# NASA Lunar Volatiles Acquisition Technology

**ISECG Lunar Polar Volatiles Virtual Workshop #4**

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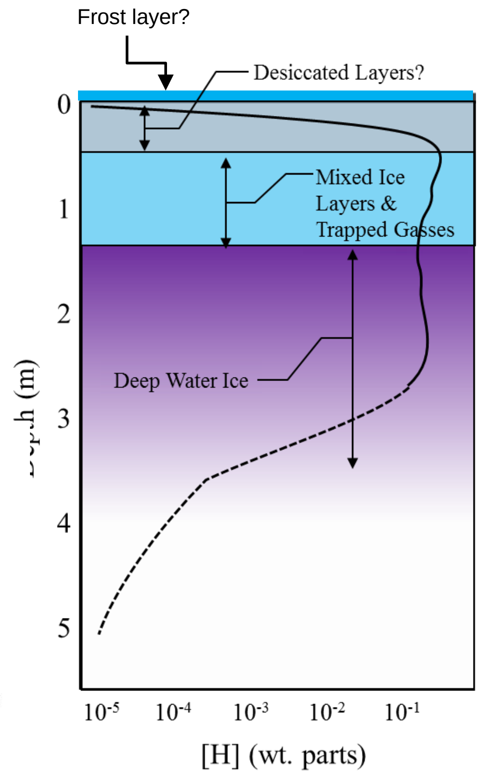
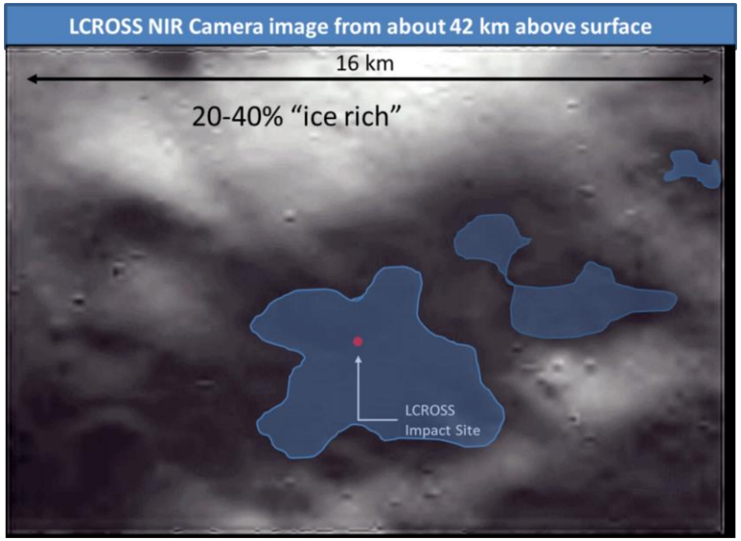
**Swamp Works**

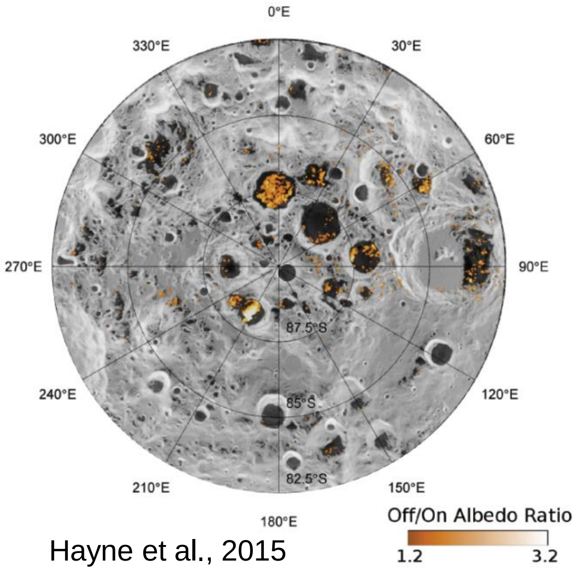
- **What are the most needed lunar exploration technologies to demonstrate polar volatile sample acquisition (e.g. extraction, excavation, transfer)?**

# Where to Dig for Ice?

- Data from LRO, LCROSS, and M3 suggest patchy and/or buried distributions of hydrogen
- Impact gardening will create heterogeneity at lengths scale of ~10-100s m
- Several data sets suggest potential different reservoirs, including near surface and buried
- In areas of limited sun near sub-surface temperatures are cold enough to retain water




Hayne et al., 2015

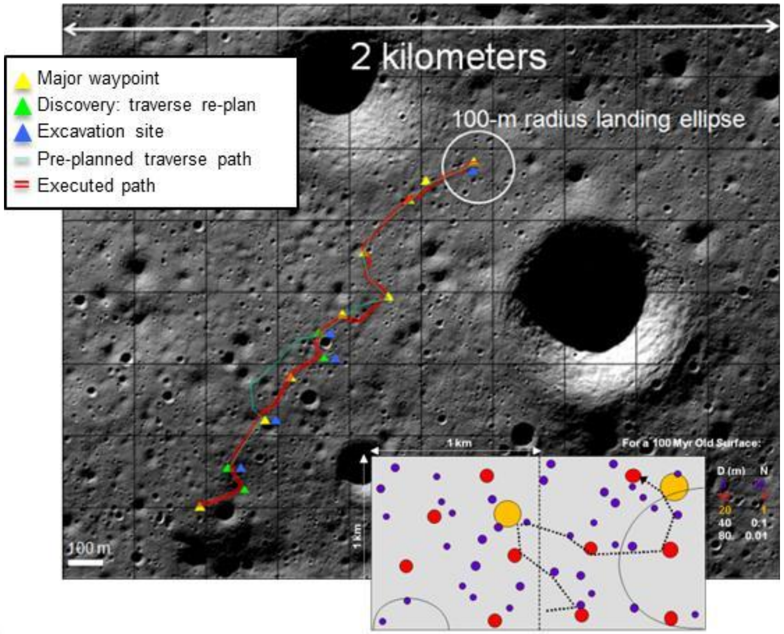
**…but how are they distributed and accessed at the "human" level?**

