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Aerospace Division (ASD)

The 19th Biennial ASCE ASD International Conference on Engineering, Science, Construction and Operations in Challenging Environments
(Earth & Space 2024)

Greater Miami, FL; April 15-18, 2024

Pre-Conference Short Course

“LUNAR GEOTECHNICS AND FOUNDATION DESIGN”

TOPIC: Excavation and Regolith Work on the Moon

by

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NASA Kennedy Space Center, Florida

April 15, 2024

Importance of Regolith Manipulation

- Two of the goals of NASA's Artemis Program are to establish a sustained presence on the Moon and facilitate a lunar economy
- Two of the goals of NASA's Artemis Program are to establish a sustained presence on the Moon and facilitate a lunar economy
- Two enabling factors:
 - Production of commodities to create a market
 - Infrastructure to facilitate exchange of goods and services and reduce risk
- Regolith is the most plentiful resource on the Moon for:
 - In-Situ Resource Utilization (ISRU)
 - Construction of surface infrastructure
- Mastering the ability to manipulate regolith is critical to achieving Artemis goals



Regolith for ISRU

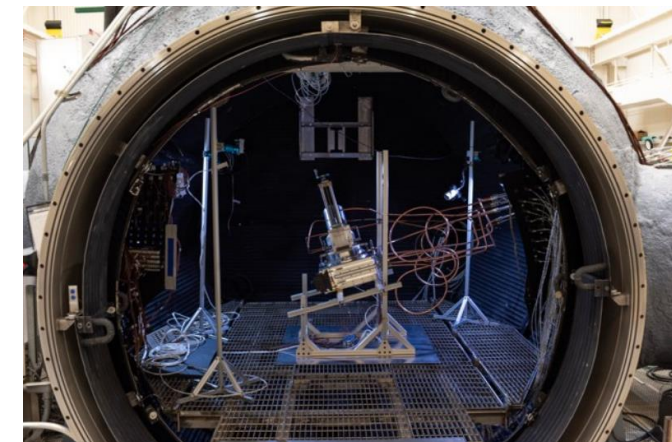
- Regolith based ISRU commodities:
 - Oxygen
 - Metals
 - Water
 - Volatiles
 - Construction feedstock
- Regolith manipulation functions:
 - Prospecting
 - Excavation/mining
 - Hauling/transportation
 - Stockpiling/storage
 - Beneficiation
 - Size screening
 - Transfer and conveyance
- Quantities:
 - 100s to 1000s mt/year



Volatiles Investigating Polar
Exploration Rover (VIPER)



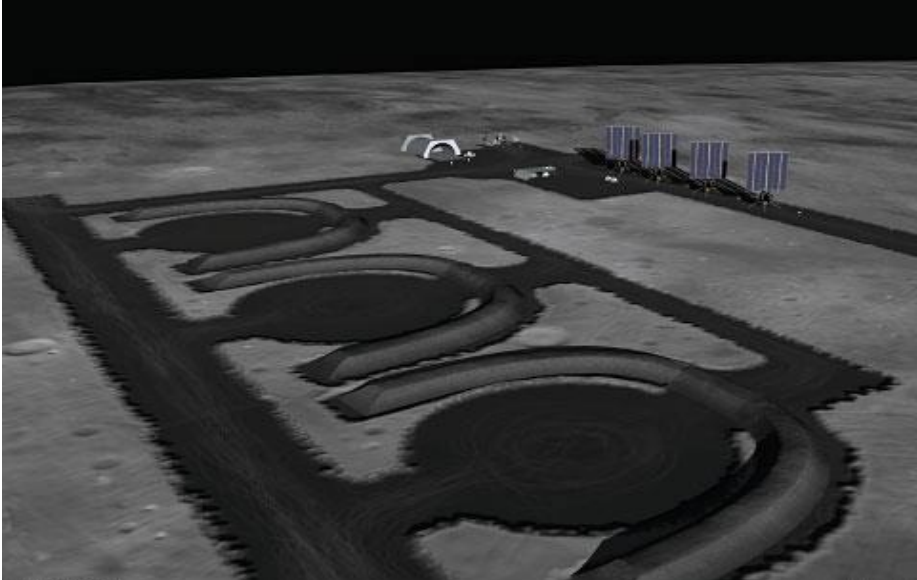
Molten Regolith Electrolysis (MRE)



Carbothermal Reduction
Demonstration (CaRD)

Bulk Regolith Infrastructure

- Initial infrastructure will likely be composed of bulk regolith:
 - Berms/blast protection
 - Flat, level, rock free operational areas
 - Improved trafficability pathways
 - Access to challenging locations
 - Trenches and utility corridors

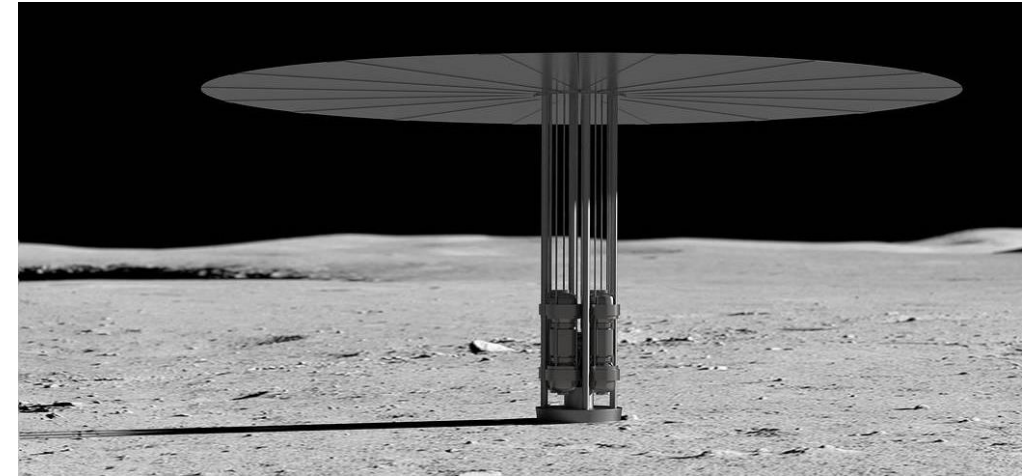


Concept of an early Lunar base with bulk regolith infrastructure



Hazards of astronauts walking on unprepared surfaces
(https://www.youtube.com/watch?v=Ke65jU_yYso&list=PPSV)

- Advanced construction tasks will need site preparation and bulk regolith features:
 - Foundations (towers, habitats, launch/landing pads, roads, dust free zones)
 - GCR/SPE Shielding
 - Fission surface power shielding
 - Thermal insulation
 - Tunneling



Surface fission power may need regolith radiation shielding



Foundations for launch/landing pads
(image courtesy of ICON/BIG-Bjarke Ingles Group)

