticello.org/site/research-and-collections/moldboard-plow

Continuous trench sampling in mining

https://www.youtube.com/watch?v=s1Umh-5Yqyw

https://www.cmwgeosciences.com/geotechnical-services/site-investigation/trench-test-pit-sampling

http://test318.weebly.com/trenching-cuts-outcrop-sampling.html



LONG-RANGE LUNAR ROVER MISSION CONCEPTS

five rovers with a common design lineage

2023–2032 Planetary Science and Astrobiology Decadal Survey

Intrepid		Endurance		INSPIRE (In Situ Solar System Polar Ice Roving Explorer)
Intrepid (RTG) (baseline Intrepid)	Intrepid (Solar)	Endurance-R (R = robotic sample return)	Endurance-A (A = astronaut sample return)	
Pre-Decadal Planetary Mission Concept Study (PMCS)		Decadal Survey Mission Concept Study		
PI: Mark Robinson (ASU)		Science Champion: James Tuttle Keane (JPL) Deputy Science Champion: Sonia Tikoo (Stanford)		Science Champion: Jennifer Heldmann (NASA Ames)
		Study Lead: John Elliott (JPL)		

CONCEPT SUMMARY:

	Intrepid (RTG)	Intrepid (Solar)	Endurance-R	Endurance-A	INSPIRE
Description:	Long-range lunar rover for investigating six diverse geologic regions on the lunar nearside, to determine the evolution of lunar interior, characterize the diversity of styles of magmatism, and post emplacement modification of magmatic materials.		Long-range lunar rover for exploring, collecting, and returning samples and the largest and oldest impact basin on the Moon, South Pole–Aitken (SPA) basin, in order to answer critical questions about Solar System chronology and planetary evolution. Endurance-R delivers samples to a separately landed robotic Earth Return Vehicle.	Endurance-R delivers samples to a Artemis astronauts at the Moon's south pole	Long-range lunar rover for exploring the Moon's permanently shadowed regions (PSRs) to determine the origin, age, and evolution of lunar volatiles.
Landing Site:	Lunar nearside, Oceanus Procellarum (6.5°N, -58.9°E)		Lunar farside, Poincaré basin (57.2°S, 163.0°E)	Lunar farside, central South Pole–Aitken basin (57.9°S, -161.7°E)	Lunar south pole, Cabeus crater (84.7°S, -45.2°E)
Lunar Delivery:	Rover delivered by a CLPS lander (for comparison, VIPER a ~500-kg rover will be delivered by CLPS to the lunar south pole in 2022)				
Nominal Launch Date:	2030 (set by RTG availability for most options; launch dates for the Moon are extremely flexible)				
Nominal Traverse Distance:	1,800 km		1,750 km	2,000 km	750 km
Mission Duration:	4 years (including 1 year of margin)	7 years (including 1 year of margin)	4 years (including 1.3 years of margin)	4 years (including 1.1 years of margin)	3 years (including 1 year of margin)

	Intrepid (RTG)	Intrepid (Solar)	Endurance-R	Endurance-A	INSPIRE
Instruments:	Stereo cameras				
	Long-range camera (FarCam)				Near-IR spectrometer (NIRVSS)
	Visible/Near-IR point spectrometer				Neutron spectrometer
	Hand lens imager (HLI)				Mass spectrometer (MSolo)
	Alpha-particle X-ray spectrometer (APXS)				Ion and electron detector (IES)
	Magnetometer				Thermal-IR spectrometer (TIRS)
	Gamma-ray and neutron spectrometer (GRNS)				Mini Ground Penetrating Radar (Mini-GPR)
	Radiation monitor (ARMAS)				
	Electrostatic analyzer (ESA)				
	Laser retro-reflector (LRR)				

IN situ Solar system Polar Ice Roving Explorer (INSPIRE)

J Heldmann, team lead - 2022 Decadal Paper (200p.)