# Determining 'Operationally Useful' Deposits

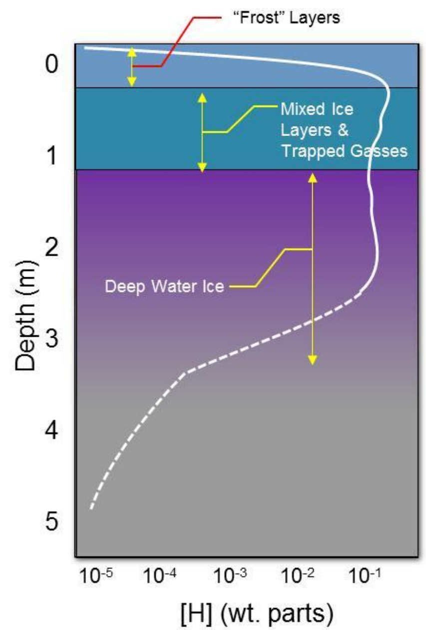
**We know that water (and other H-bearing compounds) is there, but not at the scales of utilization**

**Need to assess the extent of the resource 'ore body'**

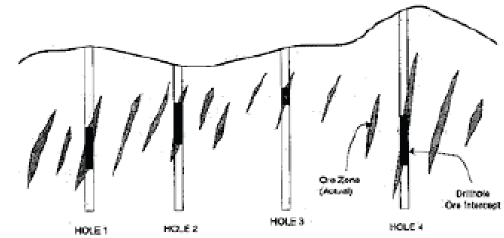
**Local Regions (100s to 1000s of meters)**



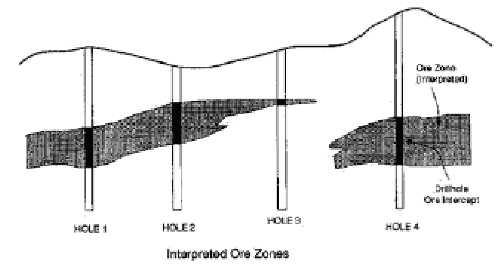

**Vertical Profiles**




**Distribution and Form**




**OR**



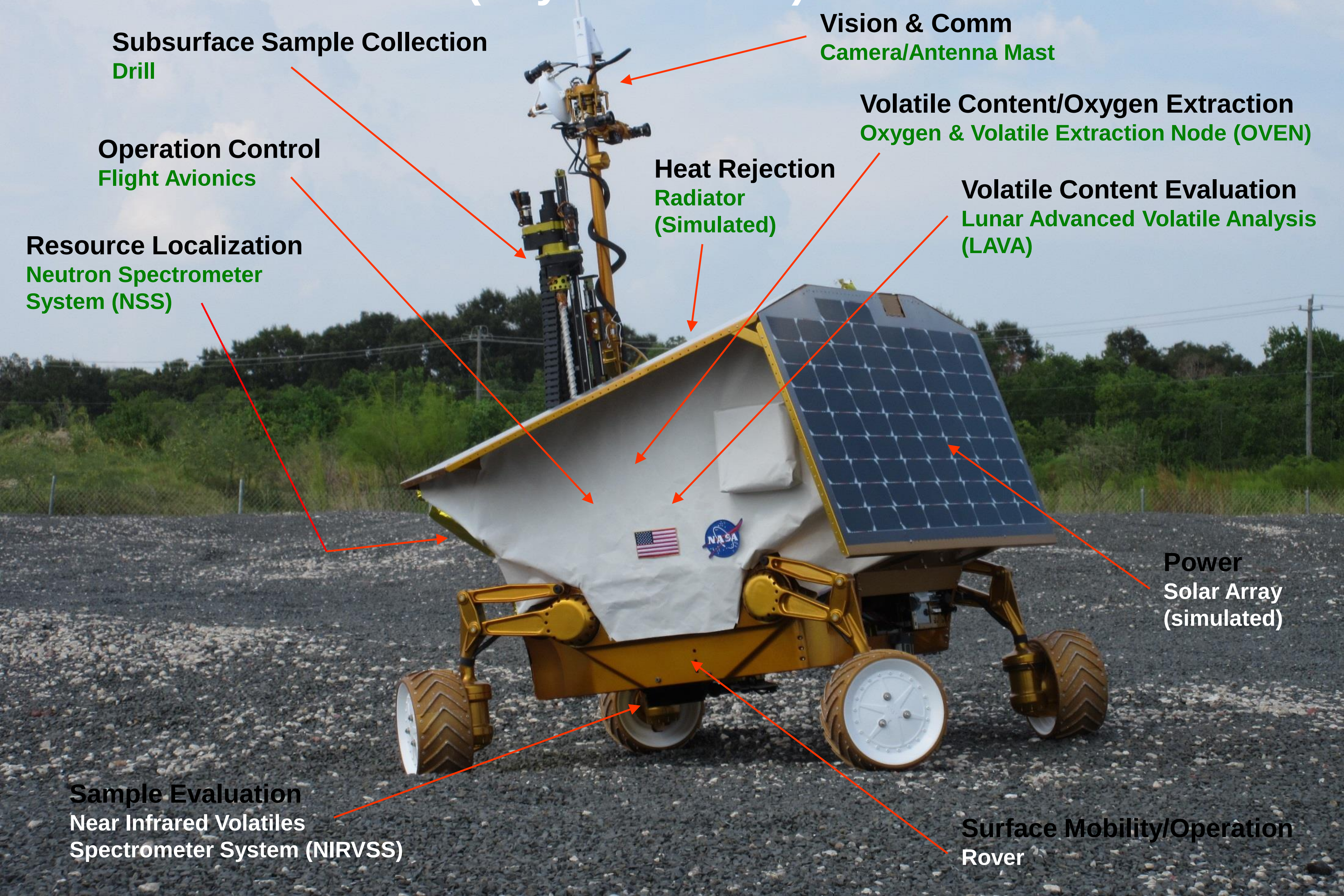

**An 'Operationally Useful' Resource Depends on What is needed, How much is needed, and How often it is needed**

Potential Lunar Resource Needs*

- 1,000 kg oxygen ($O_2$) per year for life support backup (crew of 4)
- 3,000 kg of $O_2$ per lunar ascent module launch from surface to $L_1/L_2$
- 16,000 kg of $O_2$ per reusable lunar lander ascent/descent vehicle to $L_1/L_2$ (fuel from Earth)
- 30,000 kg of $O_2$/Hydrogen ($H_2$) per reusable lunar lander to $L_1/L_2$ (no Earth fuel needed)

