Robotic Construction on the Moon

International Space University

Space Studies Program (SSP) 21

July 23, 2021

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Outline

- Introduction – NASA Lunar Artemis Program
- In Situ Resources for Construction Materials
- Project Site Characterization
- Robot Operations
- Robot Characteristics
- Lunar Challenges
- Examples of Robotic Construction


NASA
ARTEMIS
PHASE ONE:
Lunar South Pole by 2024

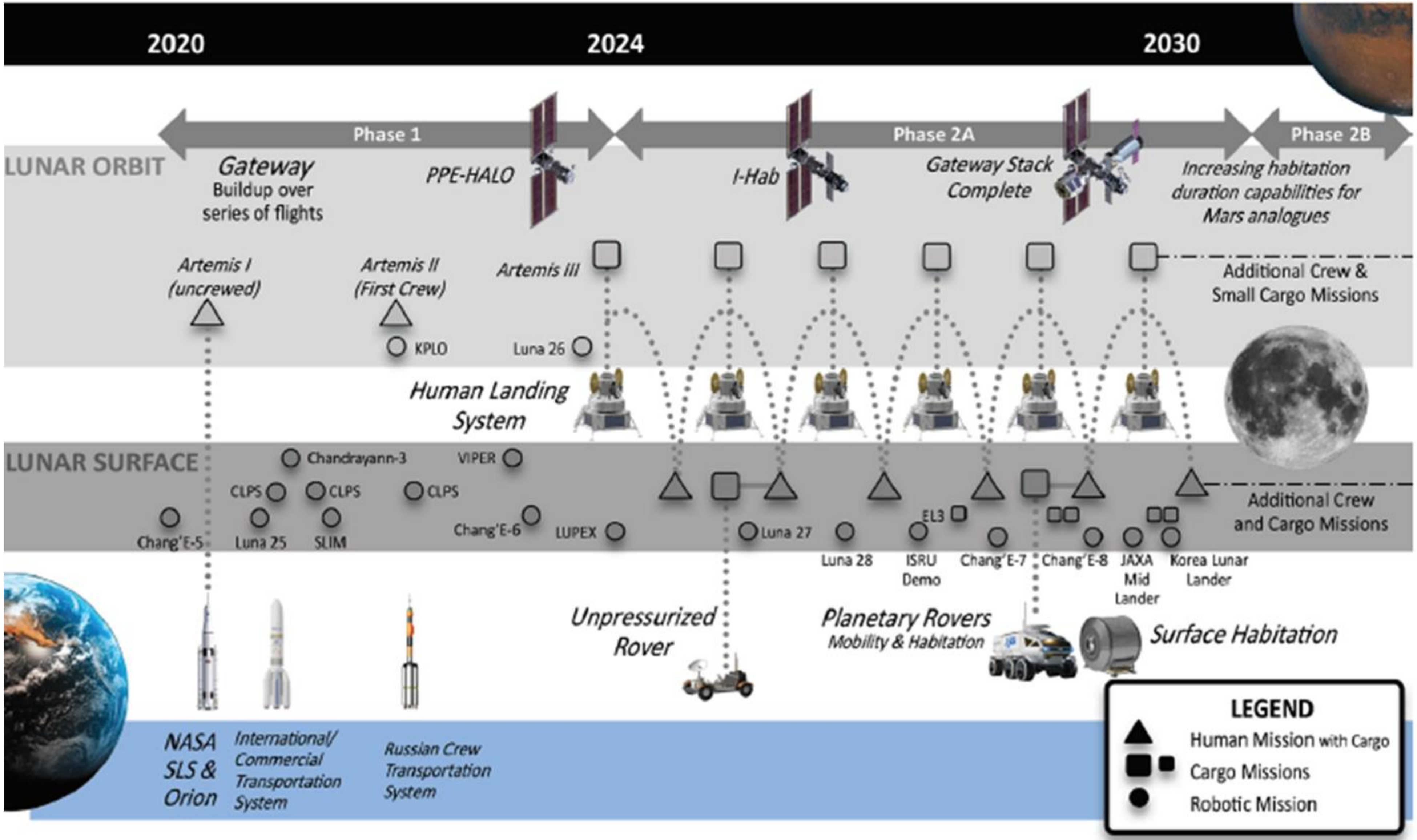
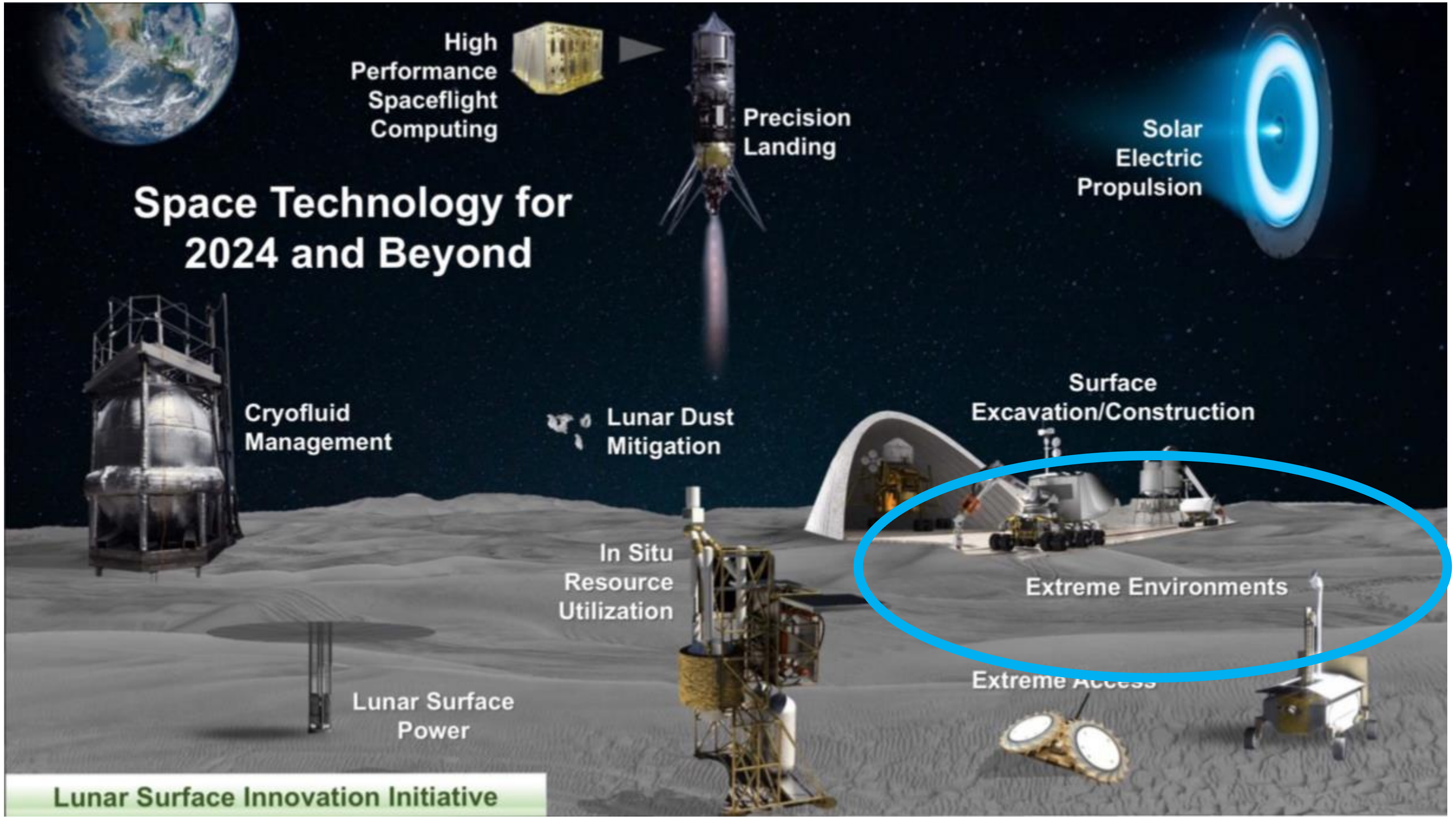


Figure 1. Updated ISECG Lunar Surface Exploration Scenario.

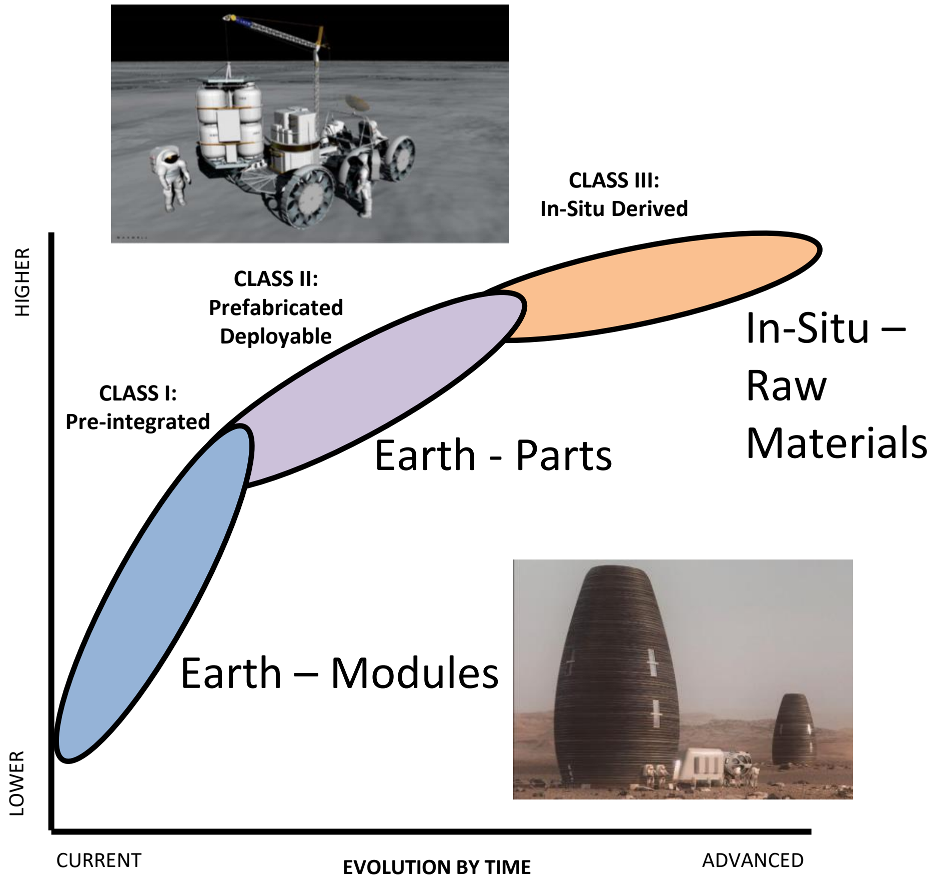

NASA
ARTEMIS
PHASE TWO:
Mars Forward Capabilities,
Sustainable Lunar Presence

Lunar Surface Innovation Initiative (LSII)



http://lsic.jhuapl.edu/

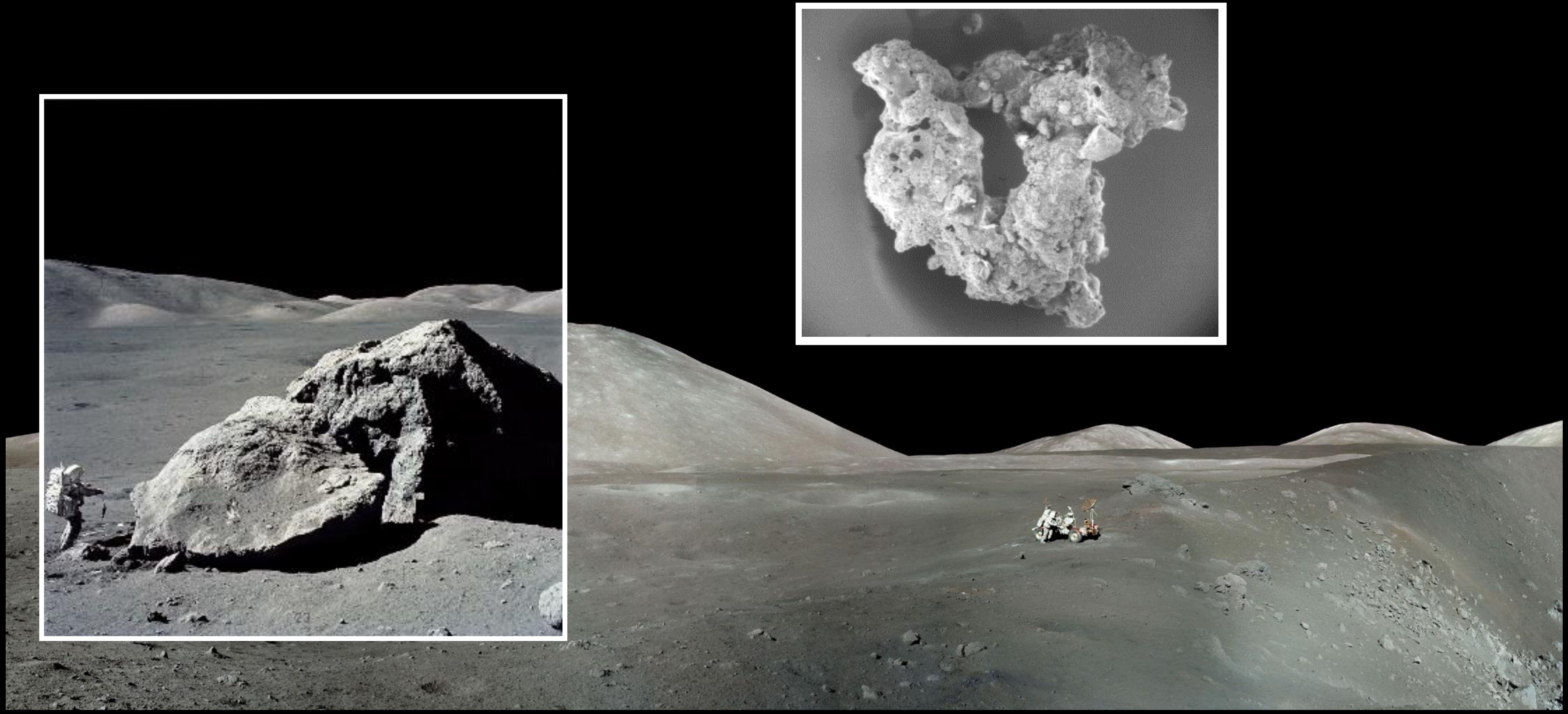
Surface Construction Classifications:



Raw Materials ⇨ Regolith + Volatiles

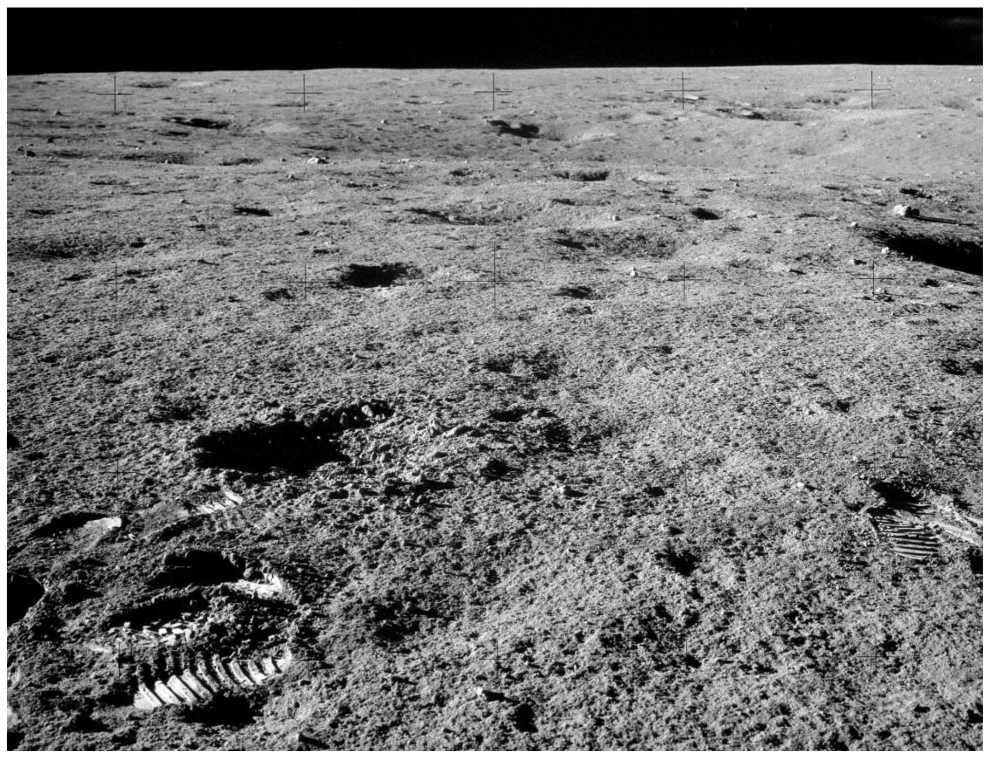
Habitat Classification	Key Characteristics
CLASS I **Pre-integrated** Modular	• Earth Manufactured • Earth Assembled & Fully Outfitted • Pre-Integrated & Tested prior to Launch • Space Delivered with Immediate Habitation Capability • Launch Shroud Constrained • Limited to Launch Vehicle Payload Size Capability • Limited to Launch Vehicle Payload Mass Capability
CLASS II **Prefabricated Deployable. Space or Surface Deployed & Assembled** Parts	• Earth Manufactured • Requires Space Deployment, Assembly & Outfitting • Requires Robotic and Human Labor During Assembly • Partial Integration Capable for Subsystems • Requires some or all Internal Outfitting emplacement • Critical Subsystems are Earth Based and Tested prior to Launch • Requires Assembly & Checkout prior to Human Occupancy • Larger Volumes Capable • Not Restricted to Launch Vehicle Shroud Size • Restricted to Launch Mass. Deliver on multiple vehicles
CLASS III **In-Situ Derived and Constructed** Raw Materials	• Manufactured In-Situ Derived with Space Resources (Lunar or Mars) • In-Space Constructed • Requires Robotic Manufacturing Capability & Infrastructure • Requires Robotic and Human Labor During Construction • Requires Integration of Subsystems • Requires all Internal Outfitting emplacement • Critical Subsystems are Earth Based and Tested prior to Launch • Requires Assembly to become Operability • Larger Volumes Capable • Not Restricted to Launch Vehicle Size • Not Restricted to Launch Mass

Regolith: *S*urficial layer covering the entire lunar surface ranging in thickness from meters to tens of meters formed by impact process – physical desegregation of larger fragments into smaller ones over time.



Rock Granular Material =
In-Situ Construction Material

APOLLO 16



APOLLO 12

Lunar Regolith Geotechnical Properties

National Aeronautics and
Space Administration

SLS-SPEC-159
REVISION G
EFFECTIVE DATE: DECEMBER 11, 2019

CROSS-PROGRAM
DESIGN SPECIFICATION FOR
NATURAL ENVIRONMENTS (DSNE)

https://www.lpi.usra.edu/lunar/strategies/NASA_SLS-SPEC-159G_DSNE_2019-12-11.pdf

https://www.lpi.usra.edu/publications/books/lunar_sourcebook/

Lunar Regolith Geotechnical Properties for Civil Engineering Analysis

Table 3.4.2.3-1 Summary of bulk regolith properties taken as representative of typical lunar characteristics based on prior landed missions and sample properties.

Property	Value	Units	Notes	DSNE Section	Sources
Bulk Density (ρ)	1.58 ± 0.05: 0-30 cm 1.74 ± 0.05: 30-60 cm	g cm^{-3}	Intercrater areas	3.4.2.3.1	Carrier et al. 1991
Relative Density (D_R)	74 ± 3: 0-30 cm 92 ± 3: 30-60 cm	%	Intercrater areas	3.4.2.3.2	Carrier et al. 1991
Specific Gravity (G)	3.1	-	Based on limited number of bulk samples	3.4.2.3.3	Carrier et al. 1991
Porosity (n)	49 ± 2: 0-30 cm 44 ± 2: 30-60 cm	%	Calculated	3.4.2.3.4	Carrier et al. 1991
Void Ratio (e)	0.96 ± 0.07: 0-30 cm 0.78 ± 0.07: 30-60 cm	-	-	3.4.2.3.4	Carrier et al. 1991
Permeability (Q)	1-7 x 10^{12}	m^2	Firing of Surveyor vernier engines on surface	3.4.2.3.5.1	Choate et al. 1968
Diffusivity	7.7 He, 2.3 Ar, 1.8 Kr	cm^2 s^{-1}	Measured on simulant function of gas species	3.4.2.3.5.2	Martin et al., 1973
Friction Angle (φ)	30-50	°	-	3.4.2.4.6	Carrier et al. 1991
Cohesion (c)	0.1 - 1	kPa	-	3.4.2.4.7	Carrier et al. 1991
Compression index (C_c)	0.3: loose 0.05: dense 0.01 - 0.11: range	-	Lab measurement on 1.2 to 200 g samples	3.4.2.4.2	Langseth et al. 1973
Recompression index (C_r)	0.003: avg 0 - 0.013: range	-	Lab measurement on 1.2 to 200 g samples	3.4.2.4.2.1	Carrier et al. 1991
Coefficient of lateral stress (K_0)	0.45: normally consolidated 3-5: below a few meters 0.7: recompacted	-	Lab measurement on 1.2 to 200 g samples	3.4.2.4.3	Carrier et al. 1991
Modulus of subgrade reactions (k)	8: avg 1-100: range	kPa cm^{-1}	Based on in situ observations of boot prints	3.4.2.4.5	Carrier et al. 1991

NASA SLS-SPEC-159 DSNE
Page 231

Lunar Regolith Resource Potential

Ilmenite - 15%
$FeO \bullet TiO_2$ (98.5%)
Pyroxene - 50%
$CaO \bullet SiO_2$ (36.7%)
$MgO \bullet SiO_2$ (29.2%)
$FeO \bullet SiO_2$ (17.6%)
$Al_2O_3 \bullet SiO_2$ (9.6%)
$TiO_2 \bullet SiO_2$ (6.9%)
Olivine - 15%
$2MgO \bullet SiO_2$ (56.6%)
$2FeO \bullet SiO_2$ (42.7%)
Anorthite - 20%
$CaO \bullet Al_2O_3 \bullet SiO_2$ (97.7%)

Water (?, >1000 ppm)

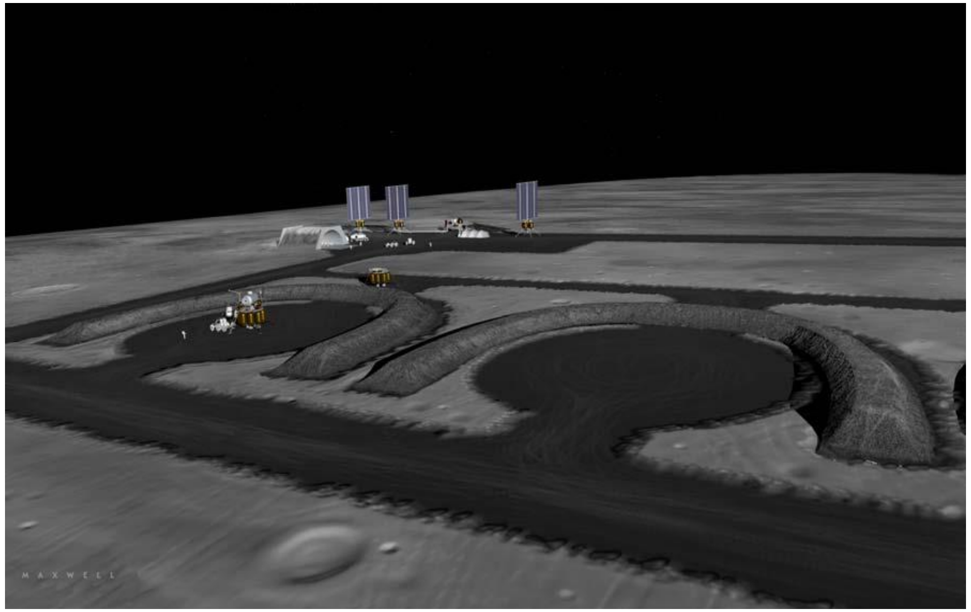
Solar Wind
Hydrogen (50 - 100 ppm)
Carbon (100 - 150 ppm)
Nitrogen (50 - 100 ppm)
Helium (3 - 50 ppm)
^3He (4 - 20 ppb)

- Oxygen is the most abundant element on the Moon
- Solar wind deposited volatile elements are available at low concentrations
- Metals and silicon are abundant
- Water may be available at poles
- Lunar mineral resources are understood at a global level with Apollo samples for calibration