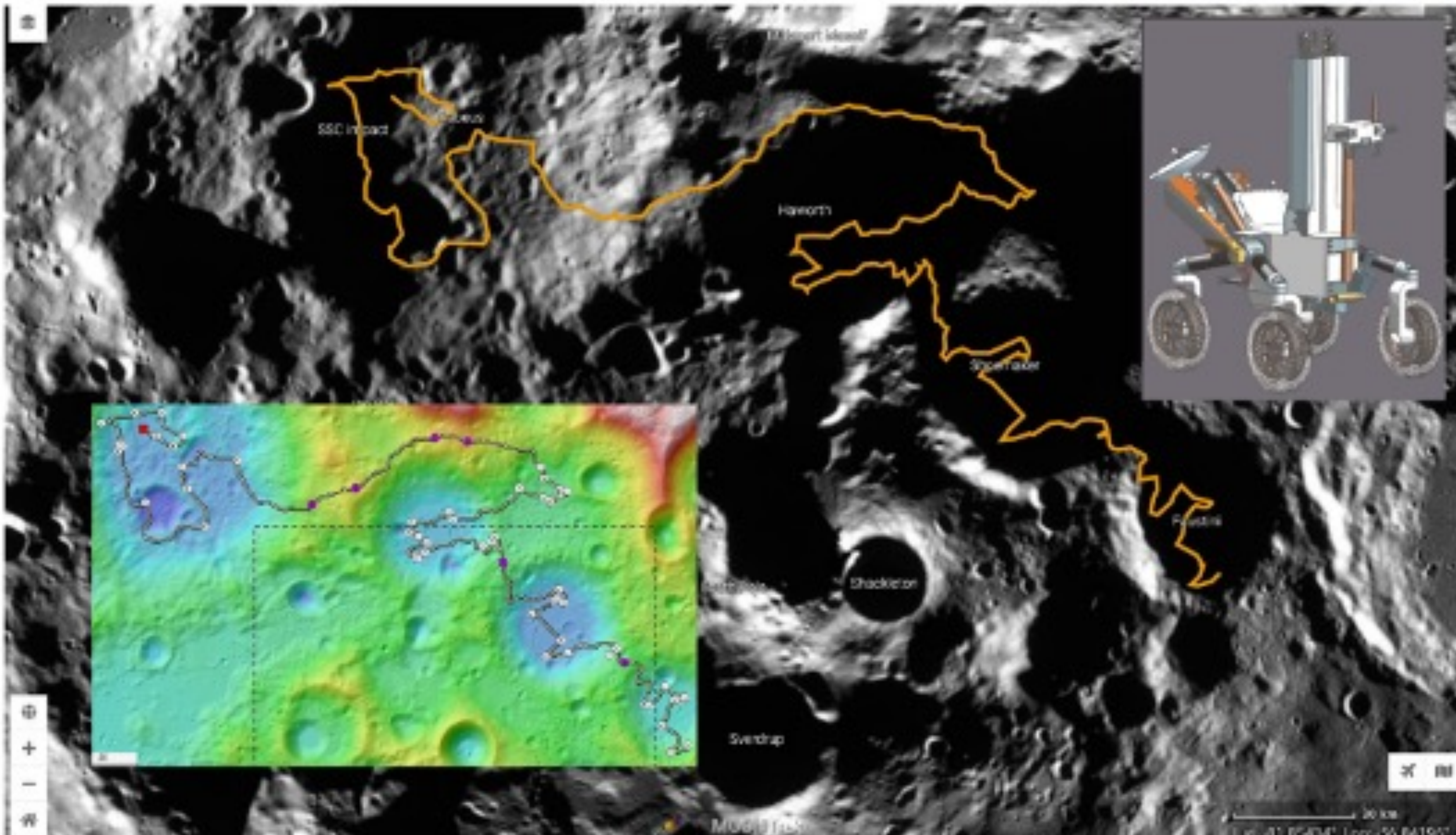