*Note: ISRU production numbers are only 1st order estimates for 4000 kg payload to/from lunar surface

# Resource Prospector (RP) 15: Surface Segment (Payload/Rover)

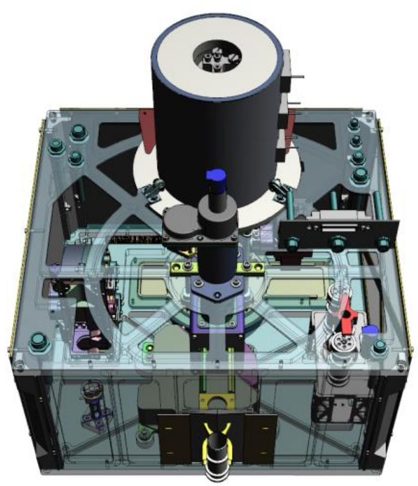


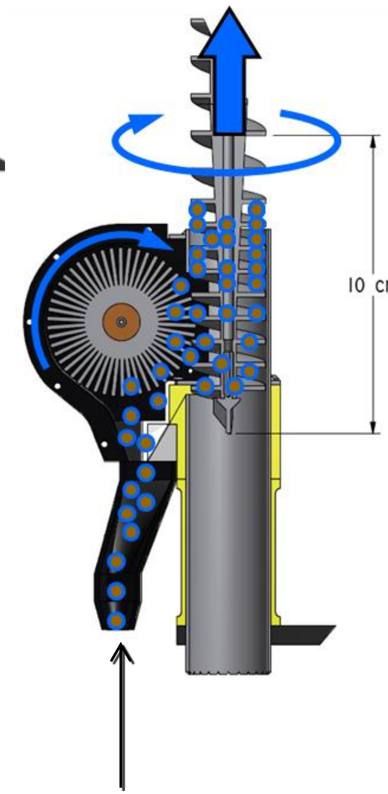
# RP Sample Acquisition System

- Subsurface sample acquisition down to 1 meter in 0.1 m “bites”
- Auger for fast subsurface assay with NIRVSS
- Sample transfer to OVEN for detailed subsurface assay
- Oxygen & Volatile Extraction Node (OVEN)
    - ➢ Volatile Content/Oxygen Extraction by step-wise sample heating (150 to 450C)
    - ➢ Total sample volume & mass