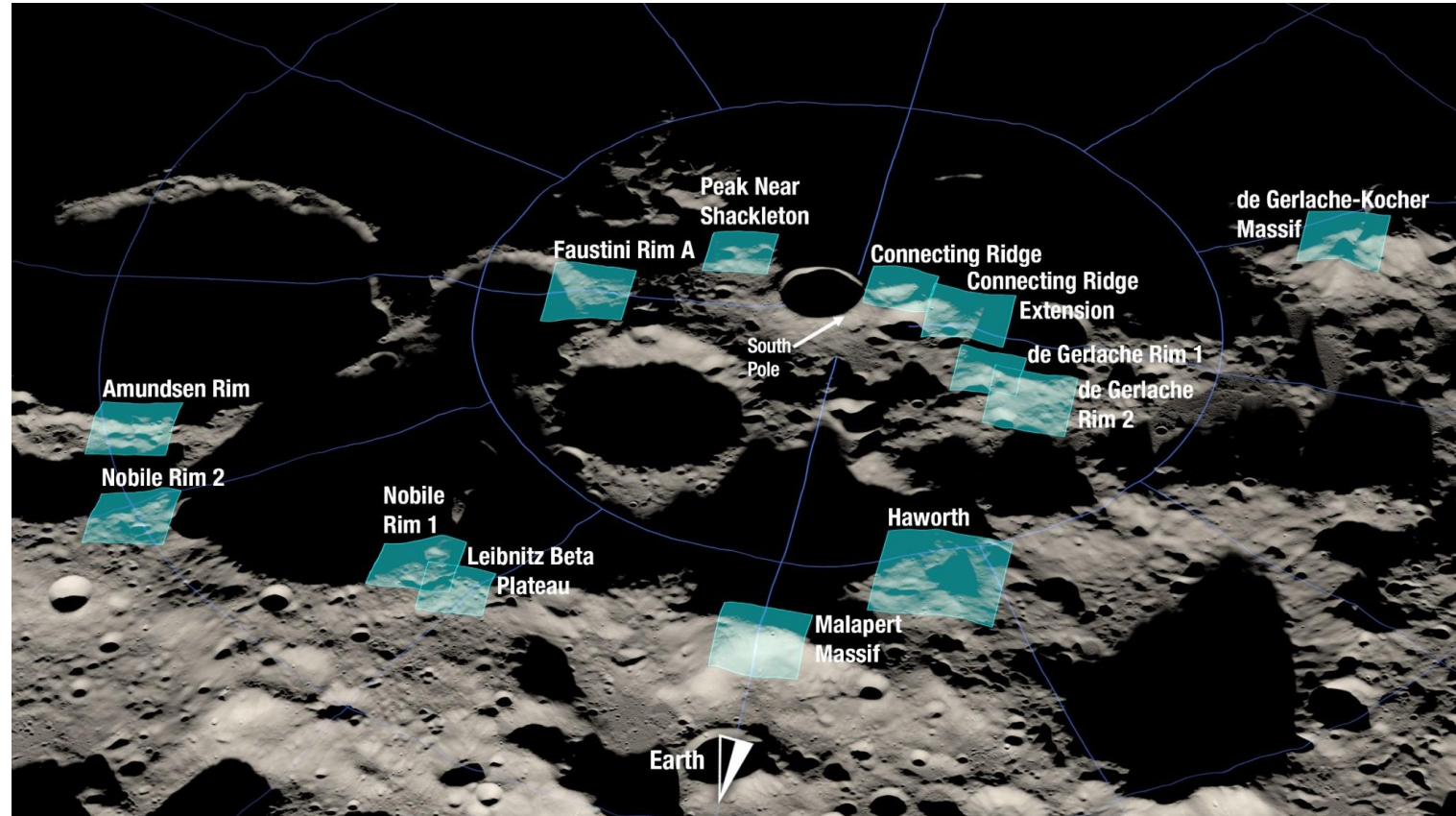


Tall lunar towers may need regolith foundations



Shelters covered with regolith overburden
(image courtesy of AI SpaceFactory)

- Regolith Manipulation Functions:
 - Excavation
 - Grading/leveling
 - Hauling/transportation
 - Compaction
 - Rock handling
 - Size screening
 - Geotechnical measurement
- Launch/Landing Pad Case Study
 - 100m diameter graded and compacted surface
 - 3m berm
 - ~30,000 m³ of regolith moved
 - ~54,000 metric tons



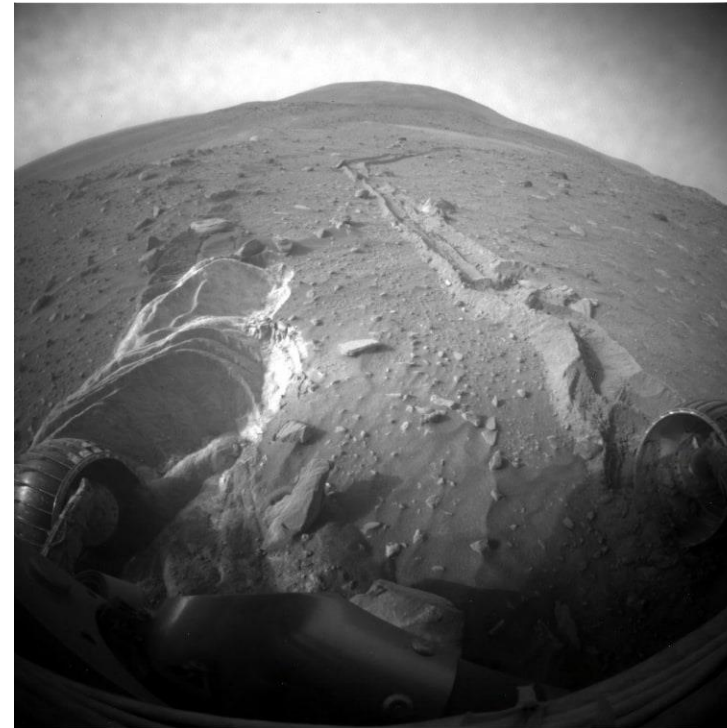
Potential landing sites for the Artemis Program

Regolith Manipulation Challenges

- Site survey – virgin site, during operations, as-built verifications
- Autonomy in a non-cooperative environment
- Distance traveled and repeated trafficking – 1000s of km
- Wear and maintenance
- Operations in permanent shadow
- Surviving lunar night



Curiosity's wheel with premature damage



Spirit is stuck in loose regolith

- Regolith is present on many extra-terrestrial bodies, and the crushed rock material it is made of contains many of the resources that are enabling for In-Situ Resource Utilization (ISRU) and In-Situ Construction (ISC)
- None of these valuable ISRU activities can proceed without first acquiring the regolith granular material with some type of excavation device and method
- Regolith Excavation in reduced gravity environments is a Critical Technology and is enabling for ISRU and ISC
- Only small scale excavation for scientific sampling has been achieved on the Moon, Mars and Asteroids (kg's)
- Lunar construction will need thousands of tons of regolith excavation with payload mass and energy constraints
- How will this happen?

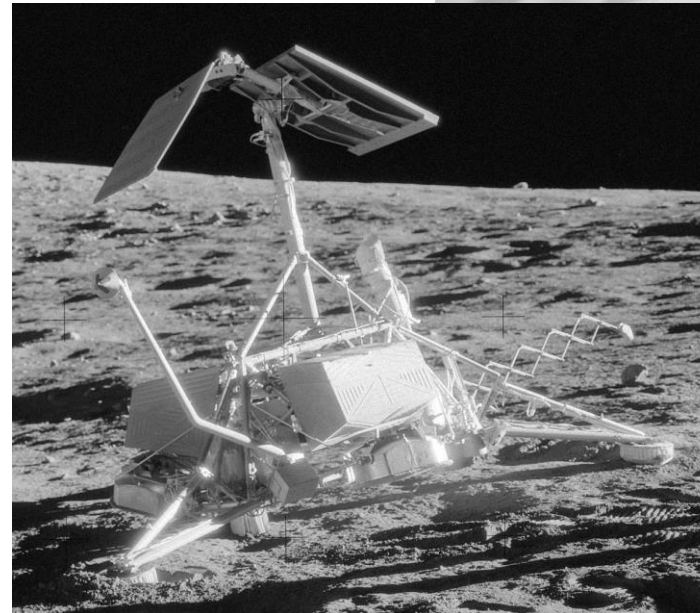
Types of Excavation

- Excavation is the act or process of digging, especially when something specific is being removed from the ground.
- In the lunar case, regolith and rocks will be removed from the lunar surface or moved across the surface
- Many different types of excavation – depending on the task being accomplished:
 - **Dig**
 - **Trench**
 - **Cut**
 - **Fill**
 - **Level**
 - **Grade**
 - **Emplace**
 - **Carve**
 - **Et.c.**

Lunar Surveyor Scoop

- The scoop is a claw-like device at the end of a frame that extends several feet through a gear drive and electrical motor.
- Soil mechanics surface scoop (SMSS) carried on Surveyor Lunar Landers 3 and 7.
- The scoop is a claw-like device at the end of a frame that extends several feet through a gear drive and electrical motor.
- These spacecraft, launched starting in 1966, were used to survey the moon's surface to help select a safe landing site for the manned Apollo lunar landings.
- The scissors jack-like arm of the sampler was hinged to the frame of the spacecraft.
- The motor driven arm was extendible up to 5 feet and able to range over an area of 24 square feet. The scoop at the end of the arm was used to dig trenches in lunar soil.
- Images of the trenches sent back by the on-board TV camera, as well as strain gages on the arm provided data on the mechanical properties of the surface of the moon.
- The SMSS was manufactured by Hughes Aircraft.

First robotic lunar excavation: Lunar Surveyor 3 mission, April 20, 1967 – small trenches for geotechnical purposes



Trenches were up to 7 inches (17.8 centimeters) deep.

Apollo Missions



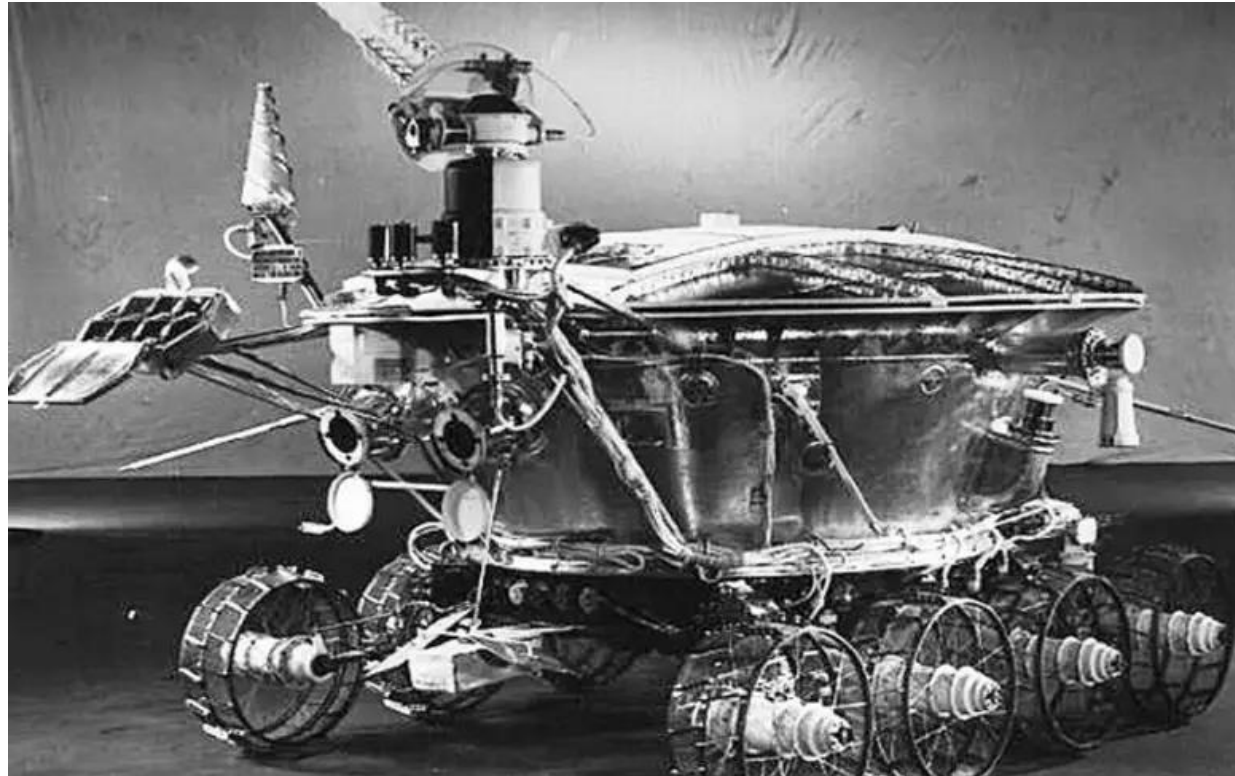
Apollo 15 trenching by Astronaut James Irwin
(NASA Photo ID: [AS15-92-12424](#))