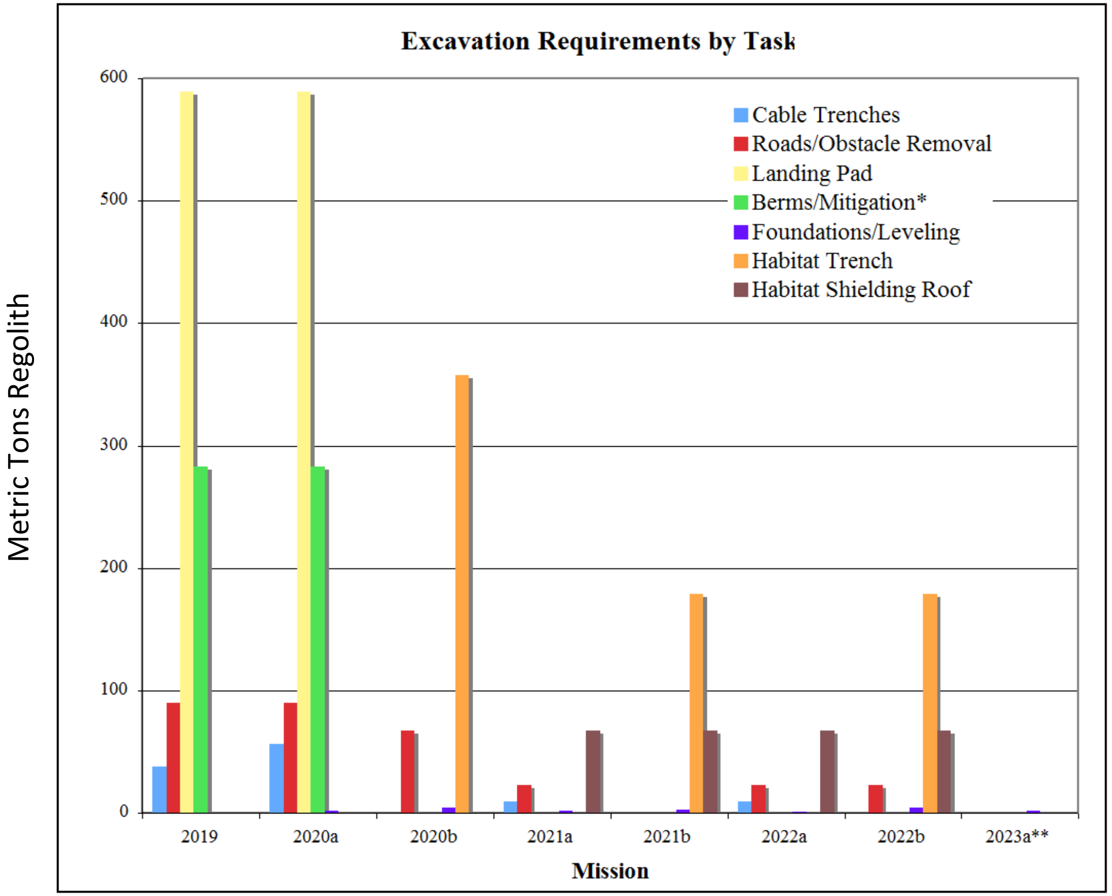
Criteria for Lunar Outpost Excavation

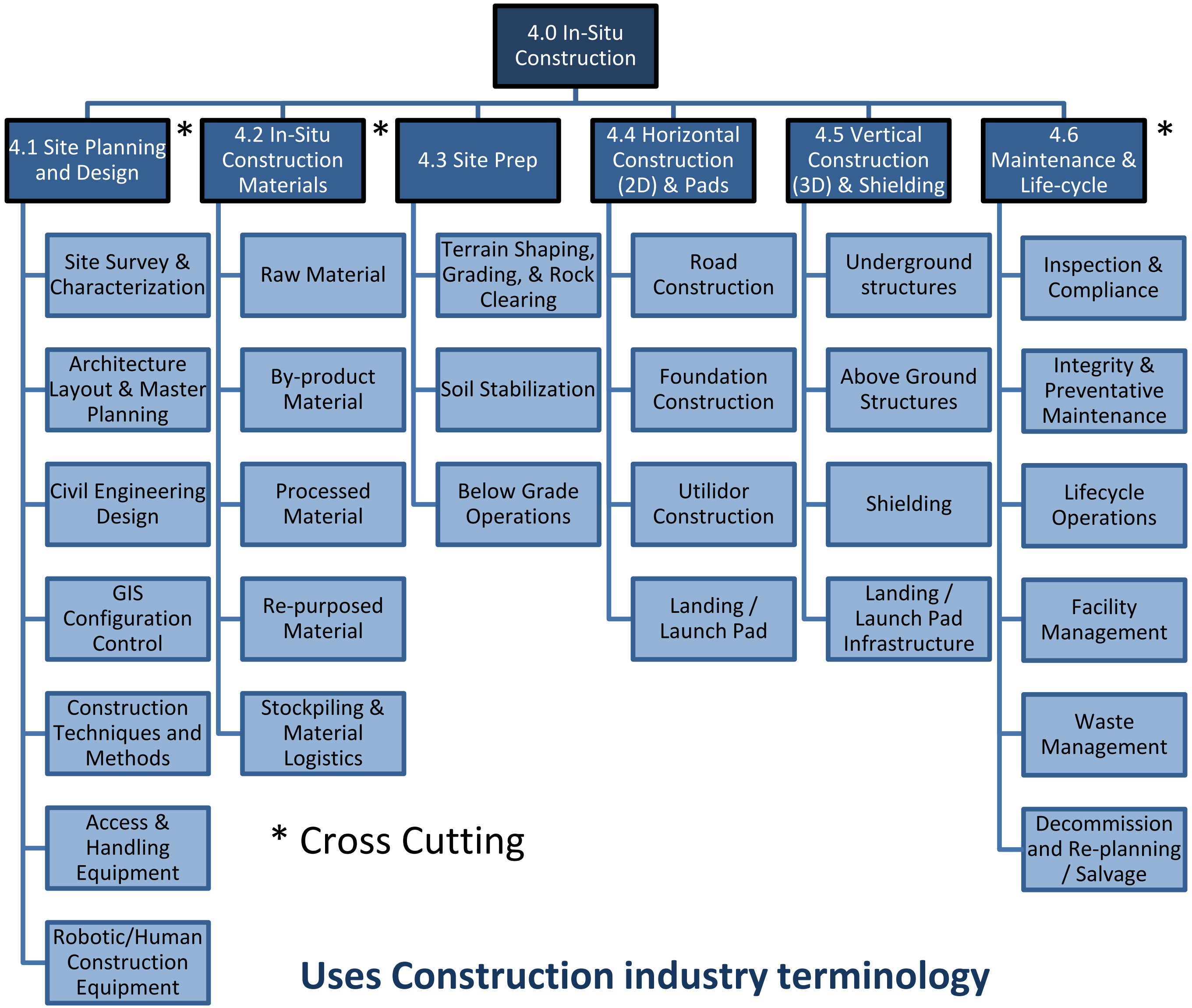
R. P. Mueller and R. H. King

Space Resources Roundtable –SRR IX
October 26, 2007
Golden, Colorado



SUMMARY	
Task	%
Trenching	4
Clearing and Compacting	48
Building Berms	18
Habitat Shielding	31
	100
Ice Mining	17
Regolith Mining	83
Construction	84
Mining	16





Uses Construction industry terminology

Lunar Surface Infrastructure

Launch/Landing Pads

Beacon/Navigation Aids

Lighting Systems

Communications Antenna Towers

Blast Protection Berms

Perimeter Pad Access & Utility Roads

Spacecraft Refueling Infrastructure

Power Systems

Radiation, Thermal & Micro Meteorite Shielding

Electrical Cable/ Utilities Trenches

Foundations / Leveling

Trenches for Habitat & Element Burial

Regolith Shielding on Roof over Trenches

Equipment Shelters

Maintenance Hangars

Dust free zones

Thermal Wadi's for night time survival

Regolith Mining for O2 Production

H2O Ice/Regolith Mining from Shadowed Craters

What is a Robot?

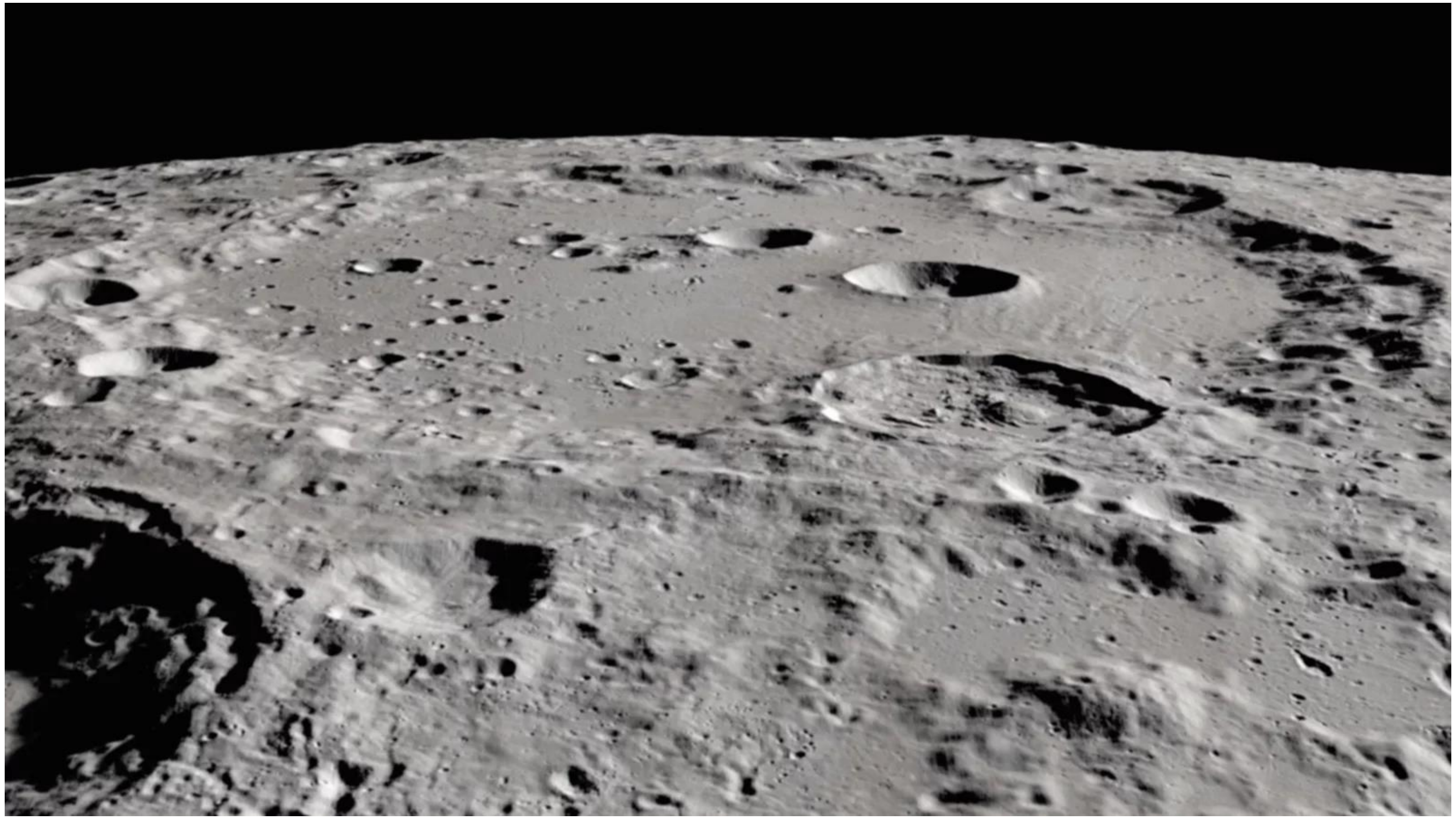
1920s: from Czech, from *robota* ‘forced labor’. The term was coined in K. Čapek's play *R.U.R.* ‘Rossum's Universal Robots’ (1920); a machine that does work.