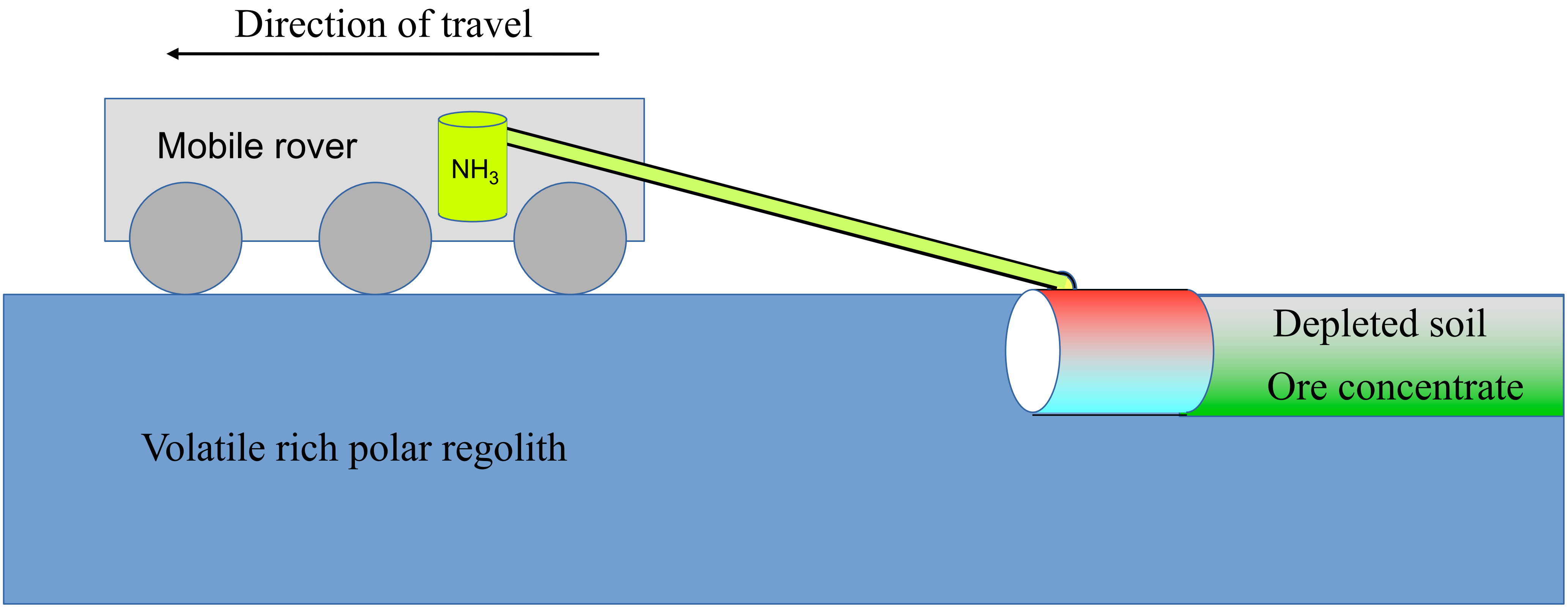