NIRVSS

OVEN

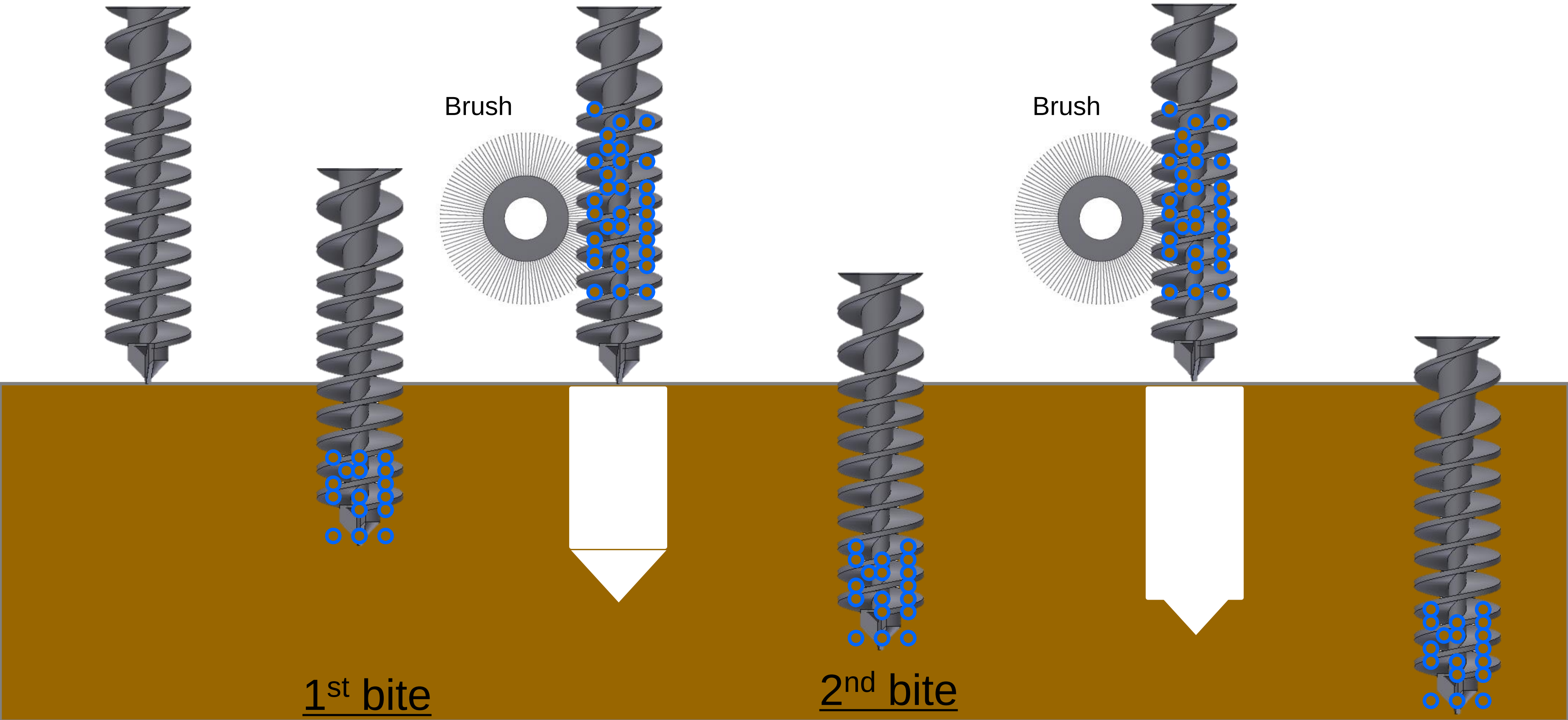




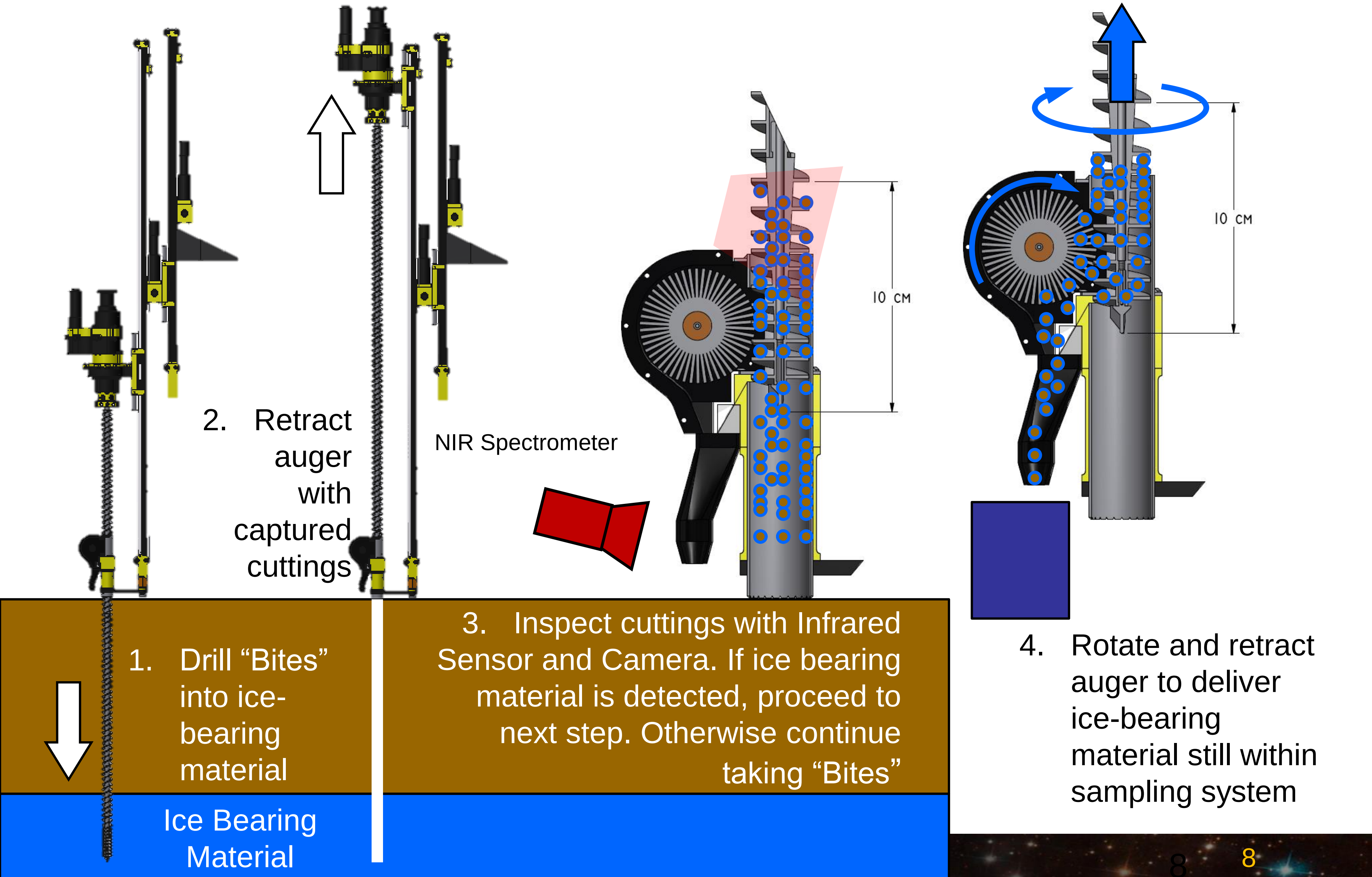

Cuttings exit

# “Bite” Sampling Concept

- Drill to 1 meter in short (~ 10 cm) “bites”
- Preserve stratigraphy in “bites”
- More accurate strength measurement of subsurface
- Lower risk (“graceful failure”) – if stuck at 60 cm, 5 bites done
- Time for analysis while drill in ‘safe’ place (above the hole)
- Time for subsurface to cool down