Trench dug during the Apollo 16 mission showing the cohesive behaviour of lunar soil. Astronaut boot print for scale
(Credit: NASA AS16-107-17458).

Lunakhod Rovers

- Lunakhod 1: 1970



Regolith Mechanics

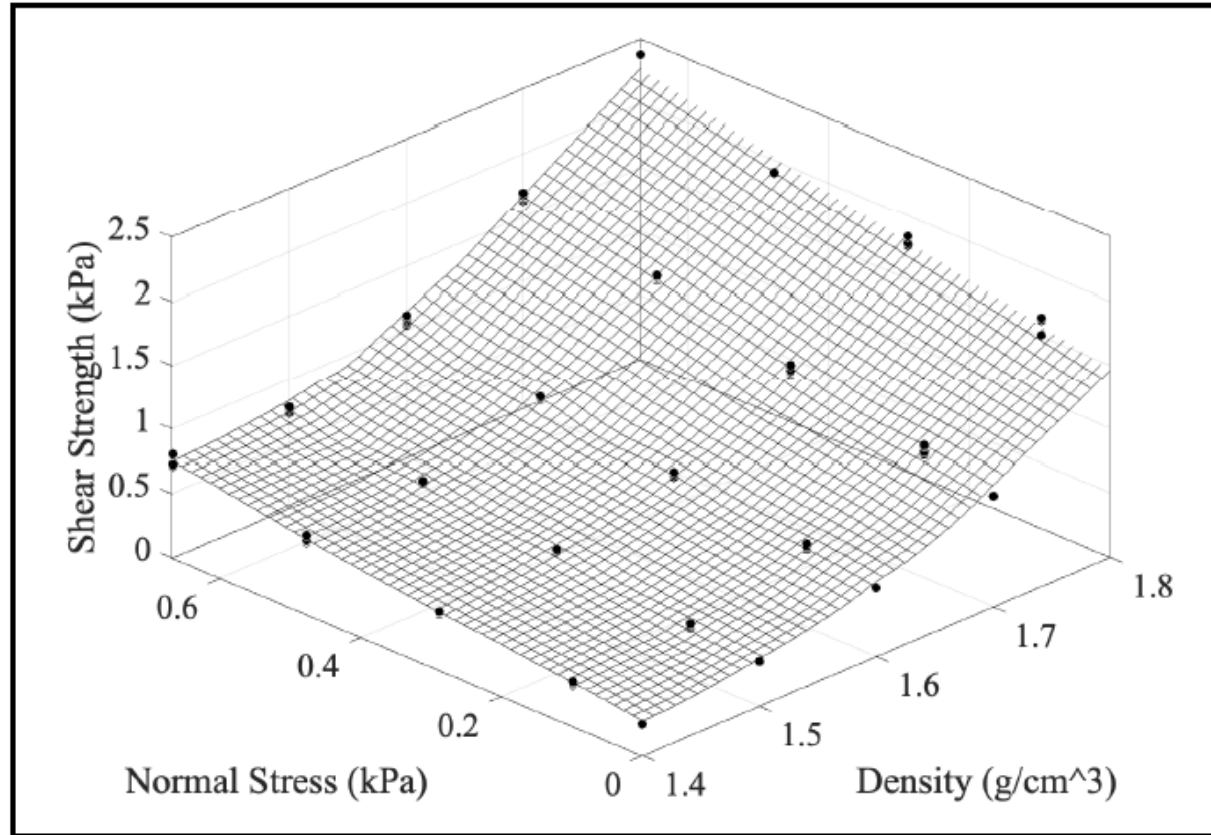


Figure 8. Shear strength model for LHS-1 as a function of normal stress and density with direct shear test results.

Dotson, B., Valencia, D. S., Millwater, C., Easter, P., Long-Fox, J., Britt, D., & Metzger, P. (2024). Cohesion and shear strength of compacted lunar and Martian regolith simulants. *Icarus*, 411, 115943.

Bearing Forces

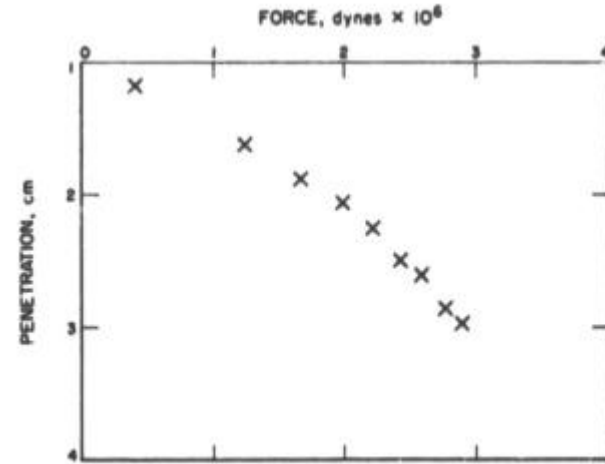
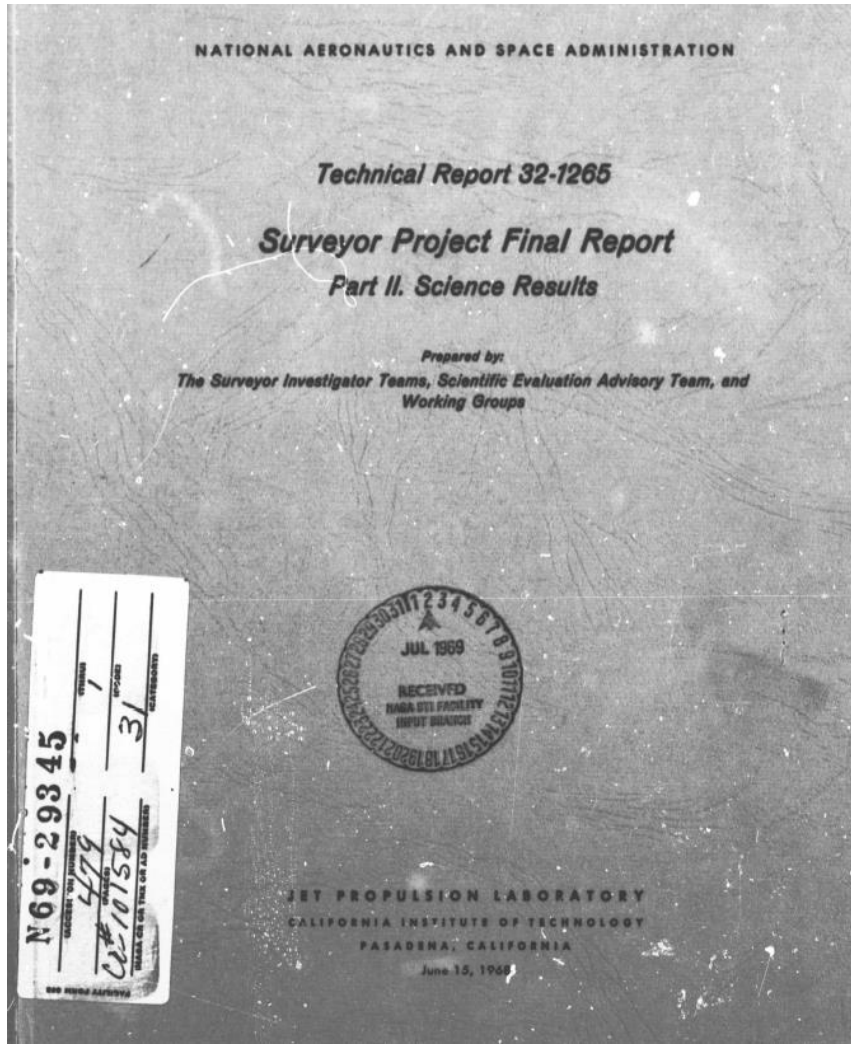


Fig. V-8. Force vs penetration curve for bearing test 2 on Surveyor VII.