Figure K-1a. INSPIRE Traverse Path.

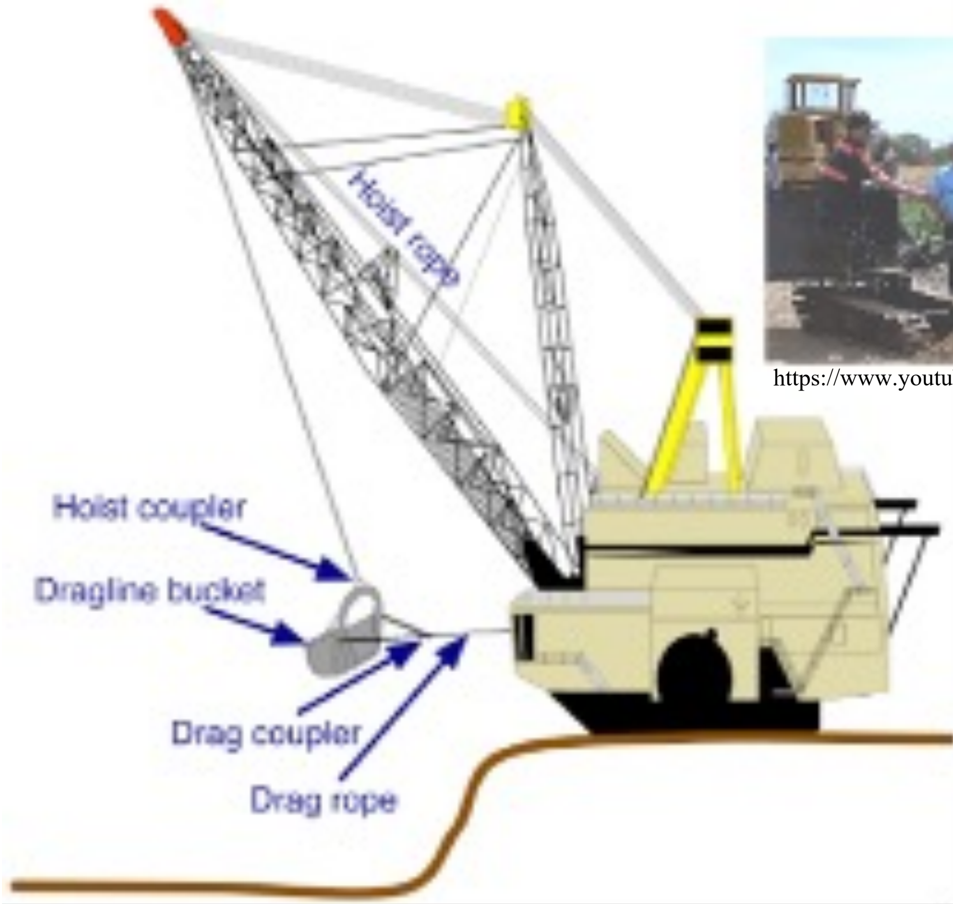
Mining Systems Design

- An early surface mining prototype could test a SANDWORM segment by dragging an engineered shape behind a rover
- A lander-based option could be adapted from dragline or slusher design
- The heated bucket (shown in a cylinder configuration for simplicity) could validate key features needed to fully specify and design a self-contained, independently powered and actuated surface & underground mining system
- Design details for mobility, science and mining are *highly dependent on geotechnical conditions* - an unknown with high uncertainty that is under scientific debate (note: measurements will settle this argument)

Test of Towed SANDWORM Segment



Dragline Excavator / Lunar Slusher

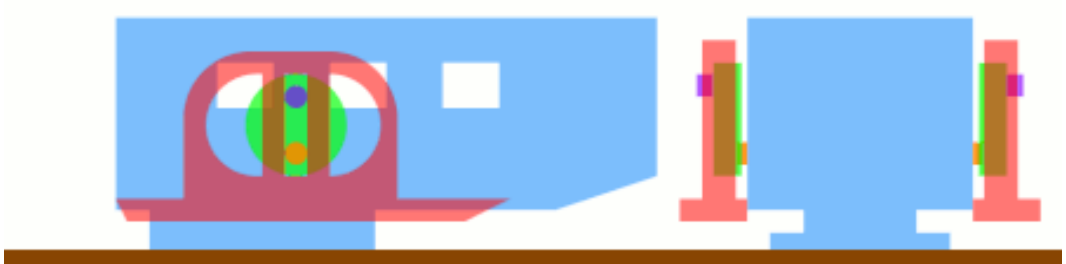


https://www.youtube.com/watch?v=A9ADBzLNDlI

https://www.couriermail.com.au/news/queensland/mackay/business/bucket-weighing-90-tonnes-finds-its-home-at-curragh-mine/news-story/5237def902e7500fac4925c7c3004a9c