# Implementation of "Bite" Sampling





8

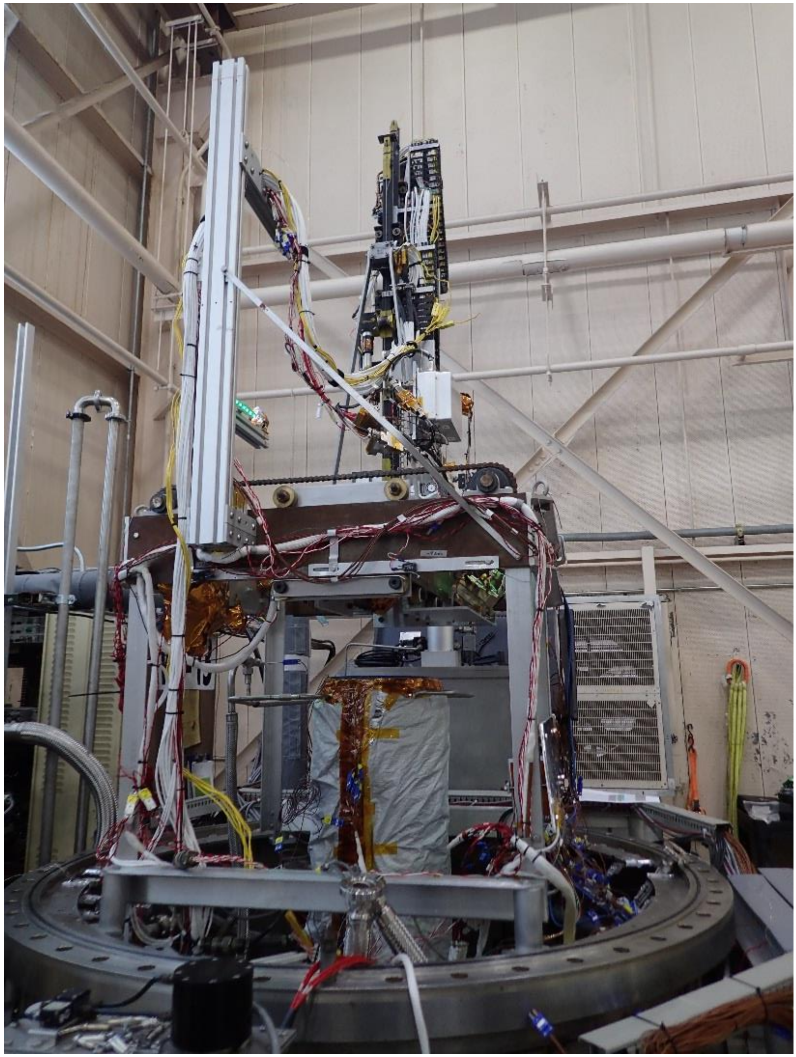
# RP Drill & Sample Capture Testing

**Drill / Sample Capture Testing**

- Performed at GRC VF13 Facility
  - 1.2 m cryo-cooled (-100C) drill tube with lunar (LHT-2M) plus water (0.2-5%), vacuum (~$10^{-6}$ torr)
  - Includes 1 meter drill, NIRVSS, Mass Spec, and sample capture to assess instrument performance and water loss during sampling
- Integrated to RP15 Rover – Field Testing
- Tested on slopes in ARGOS facility

RP15 Rover Testing

Sample Capture Mechanisms (SCMs)



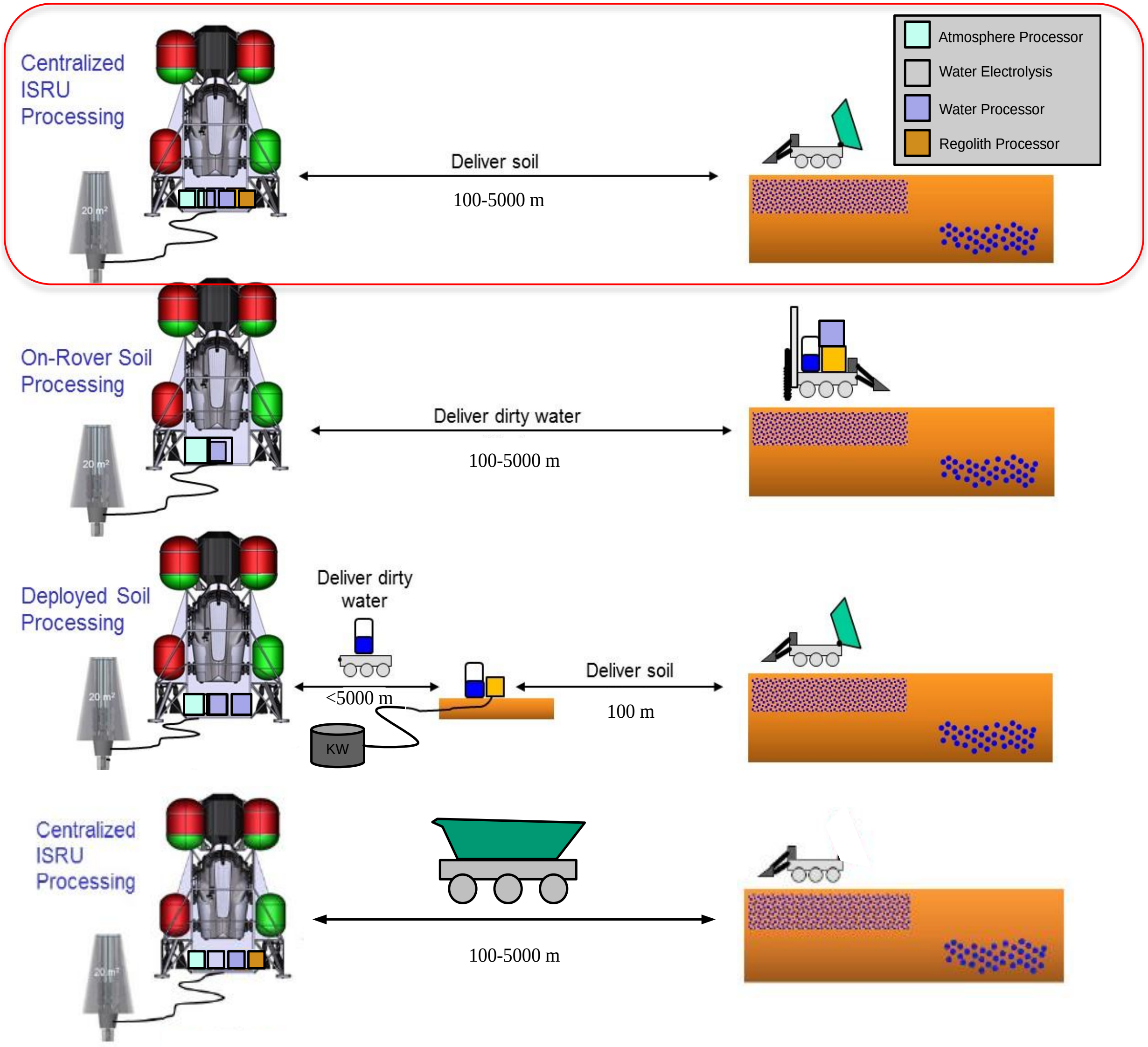
Trolley installed in VF13 Chamber with Drill Tube 2

# Scaling up Volatiles Acquisition to Mining

- Sampling for Volatiles
  - Sample size (ore) is in grams
  - Requirement is to feed instruments for volatiles characterization
  - Mission duration is short – days