NASA

NASA

Project Site Characterization

- Construction planning – phased construction
  - Manifesting strategy for Earth to Moon logistics
- Topographical, terrain, geologic and geotechnical survey
- Identify site development resources



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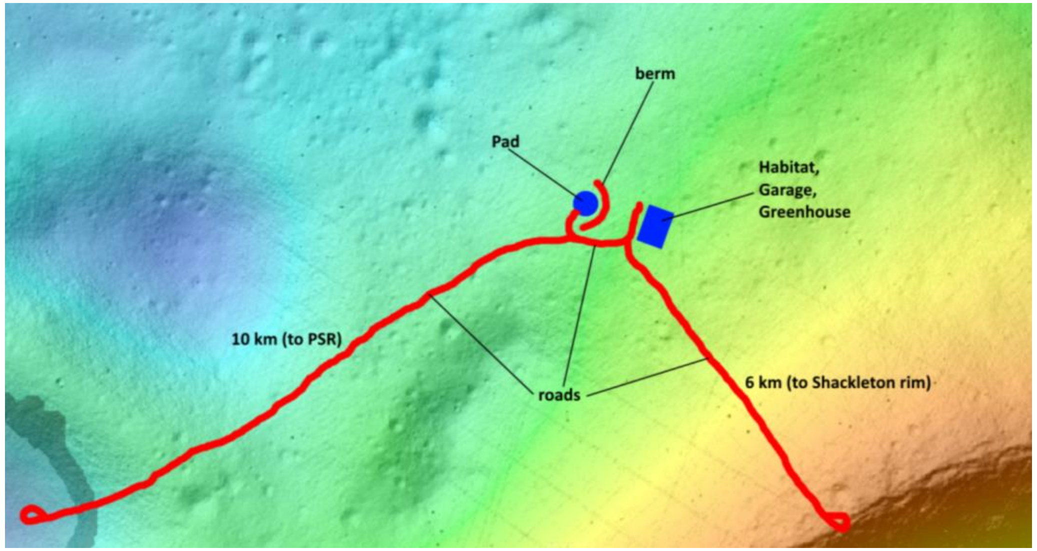
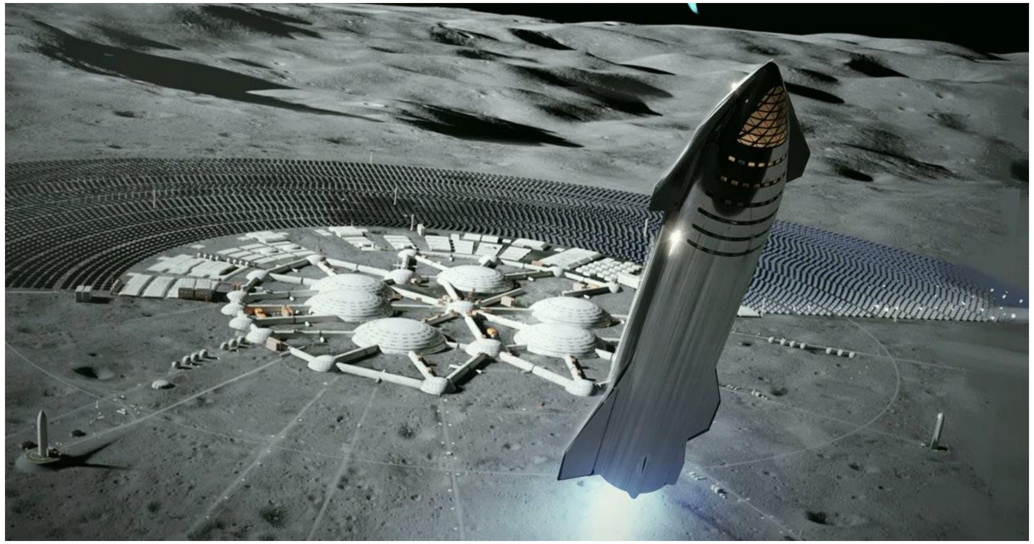
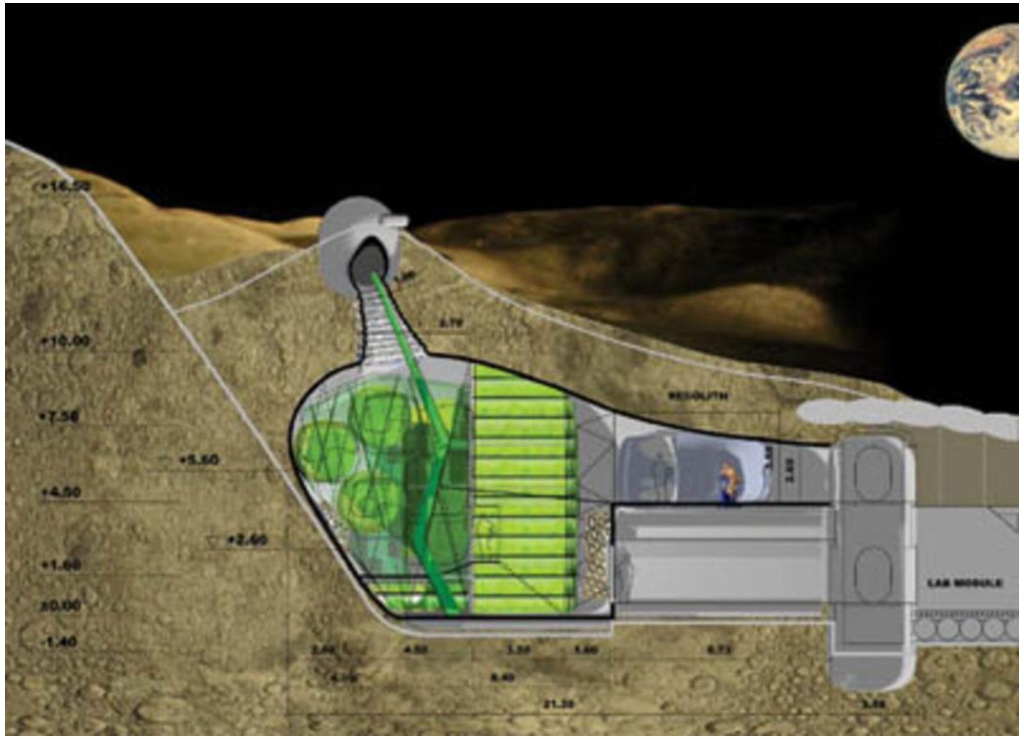
WHAT will you build?





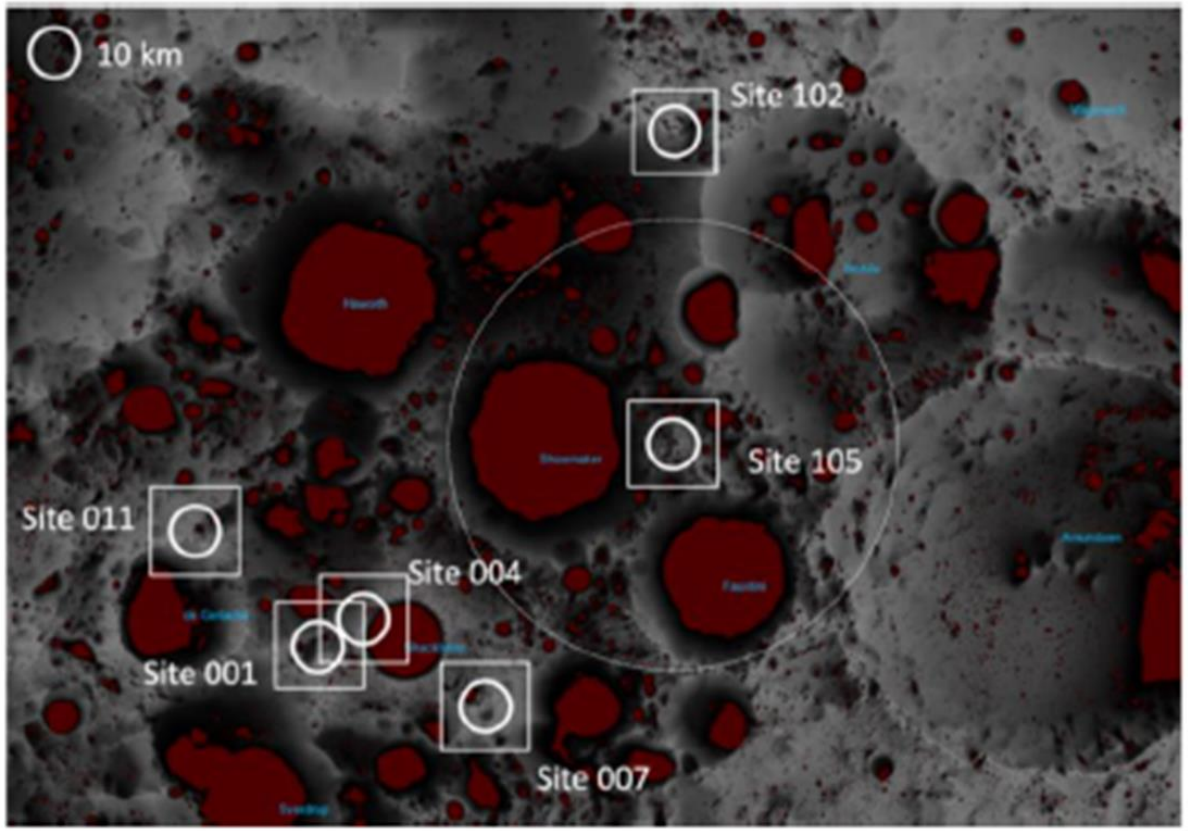
NASA/ICON/Search+



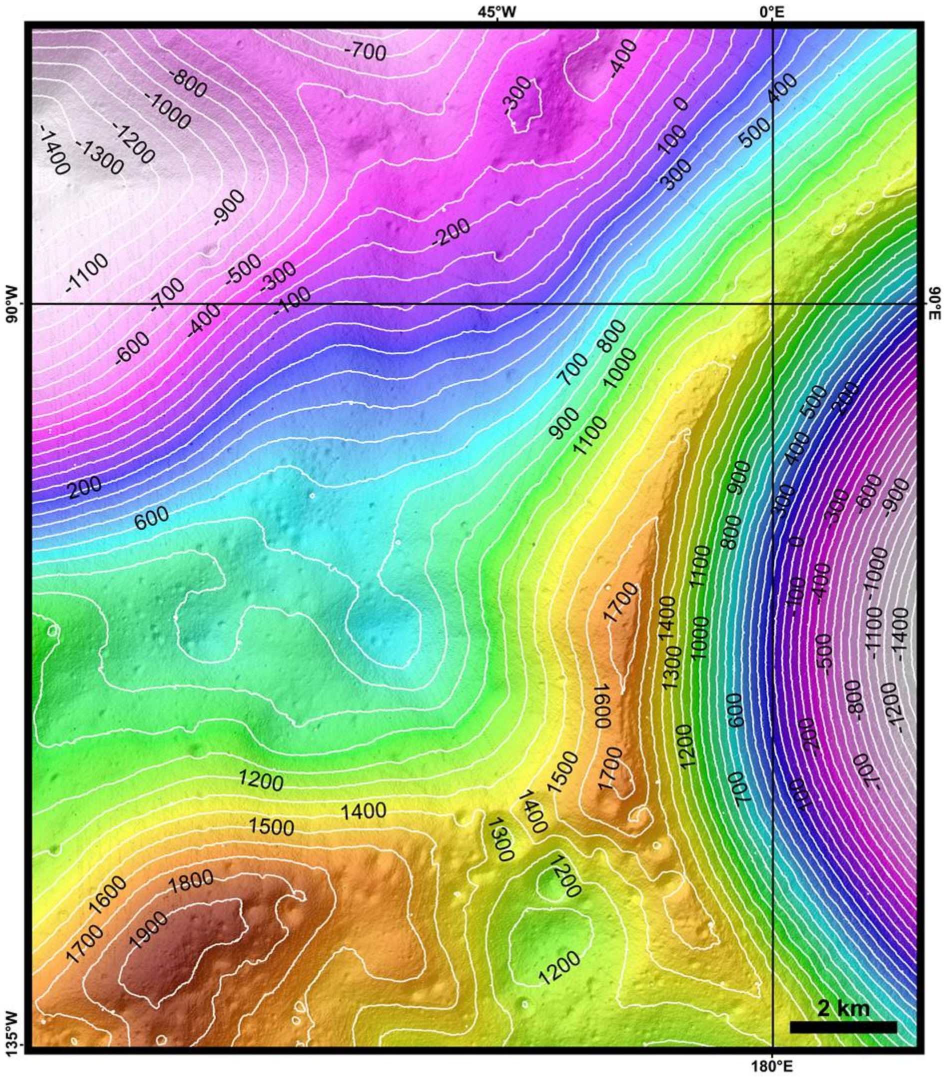
ESA Lunar Habitat for
extended scientific research

WHERE will you build?

SOUTH POLAR REGION



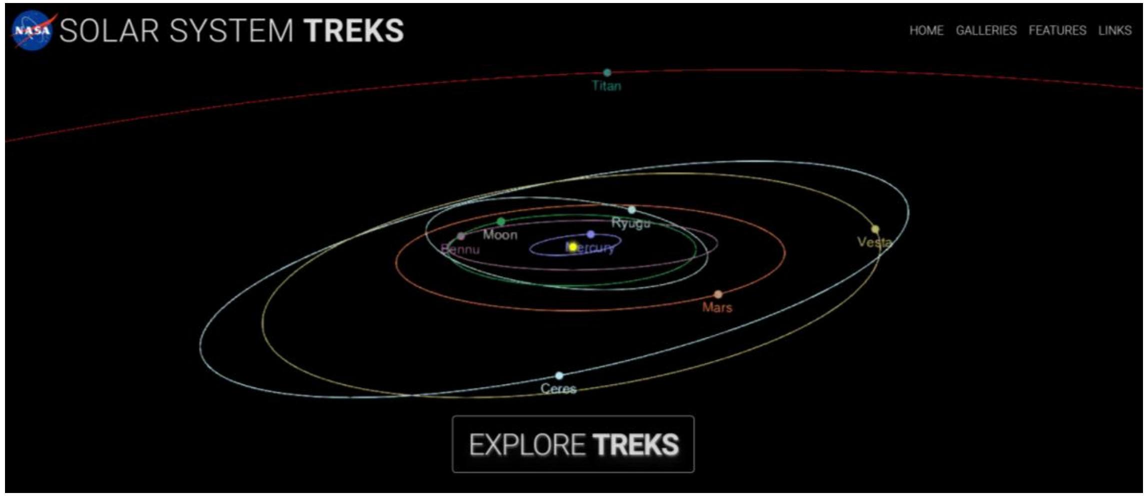
NASA Artemis III Science Definition Report

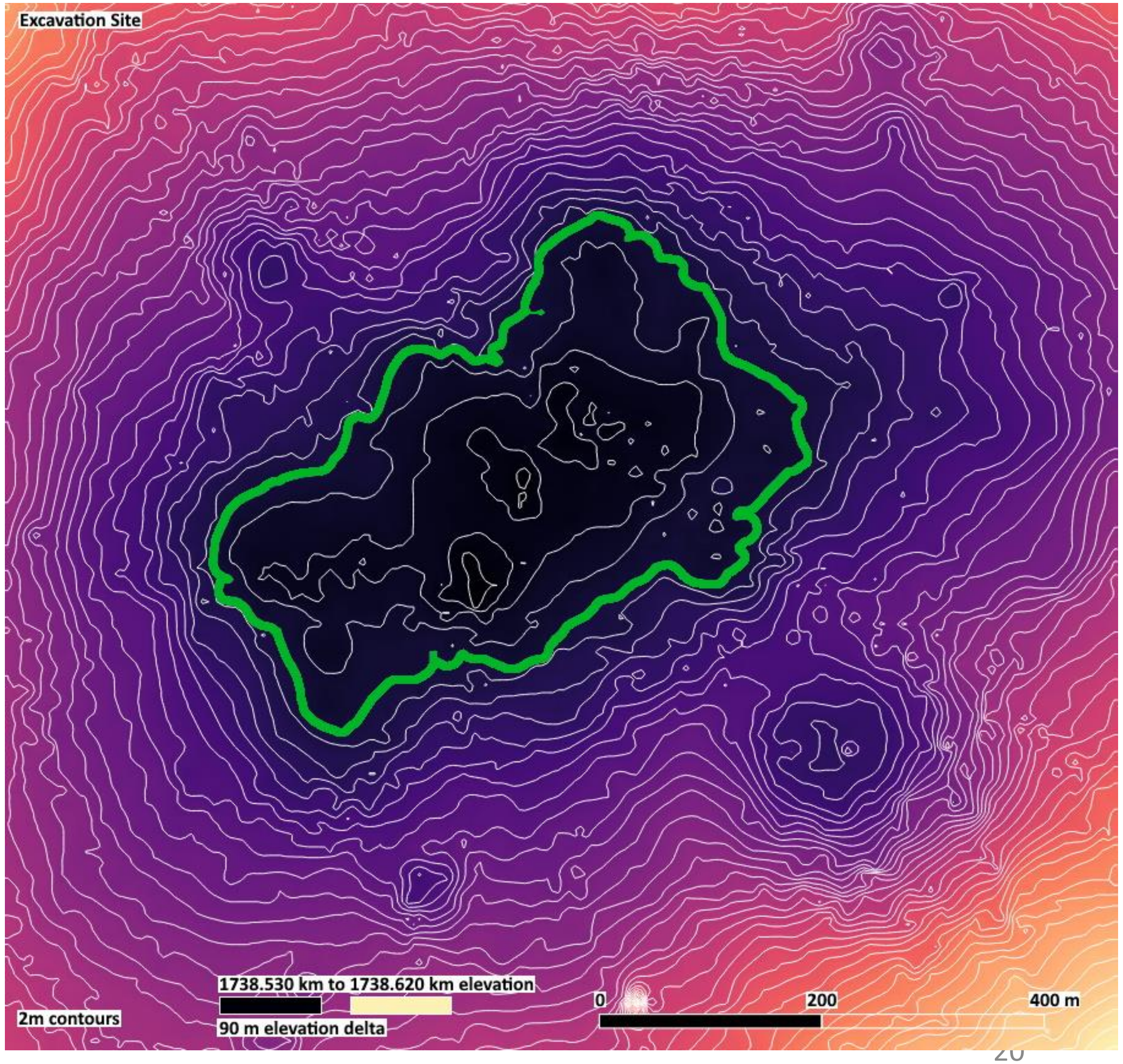


Topographic Survey

2 METER CONTOURS

https://trek.nasa.gov/





https://breaktheicechallenge.com/resources-media/

Lunar Terrain Types

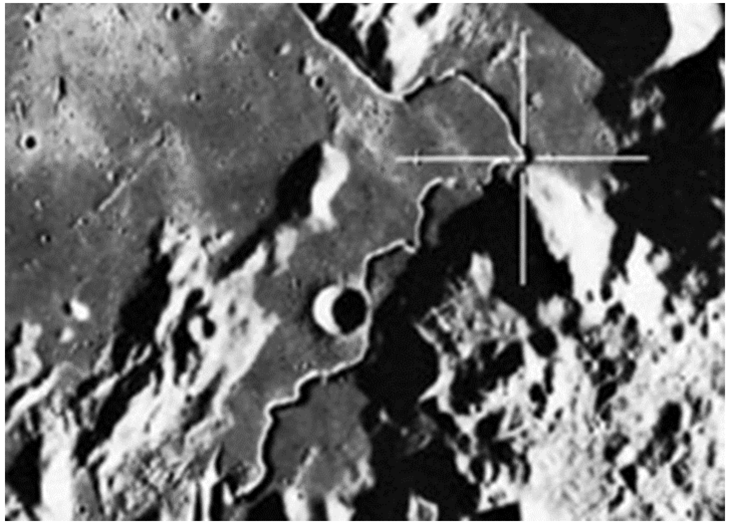
SMOOTH

BLOCKY

OBSTRUCTED

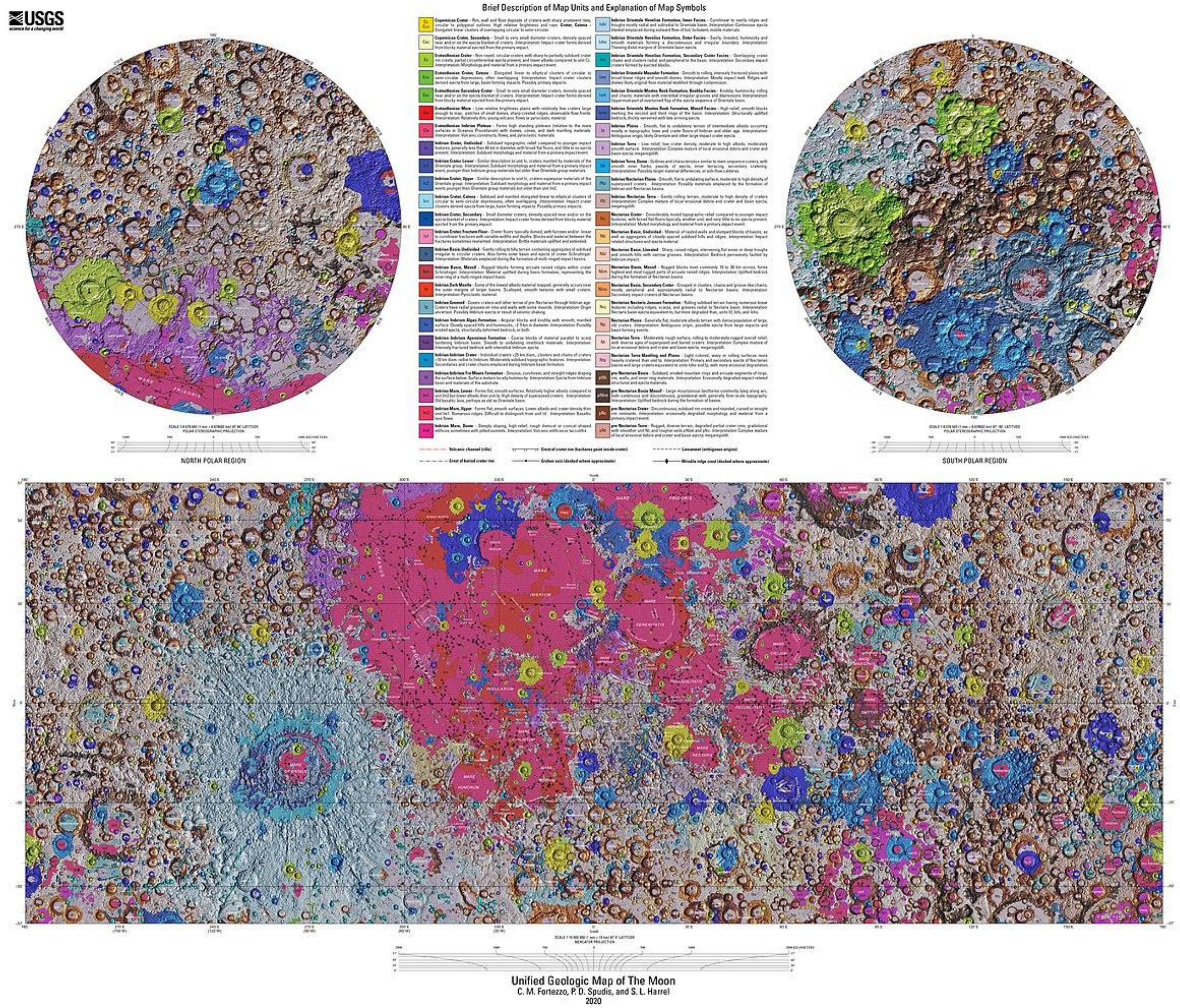
Apollo 17 SP-330

OUTCROP

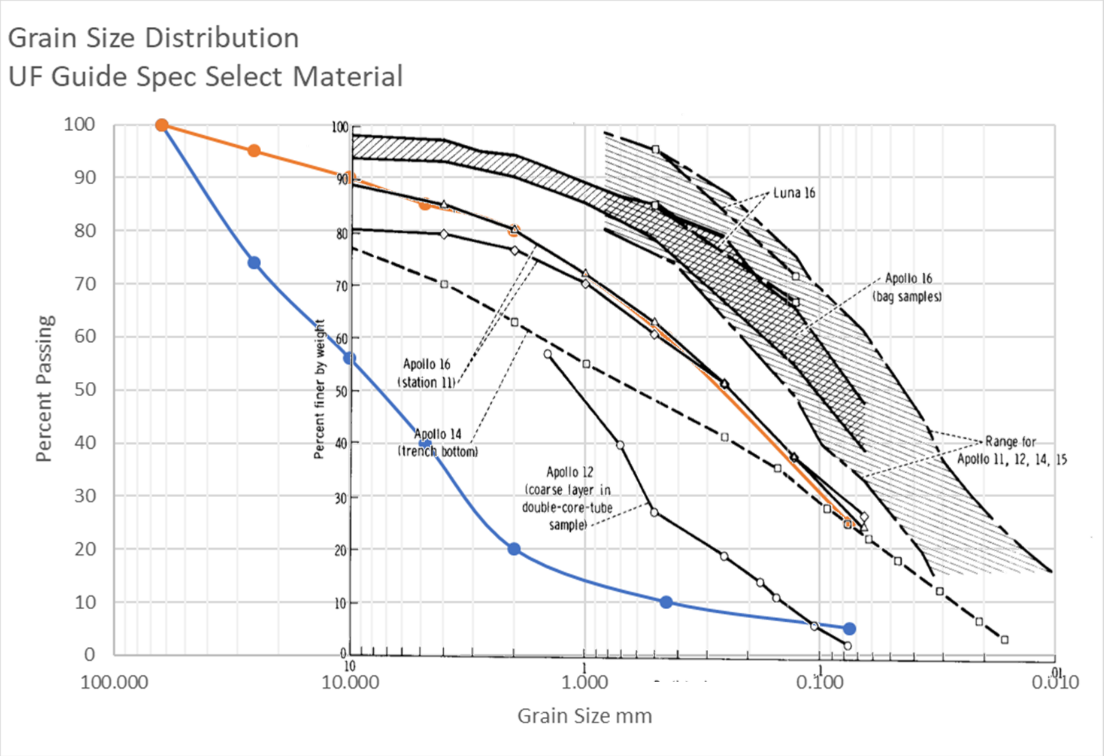


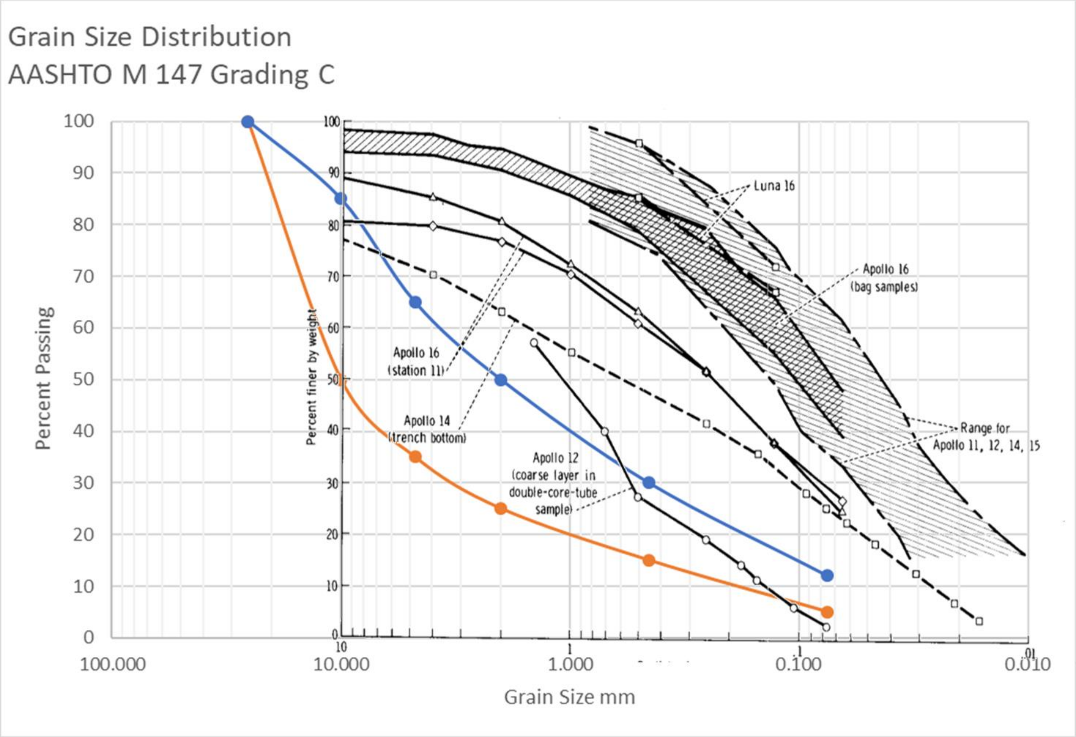
Geologic Survey

https://astrogeology.usgs.gov/search/map/Moon/Geology/Unified_Geologic_Map_of_the_Moon_GIS_v2



Geotechnical Properties





Site Development Resources

- Borrow pits
- Quarries
- Spoil piles

NASA

Robot Operations – General Purpose

- Lifting
- Excavating and Trenching
- Hauling
- Material handling (conveying)
- Grading and compacting
- Surveying

NASA

Robot Operations – Special Purpose

- Grading and paving surfaces
- Create dust free zones
- Paver, Brick and Block laying
- Anchoring & grounding systems
- Assembly of pre-fabricated components
- Molding and Formwork installation
- 3D Printing of concrete

NASA

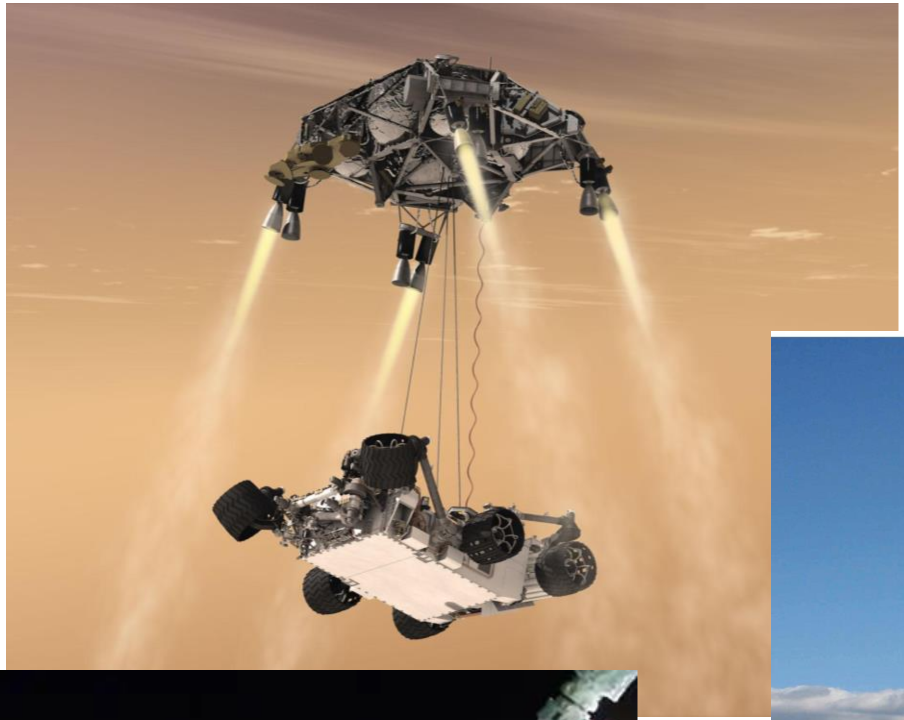
Construction material

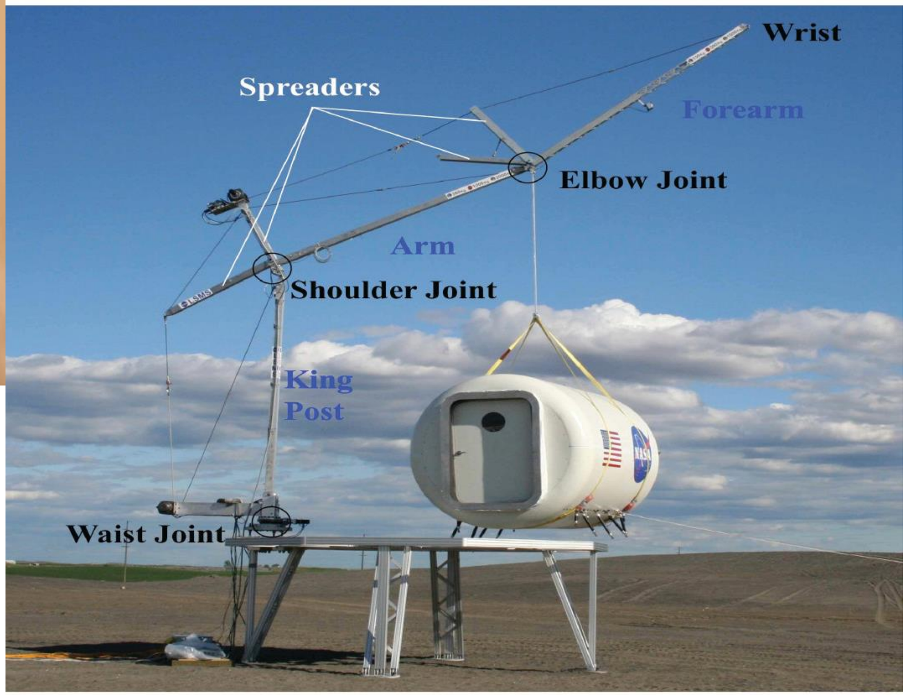
- Loose material
  - Quarry-run (as excavated)
  - Processed (crushed, sieved, sorted, blended)
- Manufactured
  - Bricks and blocks
  - Concrete
- Imported material
  - Air locks, ports, etc.
  - Mechanical and electrical equipment

NASA

Lifting

- Cranes
- Derricks
- Articulated Arm
- Mobile
    - Tire or track
    - Flying
- Fixed
    - Tower
    - Ringer





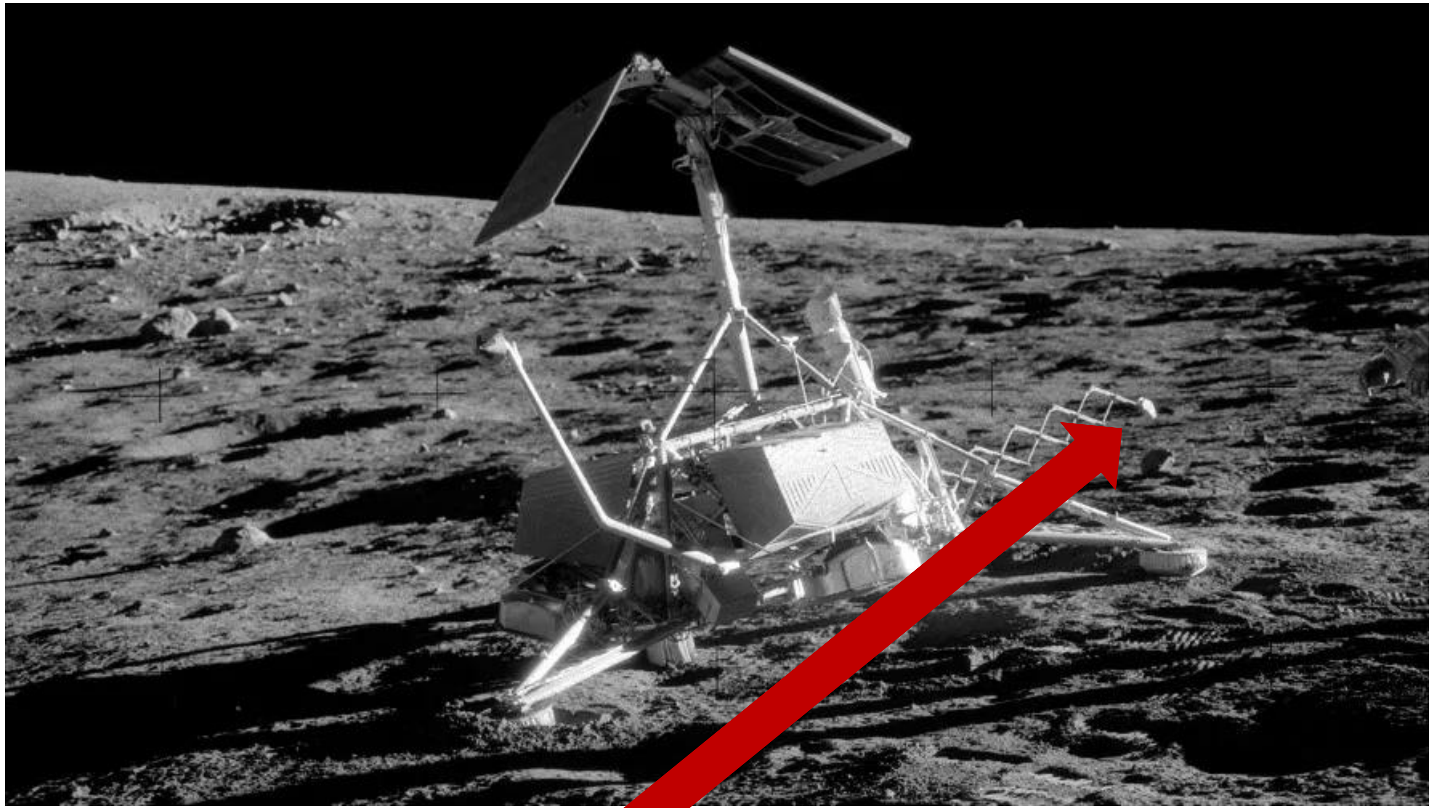
Sky Crane – NASA JPL
Lunar Surface Manipulator System – NASA LaRC
Canada Arm – Canadian Space Agency (CSA)

Excavating and Trenching

- Hoes
- Shovels
- Draglines
- Clam Shells
- Bucket Wheels
- Drill and blast
- Pneumatic

RASSOR 2.0 Prototype Excavator – NASA KSC

Surveyor 3: the first robotic excavation on the Moon (1967)

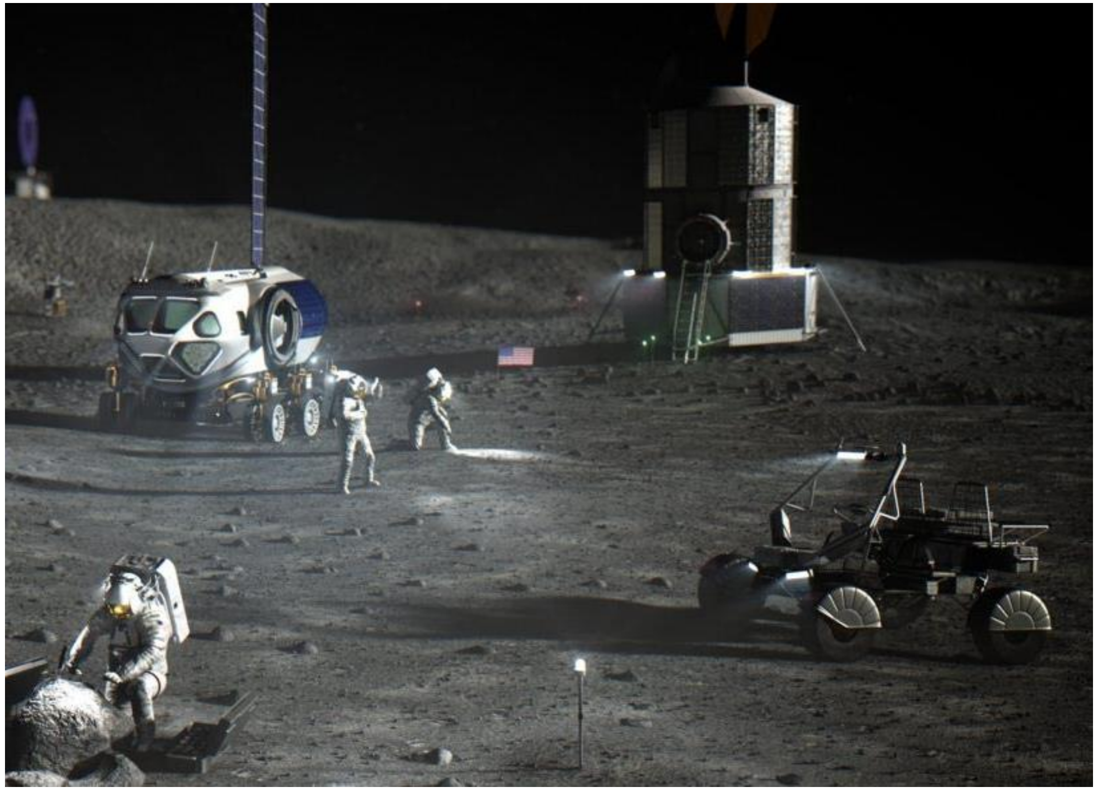


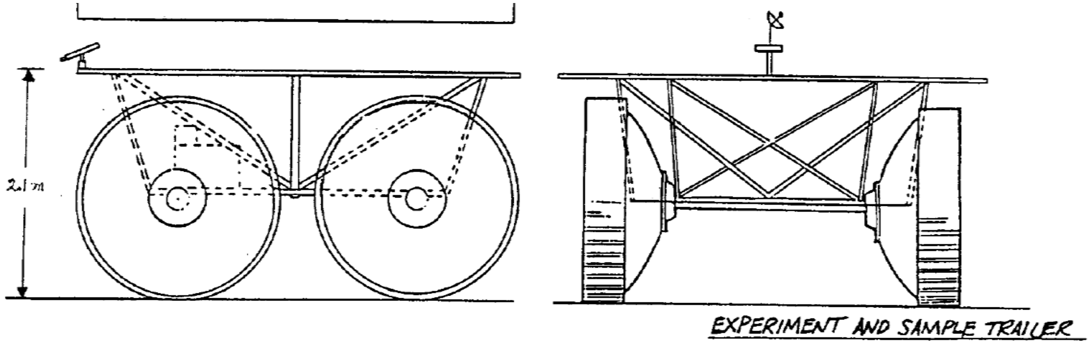
The Scoop

First Excavation on the Moon

Hauling

- End dump
- Bottom dump
- Self propelled
- Trailer
- Capacity
- Mechanical properties of payload

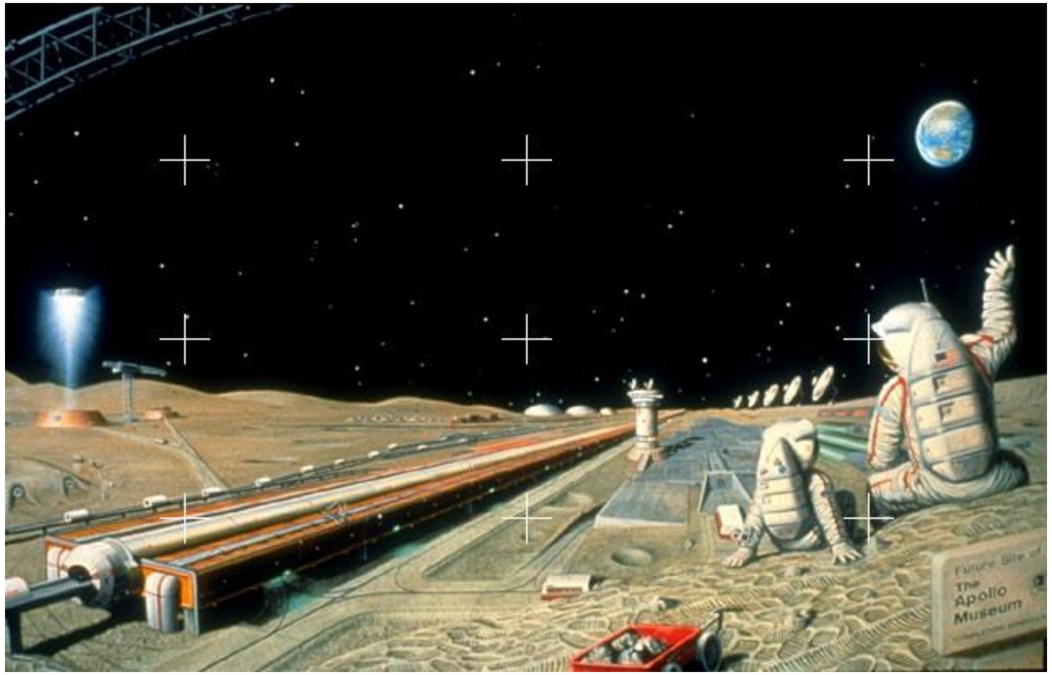


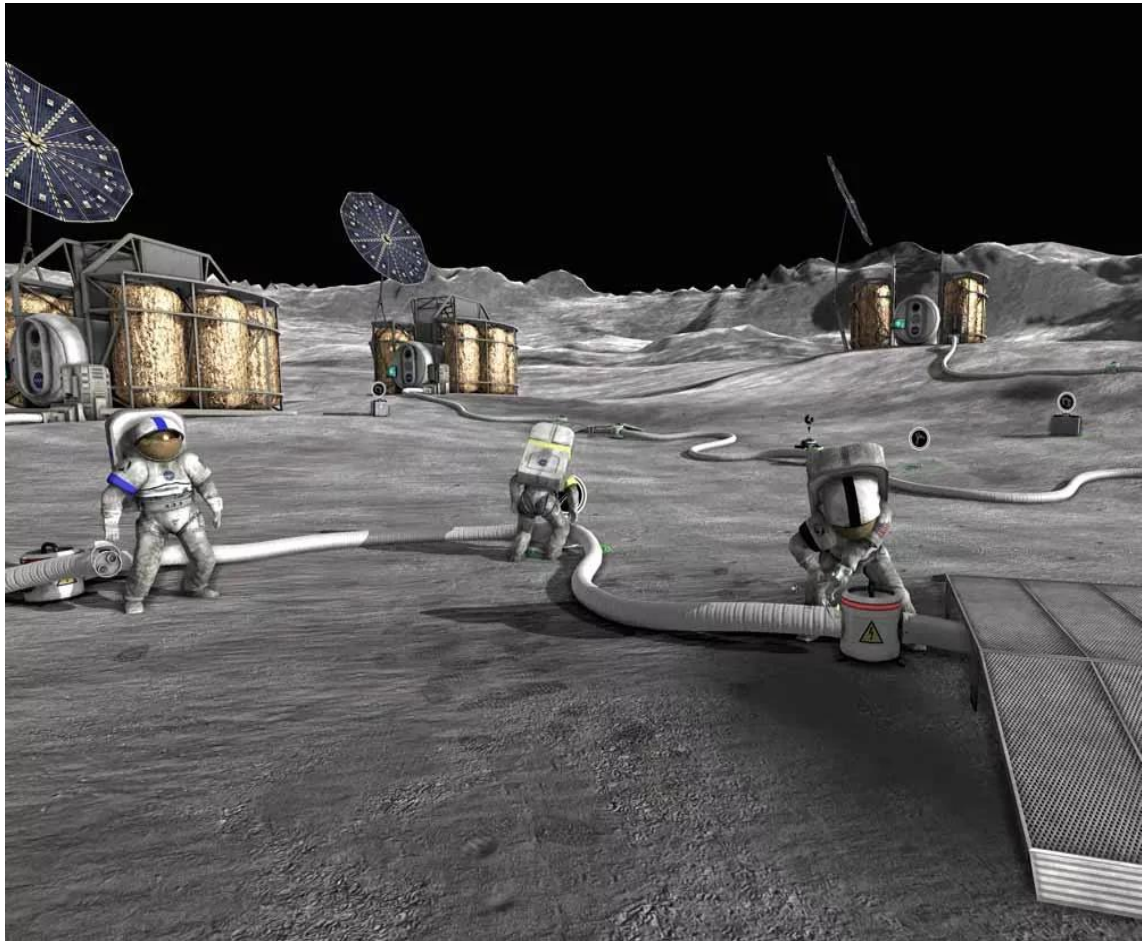


NASA Lunar Surface Construction & Assembly Equipment Study
Eagle Engineering Inc, 1988

Material handling (conveying)

- Belt conveyors
- Screw conveyors
- Pneumatic
- Ballistic
- Electrostatic

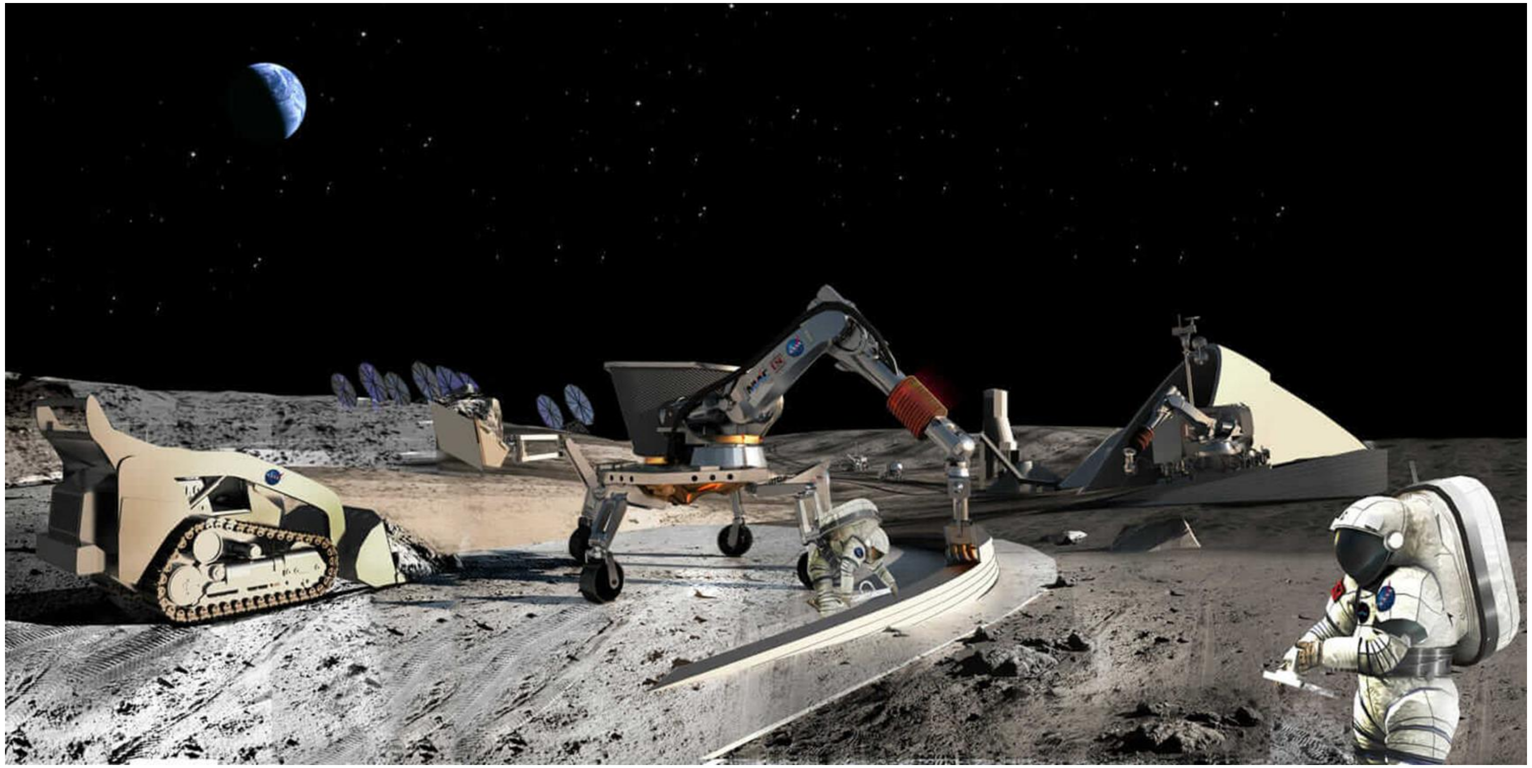




NASA

Grading and Compacting

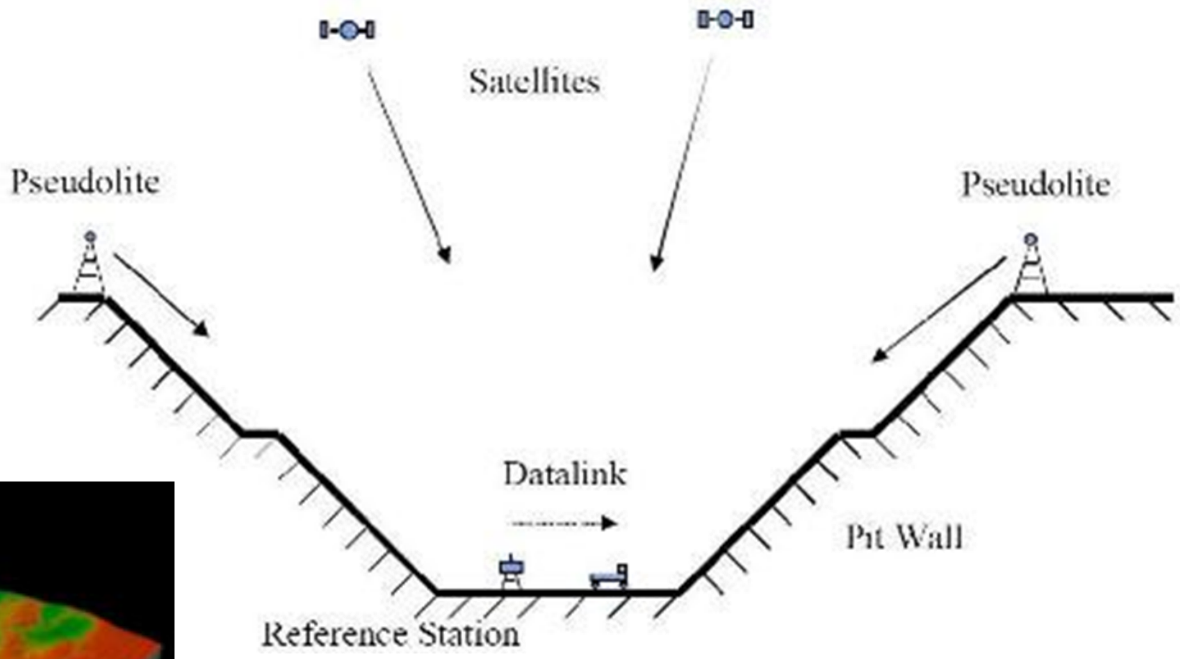
- Vibratory Rollers
- Vibratory Plates
- Blades
  - Graders
  - Dozers

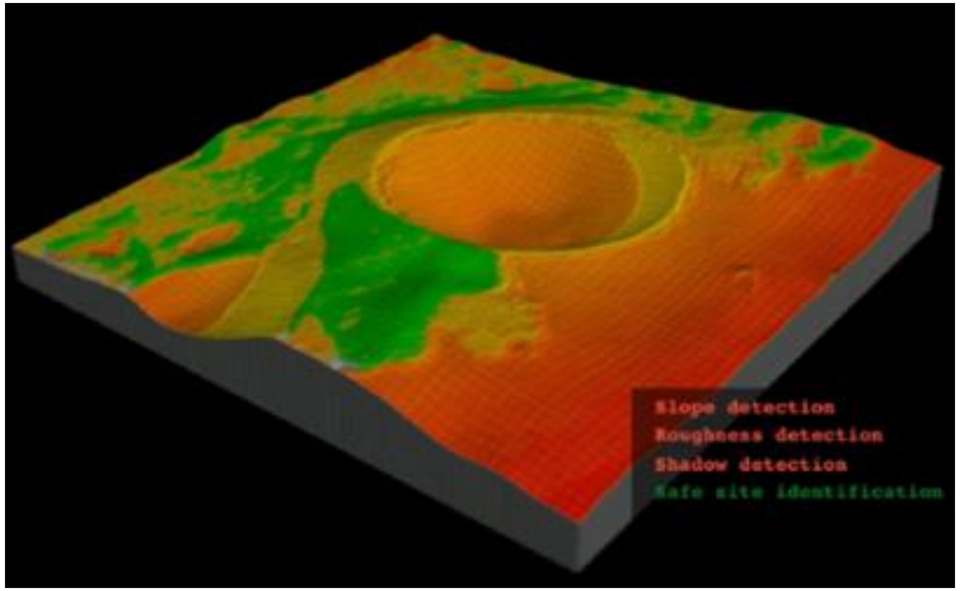


NASA/ Contour Crafting Corp

Surveying

- Orbital Operations
- Surface Operations
- Photogrammetry on Landers
- Space Drones
- LIDAR



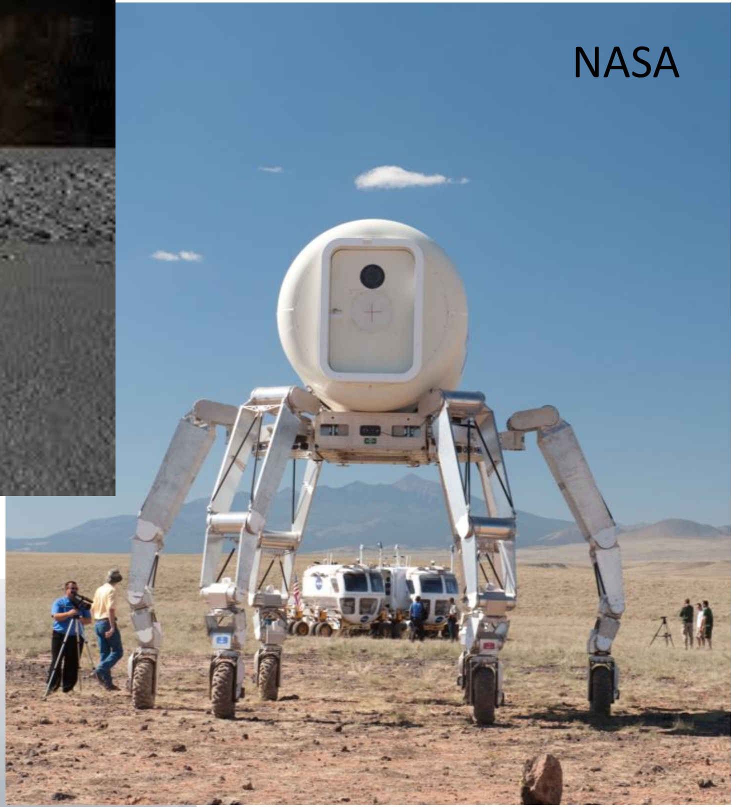


ESA, Lunar LIDAR

Robot Characteristics

- Mobility
- Terramechanics
- Power Source
- Mechanical Design
- Embedded Electronics
- State Estimation
- Modeling and Control
- Navigation
- Sensors
- Perception
- Path planning
- Machine learning
- Autonomy

VIPER Mobile Prospecting Drill



ATHLETE Hexapod

CHARIOT with LANCE Blade

Top Robotic challenges*

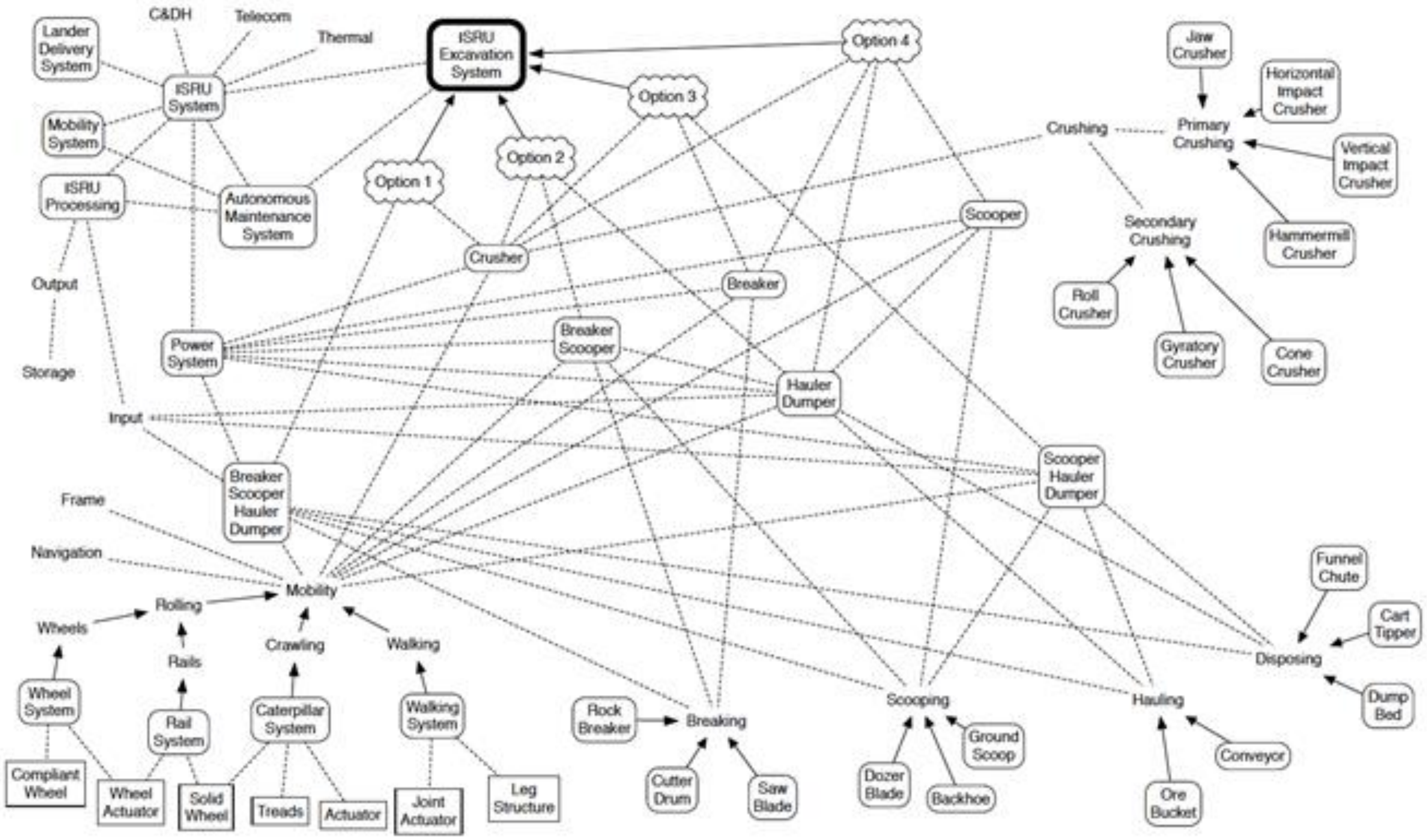
- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like 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

*(no specific order)

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

Lunar Environment and System Challenges

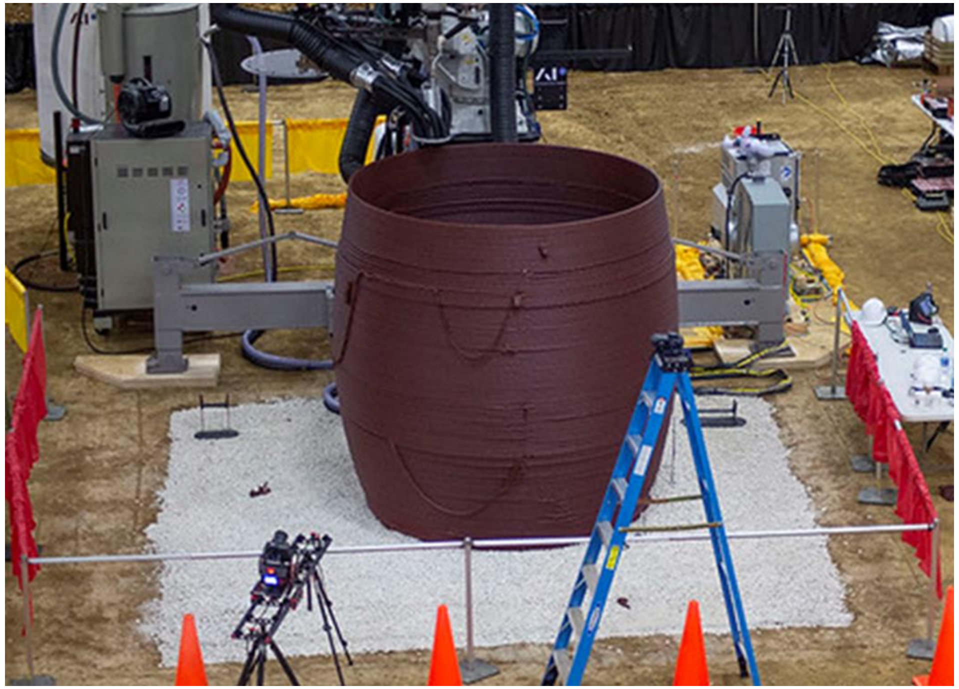
- Wheels
- Bearings
- Seals
- Heat rejection
- Electrical systems
- Remote operations
- Maintenance and repai
- And more….



NASA

Terrestrial Example:
3D Printing of Concrete

Penn State University



AI Space Factory

[Teams Build 3D-Printed Habitats for Moon and Mars | NASA's Centennial Challenges - YouTube]

Questions?