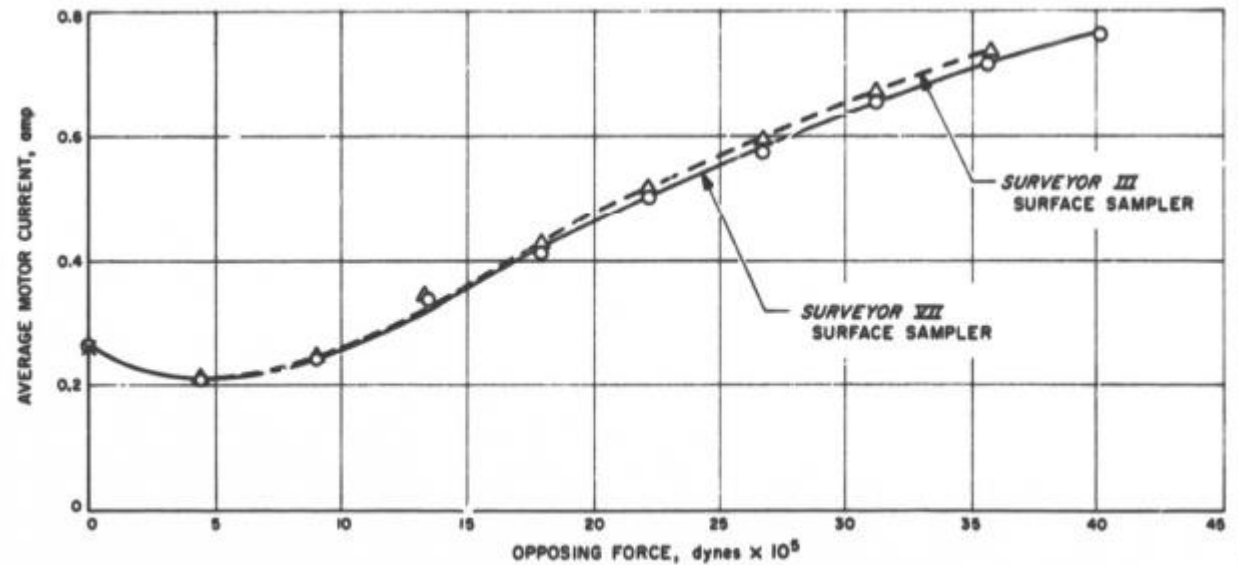


Fig. V-9. Force vs motor current for surface-sampler bearing modes on Surveyors III and VII.

Lunar Excavation Experiments in Simulant Soil Test Beds—Revisiting the Surveyor Geotechnical Data

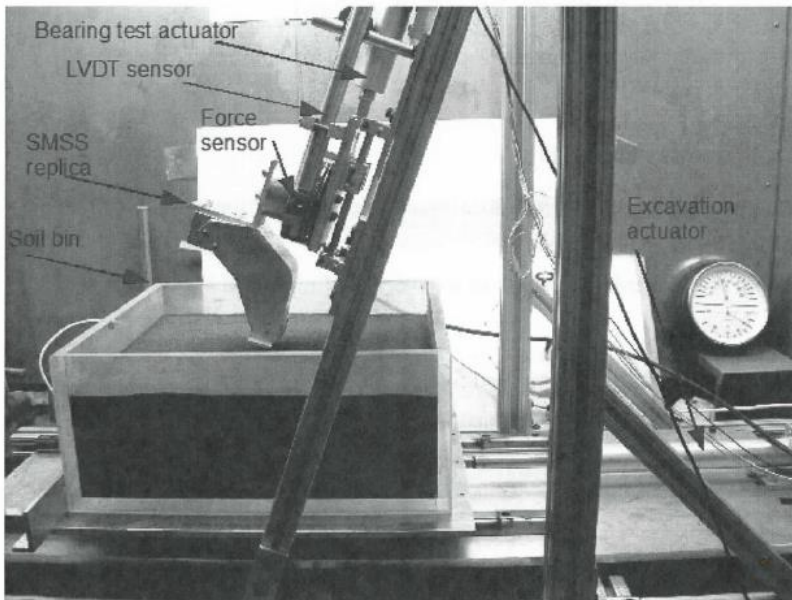
Juan H. Agui and R. Allen Wilkinson

ASCE Earth and Space 2012 Conference

April 15-18, 2012

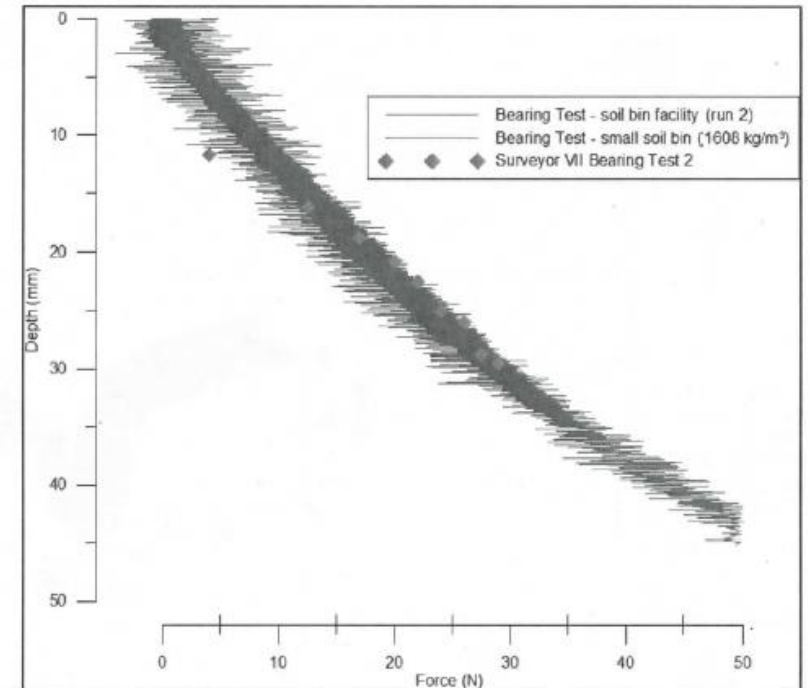
Bearing Tests

Comparison with Surveyor data



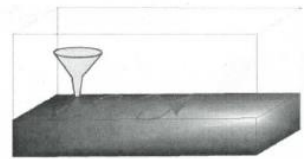
Features

- 30.5 cm x 33.0 cm footprint
- Depths of 14 and 29.2 cm
- JSC-a1 simulant
- Vertical (inclined) actuation
- Horizontal actuation of soil bed
- Six axis load cell
- Bed prep'd: controlled hand filling.



Replication of Excavation Forces

- Homogenous bed preps .
 - Raking, leveling
 - Soil depth (~ 10 cm for laboratory soil bin and ~ 60 cm for soil bin facility)
- Surveyor Scoop Bearing Test parameters
 - penetration angle (70°)
 - Stroke speed (6 mm/s)
 - Penetration stroke length (50 mm)
- Excavation Tests procedures
 - Rake angle (60°)
 - Speed (2 cm/s)
 - Travel (~ 25 cm)

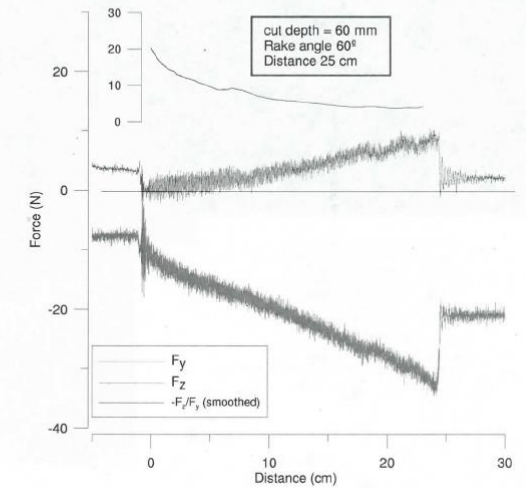
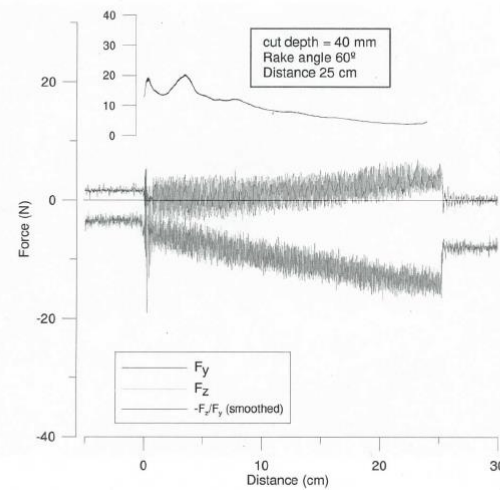


Laboratory soil bin filling



Soil bin facility preparation

Excavation Tests



Zeng, X., Burnoski, L., Agui, J., & Wilkinson, A. (2007, January). Calculation of excavation force for ISRU on lunar surface. In 45th AIAA aerospace sciences meeting and exhibit (p. 1474).

III. A Model to Calculate Excavation Force Based on Principles of Soil Mechanics
This model to calculate excavation force on an excavation blade is based on the principles of soil mechanics. The problem is illustrated in Figure 3.

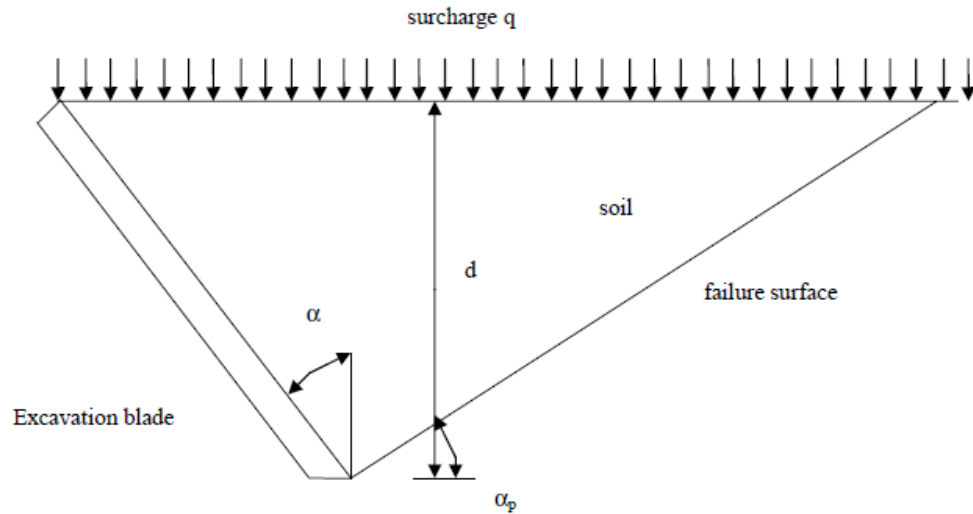


Figure 3. Excavation blade and soil body at failure

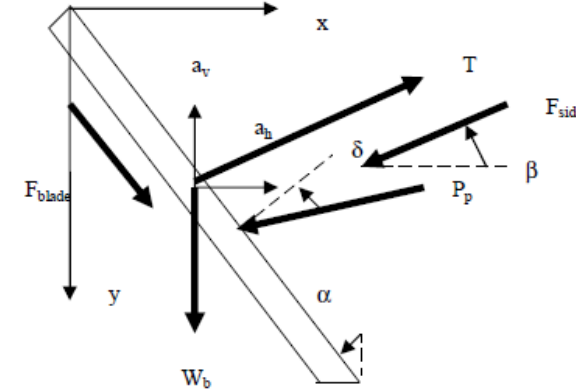


Figure 4. Forces act on the blade

Assuming the blade and the body of soil in failure state have a horizontal acceleration of a_h and a vertical acceleration of a_v , the equations of motion for the blade can be written as:

$$T_x + F_{blade} \sin\alpha - P_p \cos(\alpha - \delta) - F_{side} \cos\beta = (W_b/g)a_h \quad (2)$$

$$T_y - F_{blade} \cos\alpha - W_b - P_p \sin(\alpha - \delta) - F_{side} \sin\beta = (W_b/g)a_v \quad (3)$$

in which T_x and T_y are the horizontal and vertical components of T , respectively, and β is the inclination angle of the side friction force. The equations can be re-written to calculate T_x and T_y :

$$T_x = -F_{blade} \sin\alpha + P_p \cos(\alpha - \delta) + F_{side} \cos\beta + (W_b/g)a_h \quad (4)$$

$$T_y = F_{blade} \cos\alpha + W_b + P_p \sin(\alpha - \delta) + F_{side} \sin\beta + (W_b/g)a_v \quad (5)$$

Then, the total excavation force T is

$$T = \sqrt{T_x^2 + T_y^2} \quad (6)$$

Prediction of Excavation Forces

Zeng, X., Burnoski, L., Agui, J., & Wilkinson, A. (2007, January). Calculation of excavation force for ISRU on lunar surface. In 45th AIAA aerospace sciences meeting and exhibit (p. 1474).

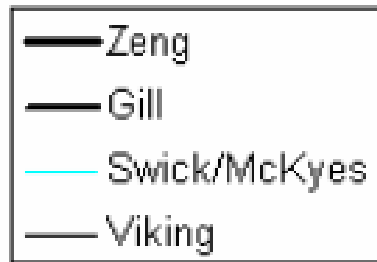


Figure 8. Comparison of results of excavation forces by four different models

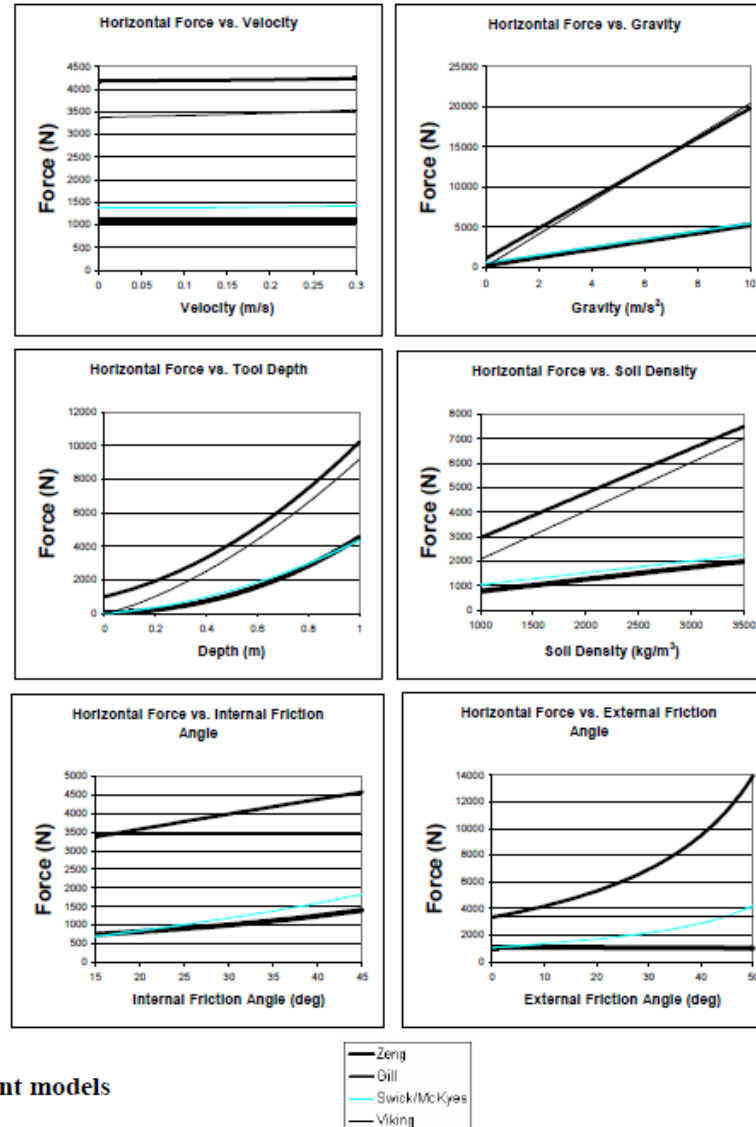


Figure 8. Comparison of results of excavation forces by four different models

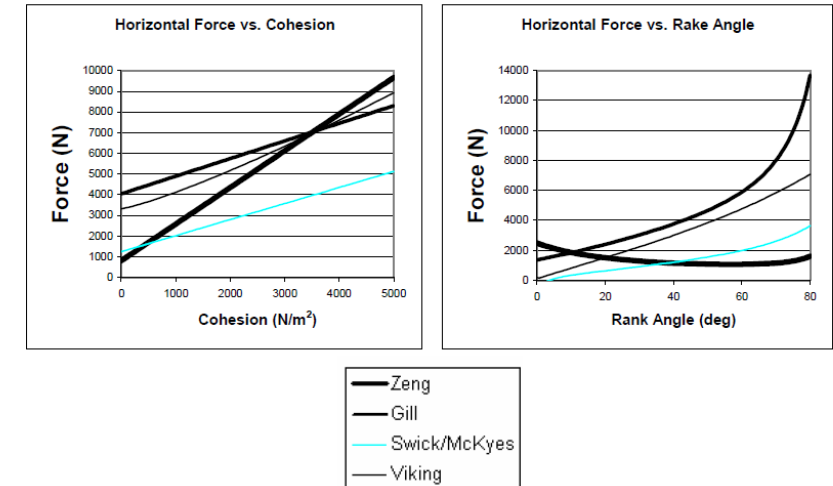
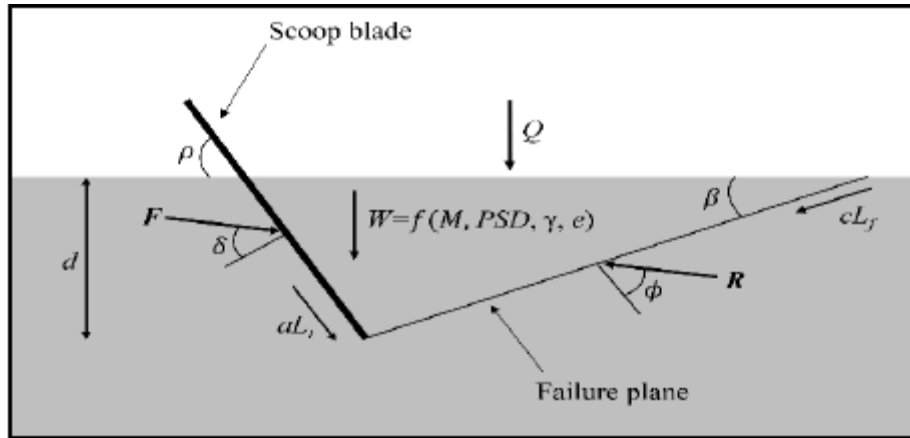


Figure 9. Influence of cohesion and rake angle on excavation force

Tool Width (w):	1 m
Tool Length (W):	0.7 m
Tool Depth (d):	0.5 m
Tool Velocity (v):	0.1 m/s
Moon Gravity (g):	1.63 m/s ²
Horizontal Acceleration (a _h):	0 m/s ²
Vertical Acceleration (a _v):	0 m/s ²
Soil Surcharge (q):	1 kg/m ²
Soil Density (ρ):	1680 kg/m ³
Gill's Cut Resistance Index (K):	1000 N/m ²
Soil Cohesion (c):	170 N/m ²
Soil-Tool Adhesion (c _a):	1930 N/m ²
Rank Angle (α):	45 deg
Internal Friction Angle (φ):	35 deg
External Friction Angle (β ₁):	10 deg
Shear Plain Failure Angle (θ):	30 deg
Soil-Blade Friction Angle (δ):	20 deg
At Rest Earth Coefficient (K ₀):	0.573

Prediction of Excavation Forces



2D excavation force diagram, modified from McKyes (1985): d is scooping depth, ρ is rake angle, F is total excavation force, δ is angle of external friction, ϕ is angle of internal friction, c is cohesion, R is resistant force, Q is surcharge load on the surface, w is the weight of the simulant (dependent on mineralogy M , particle size distribution PSD , density γ , and porosity e), β is shear plane failure angle, L_f is the length of the failure wedge, α is adhesion, and L_t is the length of the tool under the subsurface.

Reece's Fundamental Equation (2D version) of Earthmoving (FEE; Equations 1-4; Reece, 1964)

Reece, A. R. (1964), "The Fundamental Equation of Earthmoving Mechanics", *Proceedings of the Institution of Mechanical Engineers 1964-65*.

$$F = w(cdN_c + \gamma d^2 N_\gamma + QdN_q) \quad (1)$$

$$N_c = \frac{1 + (\cot(\beta) \cot(\beta + \phi))}{\cos(\rho + \delta) + (\sin(\rho + \delta) \cot(\beta + \phi))} \quad (2)$$

$$N_\gamma = \frac{(\cot(\rho) + \cot(\beta))}{2(\cos(\rho + \delta) + (\sin(\rho + \delta) \cot(\beta + \phi)))} \quad (3)$$

$$N_q = \frac{(\cot(\rho) + \cot(\beta))}{\cos(\rho + \delta) + (\sin(\rho + \delta) \cot(\beta + \phi))} \quad (4)$$

In Equations 1-4, F is total excavation force, d is scooping depth, ρ is rake angle, δ is angle of external friction, ϕ is angle of internal friction, c is cohesion, Q is surcharge load on the surface, and N_c , N_γ , and N_q are dimensionless "N factors" (Reece, 1964).

Prediction of Excavation Forces

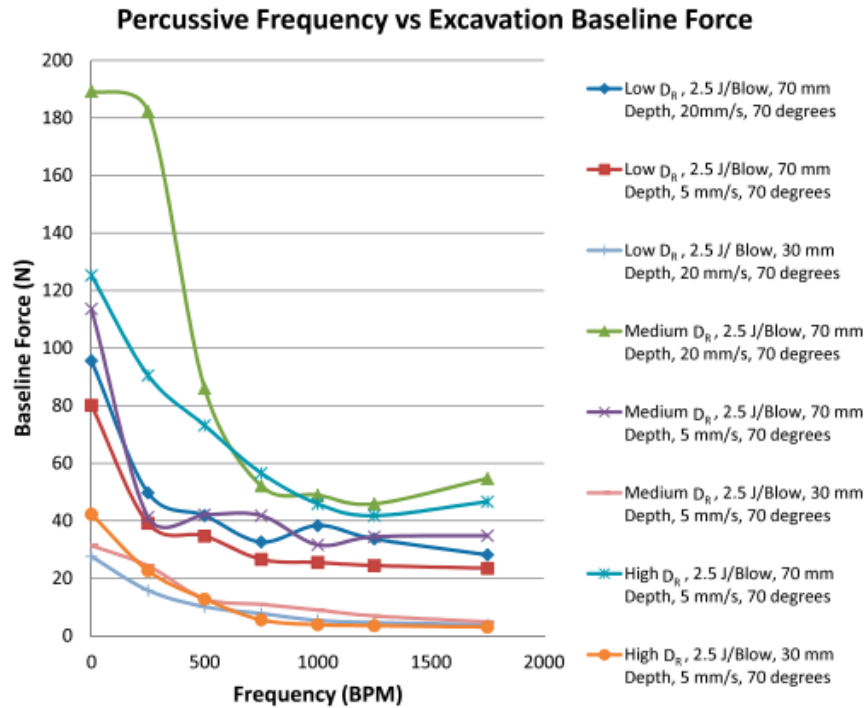


Fig. 11. Baseline excavation force as a function of applied percussive frequency: as percussive frequency is linearly increased, there is an exponential decrease in draft force

Table 3. Reece's FEE inverse model parameter estimations with 95% confidence intervals model for Green (2011) and Green et al. (2013) medium relative density, static, 30 mm depth, 70° rake angle.

Parameter	Estimated Value	Expected Value
<i>d</i> = 30 mm		
<i>c</i> (Pa)	1425.65 ± $\frac{1818.14}{1393.72}$	819.46
φ (°)	40.61 ± $\frac{34.77}{37.70}$	44.42
δ (°)	39.64 ± $\frac{25.67}{38.81}$	29.47 (0.67 φ)
θ (°)	17.92 ± $\frac{55.83}{17.20}$	33.00
<i>d</i> = 50 mm		
<i>c</i> (Pa)	649.34 ± $\frac{2153.72}{649.07}$	755.03
φ (°)	47.50 ± $\frac{27.65}{46.76}$	43.67
δ (°)	40.98 ± $\frac{40.97}{40.69}$	29.11 (0.67 φ)
θ (°)	6.64 ± $\frac{72.64}{6.04}$	35.00
<i>d</i> = 70 mm		
<i>c</i> (Pa)	1868.17 ± $\frac{1686.39}{1794.53}$	713.88
φ (°)	33.59 ± $\frac{41.27}{26.99}$	43.16
δ (°)	40.54 ± $\frac{40.015}{39.59}$	28.77 (0.67 φ)
θ (°)	31.64 ± $\frac{33.04}{30.84}$	37.00

Quantitative Optimization of Planetary Excavation
80NSSC23K1173
Jared M. Long-Fox
University of Central Florida

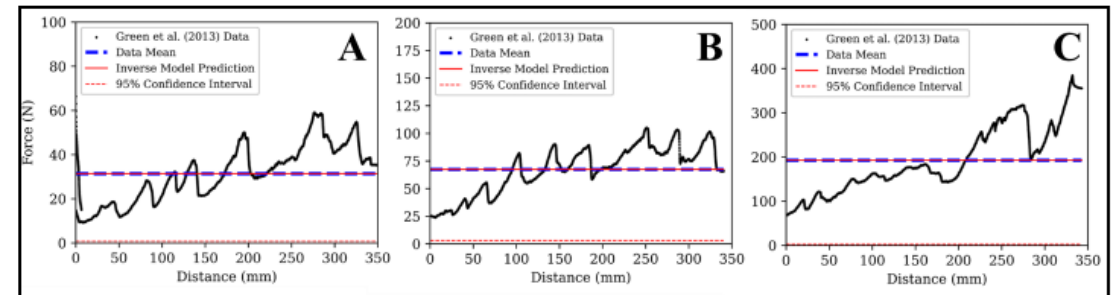


Figure 3. Reece's FEE inverse model fit to the medium relative density (A) 30 mm depth, (B) 50 mm depth, and (C) 70 mm depth 70° rake angle, 5 mm/s excavation data from Green (2011) and Green et al. (2013).

Regolith Resource Uses

- Science investigations
- Geology investigations
- Propellant Oxidizer (O₂)
Extraction from silicates
- Water Extraction (H₂O) for
industrial consumables
- H₂/O₂ propellant
- Water (ice or liquid) radiation
shielding
- Human life support
consumables
- Plant growth consumables
- Fuel cell consumables
- Other volatiles extraction (He₃, H₂, CH₄, CO, etc.)
- Metals extraction for manufacturing
- Mineral glass fibers for
manufacturing
- Regolith bulk aggregate (Berms,
Contours, sandbags)
- Radiation bulk shielding for human
health: Solar Particle Events (SPE) &
Galactic Cosmic Rays (GCR)
- Nuclear power plant bulk regolith
radiation shielding
- Construction materials feedstocks
(Concrete, bricks, pavers, etc.)
- Industrial processes (solvents,
reactant, etc.)
- Solar photo voltaic arrays
manufacturing for electrical power
- Thermal wadi's for heat energy
storage

ISRU Workflow

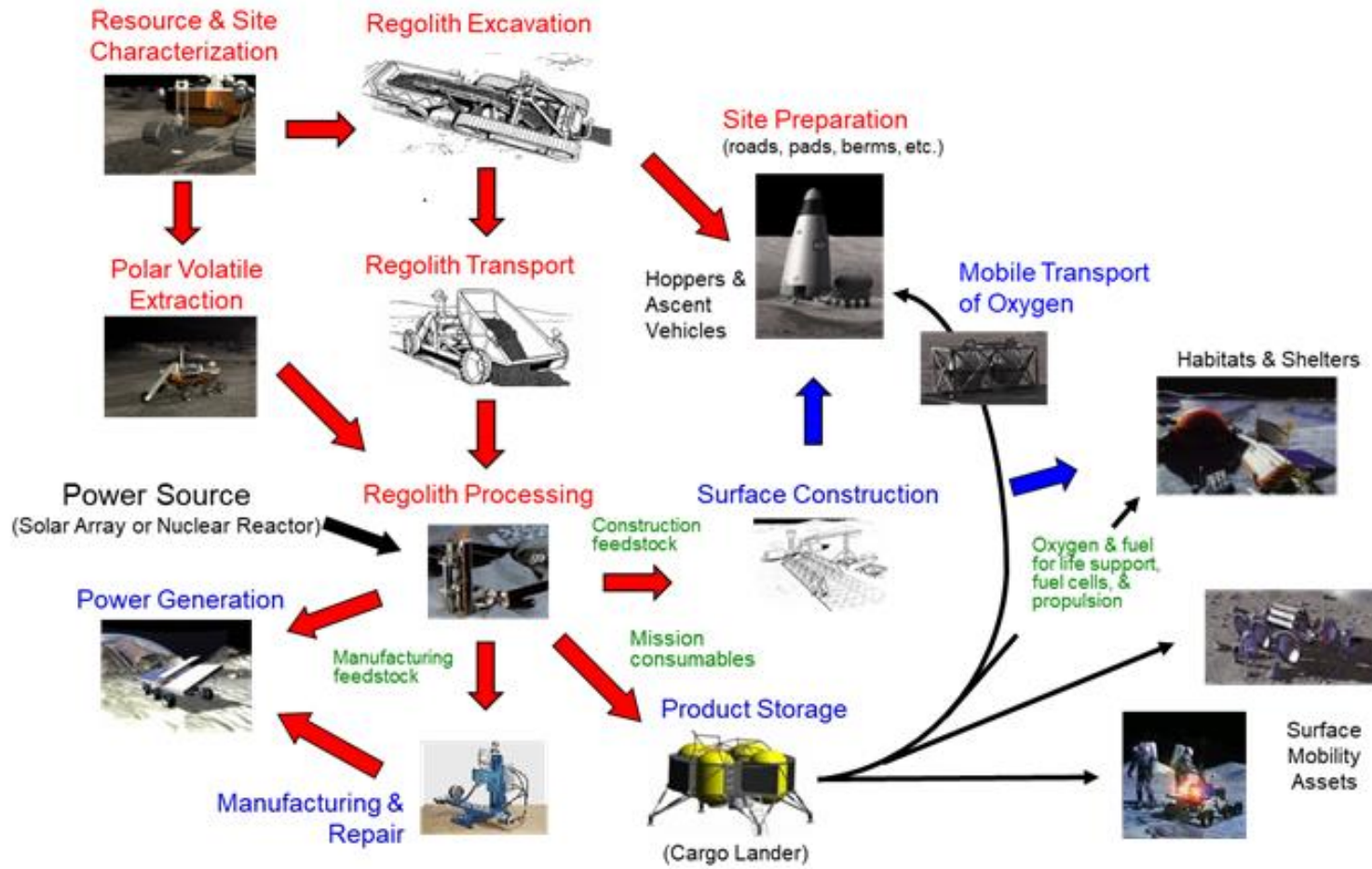


Figure 1. ISRU Workflow showing the Role of Regolith (G. Sanders, NASA)

Autonomy has been widely embraced in the Mining Industry on Earth:

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor

Differences in Space

- Lunar excavation requirements are different than terrestrial excavation
- Launch mass and volume limitations
- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering unknown sub surface rock obstacles
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of permanently shadowed craters
- Unknown soil mechanics in polar regions
- Extreme access and mobility
- Slopes >35 degrees
- Extended nighttime operation and power storage
- Electrical power storage with high power density
- Thermal management in temperature extremes
- Robust “line of sight” RF or laser communications
- Long life and reliability
- Long term maintenance & life cycle

Table 1. History of NASA lunar excavator prototypes

Dates	Excavator Prototype
1989-91	NASA Space Exploration Initiative (SEI) Eagle Engineering inc. Concept Studies
2001-2011	Colorado School of Mines (Dr. Mike Duke research initiative)
2007	NASA GRC Cratos Scraper Excavator
2007-2009	NASA Centennial Challenge for Lunar Excavation
2008	Lockheed Martin Bucket Drum - Mauna Kea, Hawai'i NASA Field Tests
2008-2012	Canadian Space Agency, Mauna Kea, Hawai'i ISRU Tests (NORCAT [#] / Ontario, Drive & Gear (ODG) inc./Neptec inc. Juno Rover)
2009-2010	NASA KSC LANCE* Dozer blade & JSC Chariot Mobility Platform
2009-2011	JPL ATHLETE [†] hexapod robot with bucket implement
2009-2010	Caterpillar inc. Multi Terrain Loader Tele-Operations at JSC
2009-2010	SysRand inc. Moonraker bucket chain excavation implement
2009-2015	Honeybee inc. Pneumatic PlanetVac Micro Excavator
2010-2012	NASA JSC Space Exploration Vehicle (SEV) & LANCE
2010-2022	NASA Lunabotics Robotic Mining Competition
2010-2012	Honeybee inc. Planetary Volatile EXtractor (PVEX)
2010-2012	Astrobotic inc. Polaris Bucket transverse bucket wheel excavator
2013-2019	NASA JSC/GRC/KSC Centaur+ APEX [^] + Badger bucket
2010-2019	NASA KSC Swamp Works RASSOR ^ε
2019-2022	NASA KSC Swamp Works ISRU Pilot Excavator (IPEX)

[#] Northern Centre for Advanced Technology (NORCAT) now Deltion, inc.

^{*} Lunar Attachment Node for Construction Excavation (LANCE)

[†] All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE)

[^] Advanced Planetary Excavator (APEX)

^ε Regolith Advanced Surface Systems Operations Robot (RASSOR)

Lunabotics Competition



The annual NASA Robotic Mining Competition (RMC): Lunabotics competition is a full-on engineering exercise where students receive practical experience in the full engineering lifecycle process from concept development, design, robot fabrication, hands on competition to system closeout.

- **Robot Controlled Remotely or Autonomously**
- **Visual and Auditory Isolation from Operator**
- **Excavates Black Point 1 (BP-1) Lunar Basalt Regolith Simulant**
- **Weight Limit - 80 kg**
- **Dimension Limits - 1.5 m length x 0.75 m width x 0.75 m height**
- **Designed, Built and Tested by University Student Teams**
- **Uses NASA systems engineering methods**
- **Over 55 US universities attend each year at Kennedy Space Center**

A Positive Experience with Personal Growth



<https://www.nasa.gov/offices/education/centers/kennedy/technology/nasarmc.html>
<https://www.facebook.com/pg/Lunabotics.Competition/posts/>

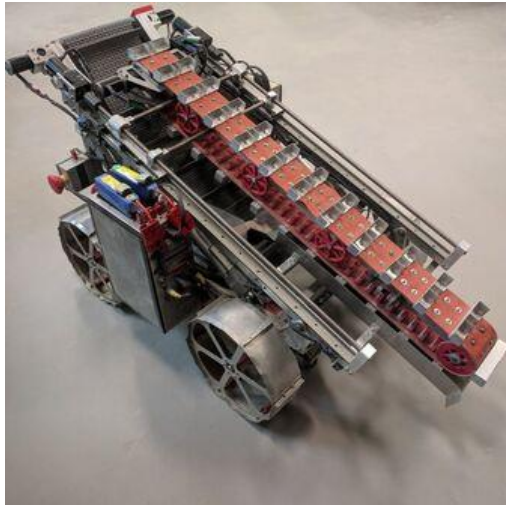
Many Lunabotics Alumni are working in the space industry today

Not necessarily the best lunar excavator designs but the most popular:

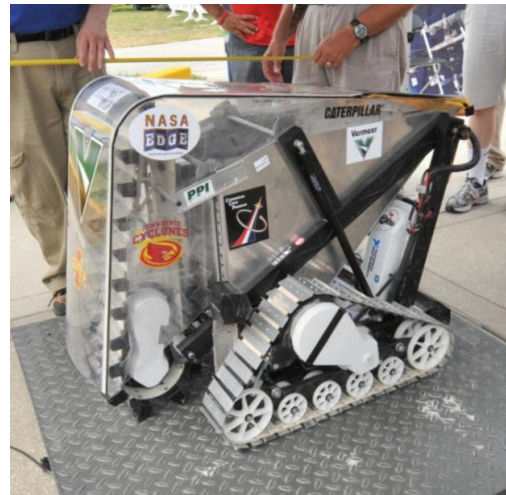
Table 2. Most popular excavation and regolith transportation mechanisms