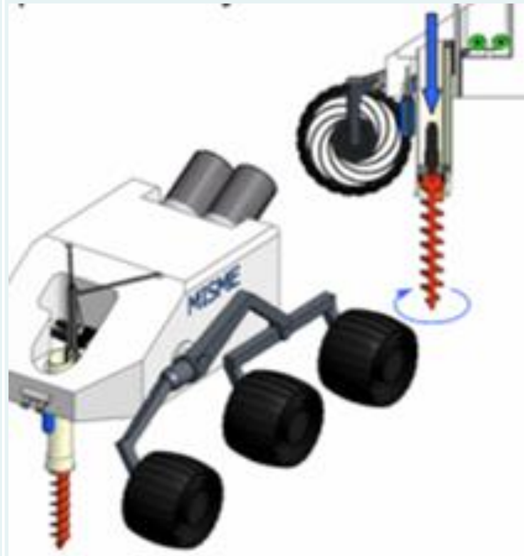
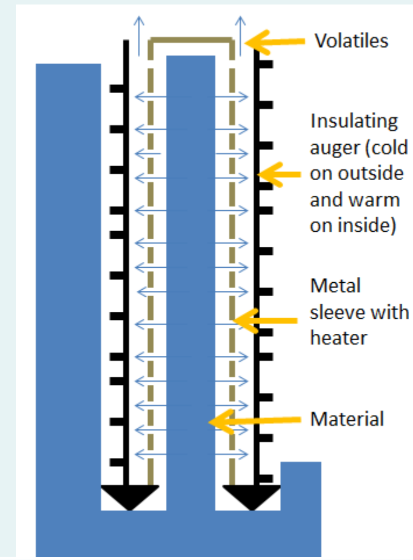
- Mining for Volatiles
  - Ore is in metric tons (t)
  - e.g. 10 t $H_20$ per year requires 200 t of regolith @ 5% yield
  - Requirement is to produce enough ore to extract viable quantities of volatiles resources ( e.g. $H_20$, $CH_4$, CO et.c.)
  - Mission duration is long - years

# Regolith Mining Scenarios for $H_20$



# Planetary Volatiles Extractor

- Investigated 3 architectures.
- Breadboards vacuum chamber tested in JSC-1a with ~12 wt% and frozen

<table>
<tr><th></th><th>Sniffer</th><th>MISWE</th><th>Corer</th></tr>
<tr><td></td><td></td><td>
</td><td>
</td></tr>
<tr><td>Description</td><td>Deep fluted auger with perforated stem. Material is heated up, volatiles flow through holes up the hollow auger stem to the cold trap.</td><td>Deep fluted auger captures sample and retracts into tube. The tube/auger is preload against the ground. Auger is heated and volatiles flow through the holes, up the annular space and into a cold trap.</td><td>Double wall corer with outer insulating auger and inner perforated and conductive tube. Material within inner tube is heated, volatiles flow through holes and up the annular space into a cold trap.</td></tr>
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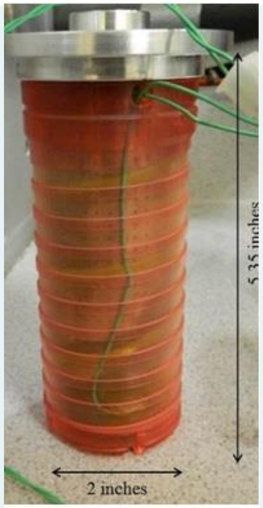
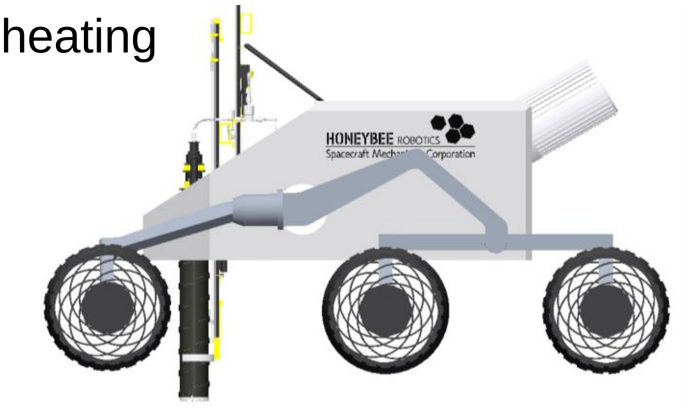
# PVEx Test Summary

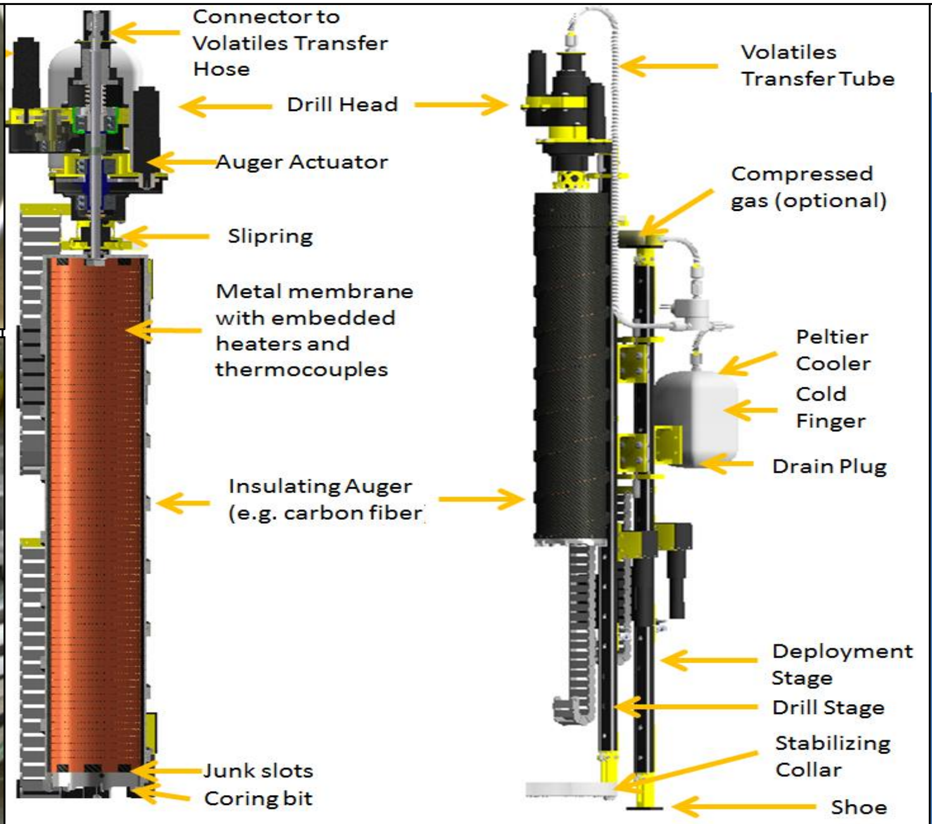
| | | Sniffer | MISWE (Org) | MISWE (Alt) | Corer |
|---|---|---|---|---|---|
| **Data Points** | |  |  |  |  |
| **Energy Efficiency [Whr/g]** | **Min** | | | | |
| | **Max** | | | | |
| | **Average** | | | | |
| | **Std. Dev** | | | | |
| **Water Recovery [%]** | **Min** | | | | |
| | **Max** | | | | |
| | **Average** | 1.2 | 25 | 44 | 65 |
| | **Std. Dev** | | | | |
| **Rankings** | | 4 | 3 | 2 | 1 |