https://en.wikipedia.org/wiki/Dragline_excavator

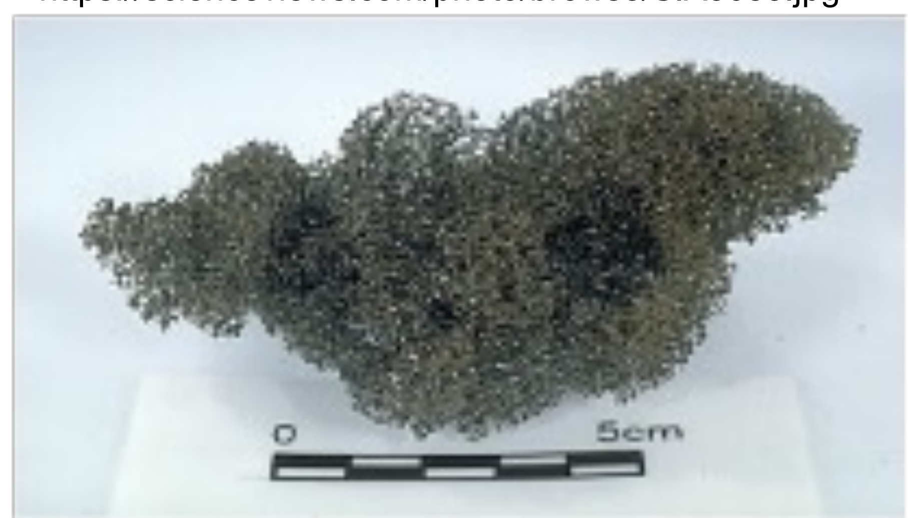
Richard Gertsch "A Baseline Lunar Mine" NASA SP509 V3 p.96



High Strength, Low Density Lunar Polar Soil Analog - Reticulite

https://www.researchgate.net/figure/Various-images-of-reticulite-The-upper-left-image-shows-a-deposit-of-reticulite_fig36_50435875

https://scienceviews.com/photo/browse/SIA3683.jpg



http://sci.sdsu.edu/how_volcanoes_work/Thumblinks/Reticulite_page.html

Low Cohesion Lunar Polar Soil Analog

http://soilquake.net/references/sandboil.pdf

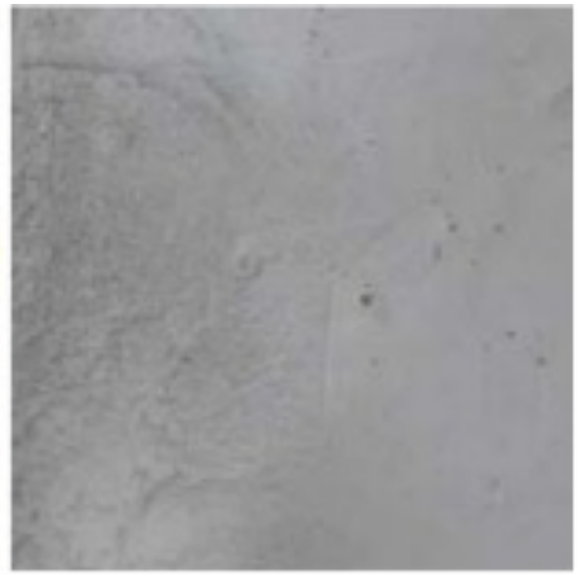
https://giphy.com/explore/dakar-rally

https://en.wikipedia.org/wiki/Sand_boil

https://tenor.com/search/dakar-gifs

Boiling in Lunar Regolith Simulant

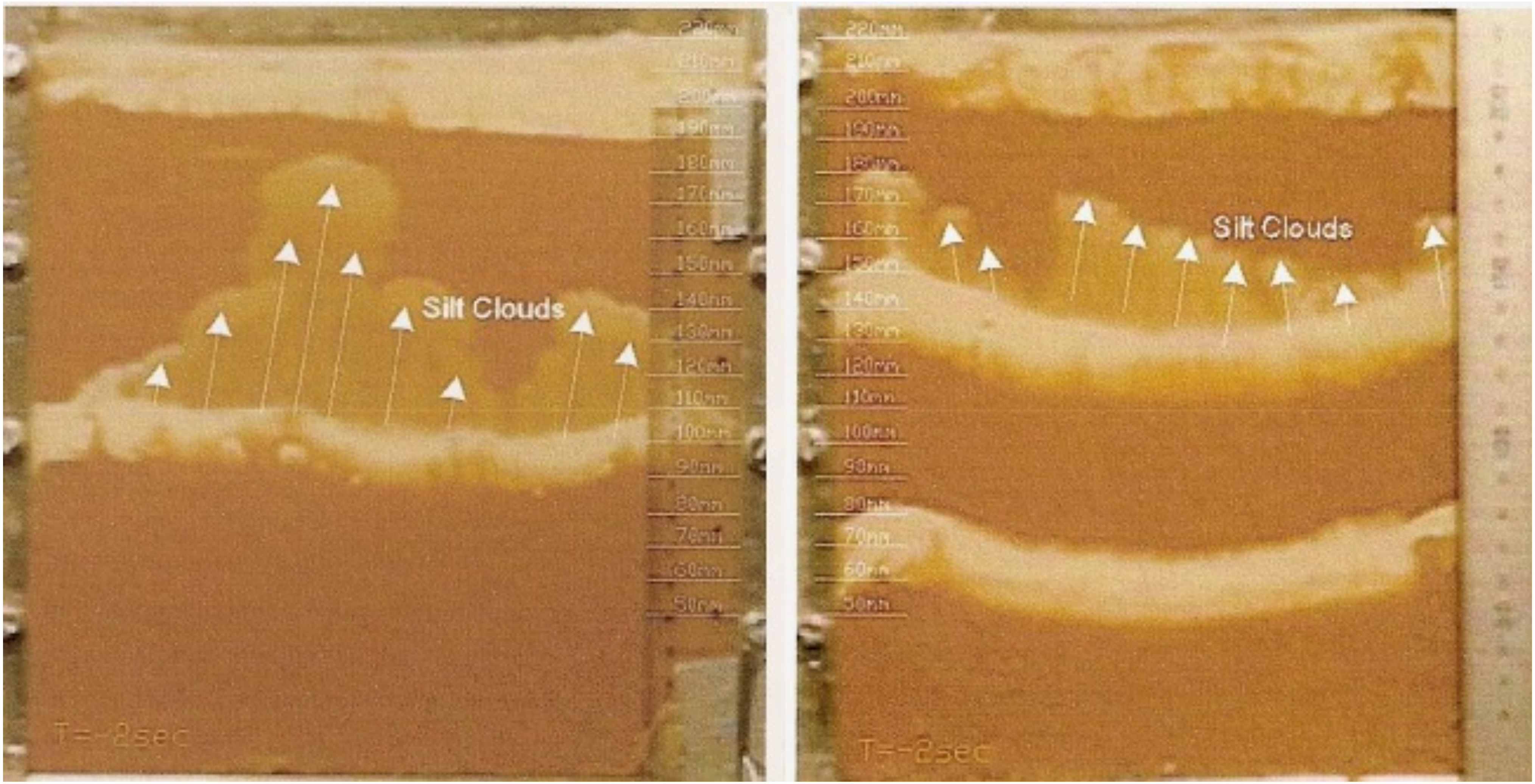
a test opportunity?



https://www.hou.usra.edu/meetings/lunarisru2019/pdf/5038.pdf

https://www.nature.com/articles/s41598-021-81317-1

Fluid Transport Through Granular Media



https://www.researchgate.net/publication/269157128_Observations_on_Sand_Boils_from_Simple_Model_Tests

Conclusions

SANDWORM is a low TRL architecture with applications in science, mineral exploration and mining of polar volatiles

Key features of a science mission enabled by SANDWORM include volatile release at variable depth horizons for measurement, specification of emission bands for continuous near field geophysical sensing, and simplicity of subsystem integration onto one or more NASA RTG science mission platforms (low volume, no power required)

Scientific exploration can inform and optimize a set of dedicated downstream commercial polar volatile and mineral exploration rovers

Key features of a mining method enabled by SANDWORM include using engineered sources of heat and cold to extract volatiles of immediate interest while sequestering a concentrate of byproduct volatiles for later collection