# sys	regolith excavation mechanism	# sys	regolith transportation mechanism
101	bucket ladder	103	bucketladder
37	front end loader	40	in scoop
29	bucket belt	22	conveyor belt
27	bucketwheel	21	bucketbelt
17	bucket drum	15	auger
15	snow blower (auger or brush)	11	Over shoulder dump into hopper
12	auger	8	chute for guiding regolith
8	backhoe	7	bucketdrum
8	bulldozer	7	drum
8	scraper	6	bucketwheel
7	large single scoop	6	impeller
4	dual auger	4	bucket rim
4	dual bucket wheel	4	bucketwheel discharge through bottom
4	rotating brush	4	in bucket
3	excavating wheels	4	rotate scoop to slide simulants in hopper
2	claw/gripper scoop	3	throw from impeller
2	dual bucketladder	2	bucketwheel with side discharge
2	dual counter rotating bucketdrums	2	paddle conveyor
2	large bulldozer scoop	2	raising scraper with chute
2	paddle conveyor	2	thrown from brush up ramp

Examples of the most popular regolith excavation and transportation mechanisms: Bucket Ladders



University of Alabama



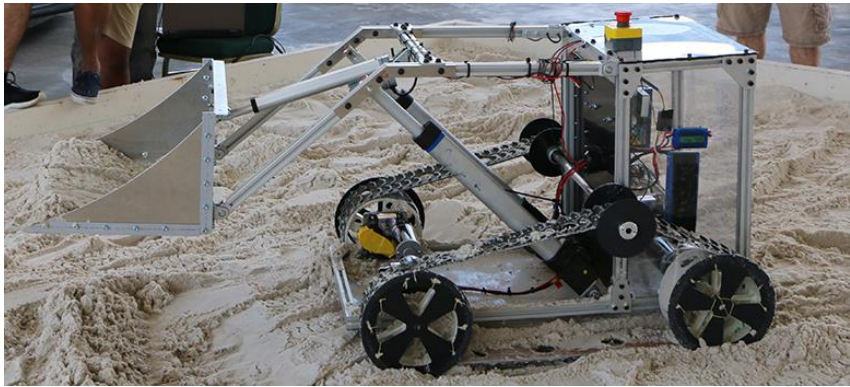
Iowa State University



Vanderbilt University

Lunabotics Competition

Examples of the most popular regolith excavation and transportation mechanisms: Front End Bucket Loader



Illinois Institute of Technology



University of Utah



U. Alabama: Outreach to the Next Generation

ISRU Pilot Excavator

Dual Bucket Drum Excavator Prototypes:



15kg excavator lunar gravity offload testing



15kg and 65kg excavator size comparison

This project will develop the ISRU Pilot Excavator: a 30 kg-class excavator for demonstration on a CLPS flight.

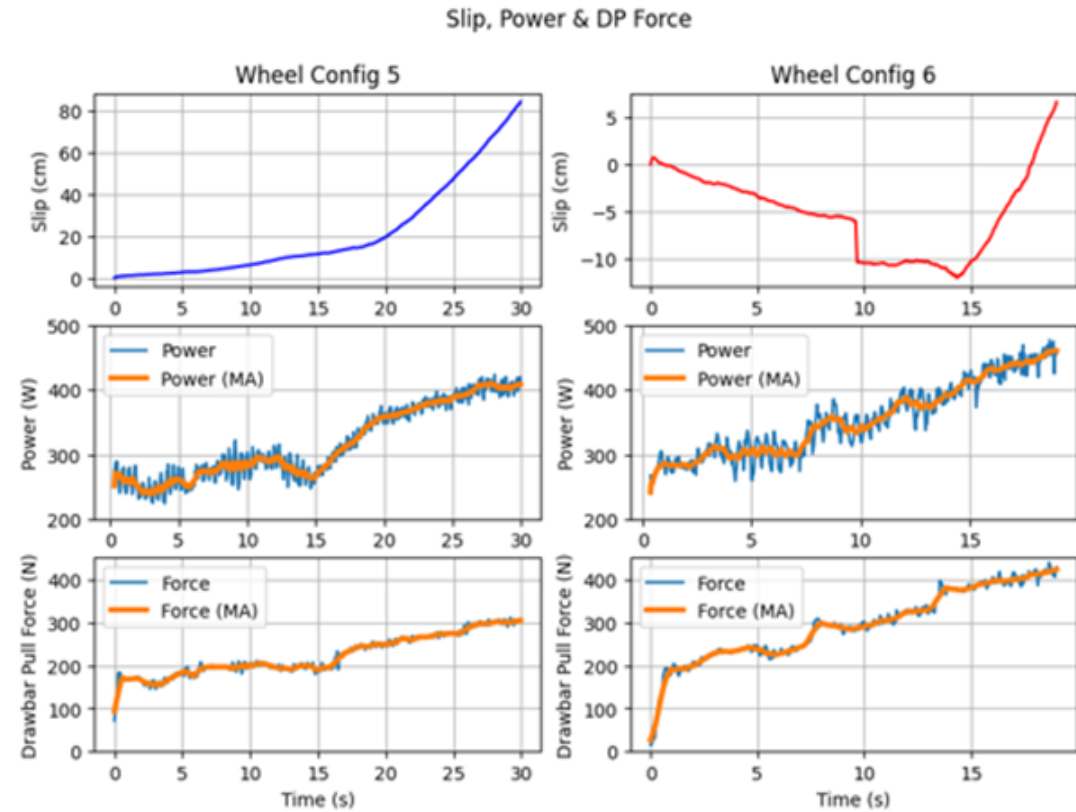
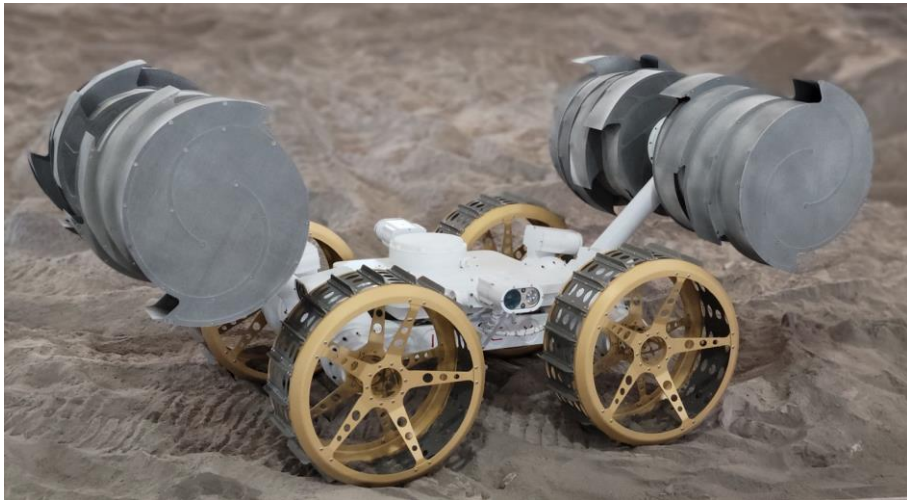
Traction vs Excavation Forces

Assume each RASSOR Excavator scoop is about the same as a surveyor Scoop ~100 N

Horizontal Excavation Force ~ 100 N

Draw Bar Pull ~ 350 N / 6 = 59 N

Excavation Force > Draw Bar Pull = Wheel Slip



ISRU Pilot Excavator Wheel Testing in Lunar Regolith Simulant

Liz Zhang,¹ Jason Schuler,² Adam Dokos,³ Yinan Xu,⁴ Evan Bell,⁵ Thomas Muller⁶

Figure 14. Comparison between slip, power, and drawbar pull (DP) force over time for two wheel configurations.

Primary Goal

Reduce risk of excavation for ISRU pilot plant demonstration

- Partnership between KSC, JSC, JPL, and Astrobotic
 - 30kg bucket drum excavator
- Astrobotic CubeRover avionics and software
 - Enter TRL 4 – Exit TRL 6
- 11 day end-to-end ground demonstration

Quantitative Impact

- Traverse total of **150km** in Lunar environment (3x current SOA)
 - Traffic over same terrain **700x** (140x current SOA)
- Move a total of **10t (metric tons)** of regolith **100 meters** over **11 days** (200x current SOA)



Summary

- Regolith excavation and transportation form the basis of regolith mining and also have critical applications in site preparation and construction activities.
- Since 2001, many robotic excavator prototypes for extra-terrestrial uses have been attempted. However, the fidelity of the testing environments remains at a low technology readiness level (TRL) of 3 or 4
- The reliability of the proposed designs has not been demonstrated.
- Since these excavation robots will be operating in a much harsher and regolith interactive manner than current Mars and Moon scientific rovers, new ways of dealing with regolith dust, rocks, cryogenic icy regolith, extreme terrain, very cold operating temperatures, lunar nights, shadowed regions and more must be developed, before the NASA Artemis program, and others, can successfully use ISRU and perform in-situ construction.