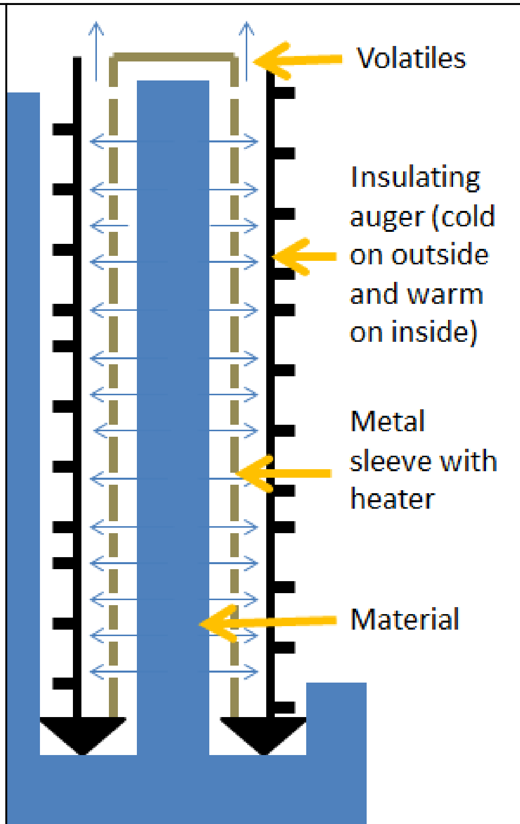

13

# PVEx-Corer: Optimal Option

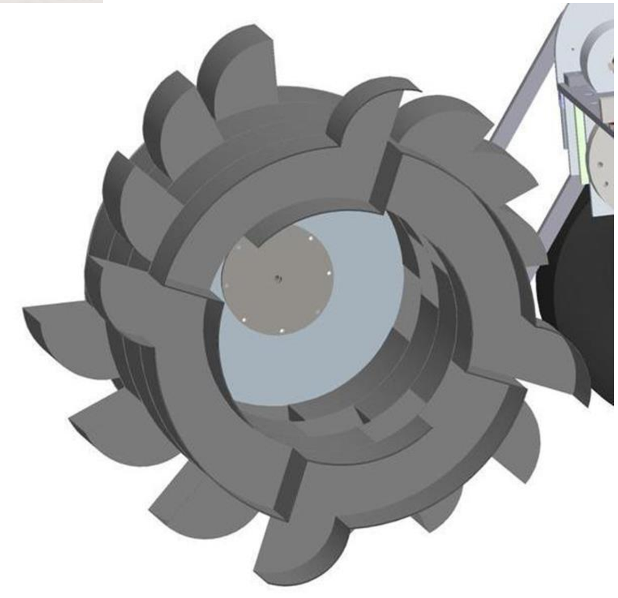
- Rover based, drills a core, extracts volatiles via in-situ heating
- Tested in vacuum chamber:
  - Extraction efficiency ~90% at 1.5 Whr/g of water
- Needs 2 MMRTGs for 30 liters of water/day
  - ~66 kWh heat and ~5 kWh electrical
- Suitable for other volatiles and hydrated water
- TRL5 system to be built in 2018 under SBIR Ph2





# Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0



| **Delivery capabilities per RASSOR per day*** (using baseline assumptions) |
|---|
| 2.3 MT |
| 23 batches |

200 t regolith ore could be mined in 87 days on the surface
Trenching would require overburden removal first

# Lunar Excavation System Concepts

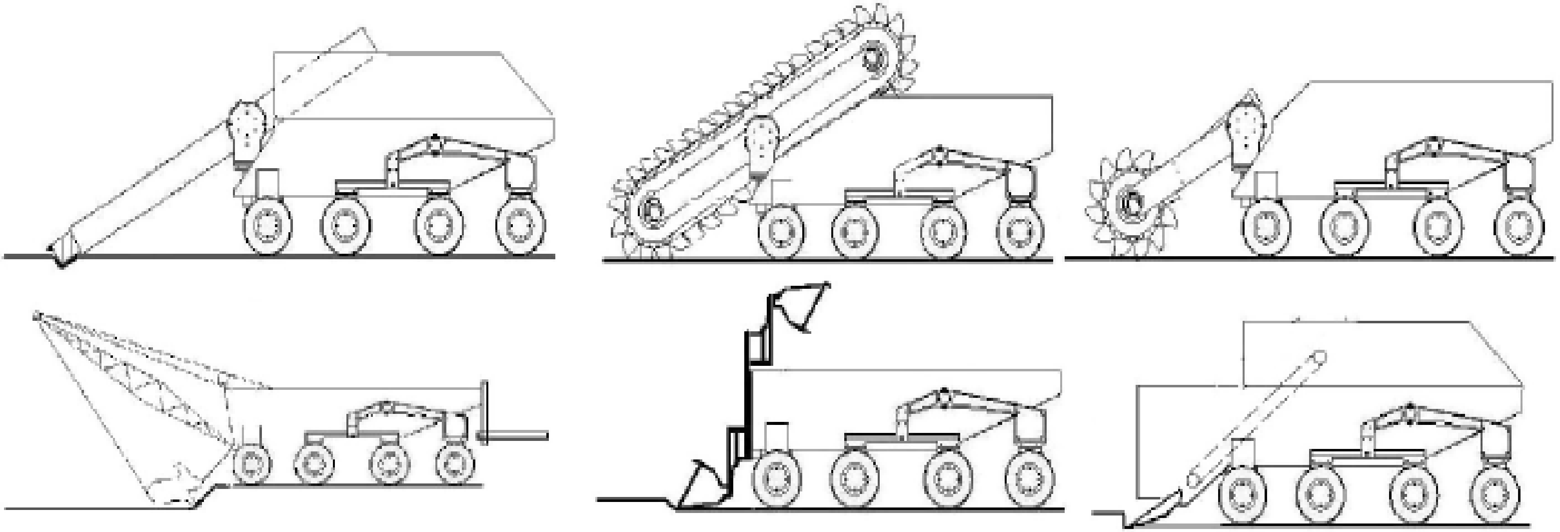


**FIGURE 3.** Additional Concepts From Top Left to Bottom Right: Auger, Bucket Ladder, Bucket Wheel or Bucket Drum, Dragline, Overshot Loader, and Scraper.

**TABLE 4. Summary** Estimated Specifications for the Additional Concepts.

| | Auger | Bucket Ladder | Bucket Wheel | Dragline | Overshot Loader | Scraper | Pneumatic |
|---|---|---|---|---|---|---|---|
| Production Cycle | 134 min | 134 min | 134 min | 224 min | 176 min | 176 min | Unknown |
| Unloaded System Mass | 17.8 kg | 18.8 kg | 19.8 kg | 28.8 kg | 16.8 kg | 14.8 kg | Unknown |
| Horizontal Reaction Force | 11.5 N | 12.2 N | 12.8 N | 18.1 N | 10.9 N | 5.6 N | Unknown |
| Vertical Reaction Force | 14.4 N | 15.3 N | 16 N | 0.4 N | 13.6 N | 12 N | Unknown |
| Subsystems | 5 | 5 | 6 | 5 | 4 | 4 | 6 |
| Motor/gear assemblies | 14 | 14 | 15 | 24 | 14 | 13 | 5 |
| Material Transfer Points | 5 | 5 | 6 | 5 | 5 | 6 | 3 |

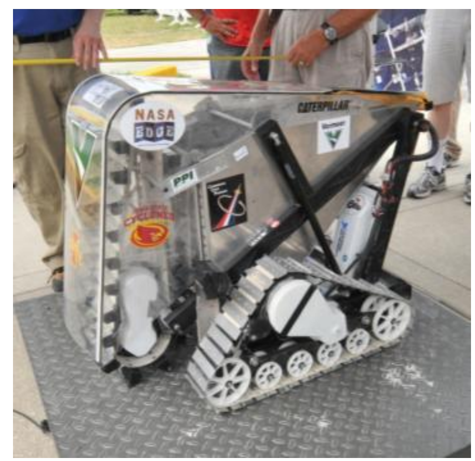
King et al, 2008

# What is the Best Lunabot Regolith Mining Design for the Moon??
# The Most Popular Winning Design? (50-80 Kg)

2009: Paul's Robotics WPI

2010: Montana State U

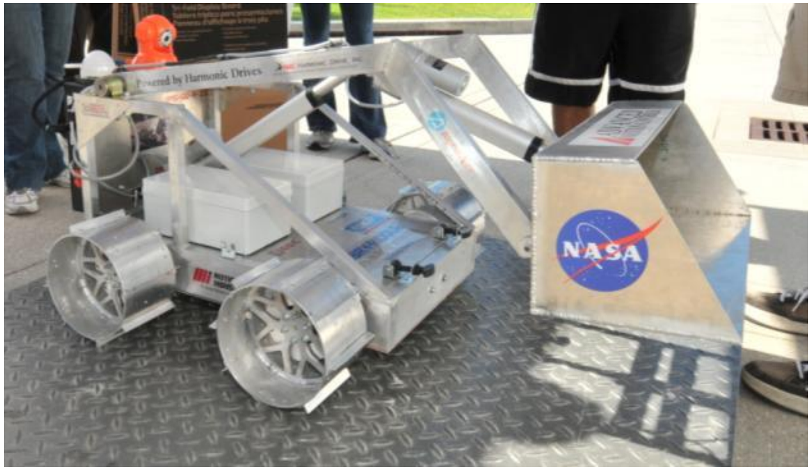
2011: Laurentian University



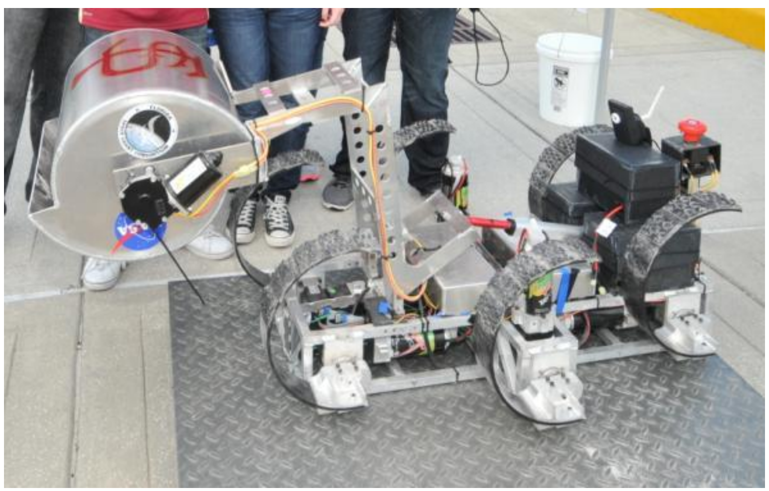
2012: Iowa State U


17

# Or are these designs better?




2012: Embry Riddle Daytona AU



2012: FAMU/ Florida State U

2011: U North Dakota

2012: Montana State U


18

# Regolith Excavation Mechanisms

**All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and two Lunabotics Mining Competitions (2010 and 2011)**

| Regolith Excavation Mechanism | # of machines employing excavation mechanism |
|---|---|
| Bucket ladder (two chains) | 29 |
| Bucket belt | 10 |
| Bulldozer | 10 |
| Scraper | 8 |
| Auger plus conveyor belt / impeller | 4 |
| Backhoe | 4 |
| Bucket ladder (one chain) | 4 |
| Bucket wheel | 4 |
| Bucket drum | 3 |
| Claw / gripper scoop | 2 |
| Drums with metal plates (street sweeper) | 2 |
| Bucket ladder (four chains) | 1 |
| Magnetic wheels with scraper | 1 |
| Rotating tube entrance | 1 |
| Vertical auger | 1 |

# Top Robotic Technical Challenges

- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans

NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al, 2010)

# Top Space Mining Technical Challenges

- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering sub surface rock obstacles
- Long life and reliability
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications