Construction with Regolith

CLASS / SSERVI / FSI
The Technology and Future of In-Situ Resource Utilization (ISRU)
A Capstone Graduate Seminar
Orlando, FL
March 6, 2017

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NASA

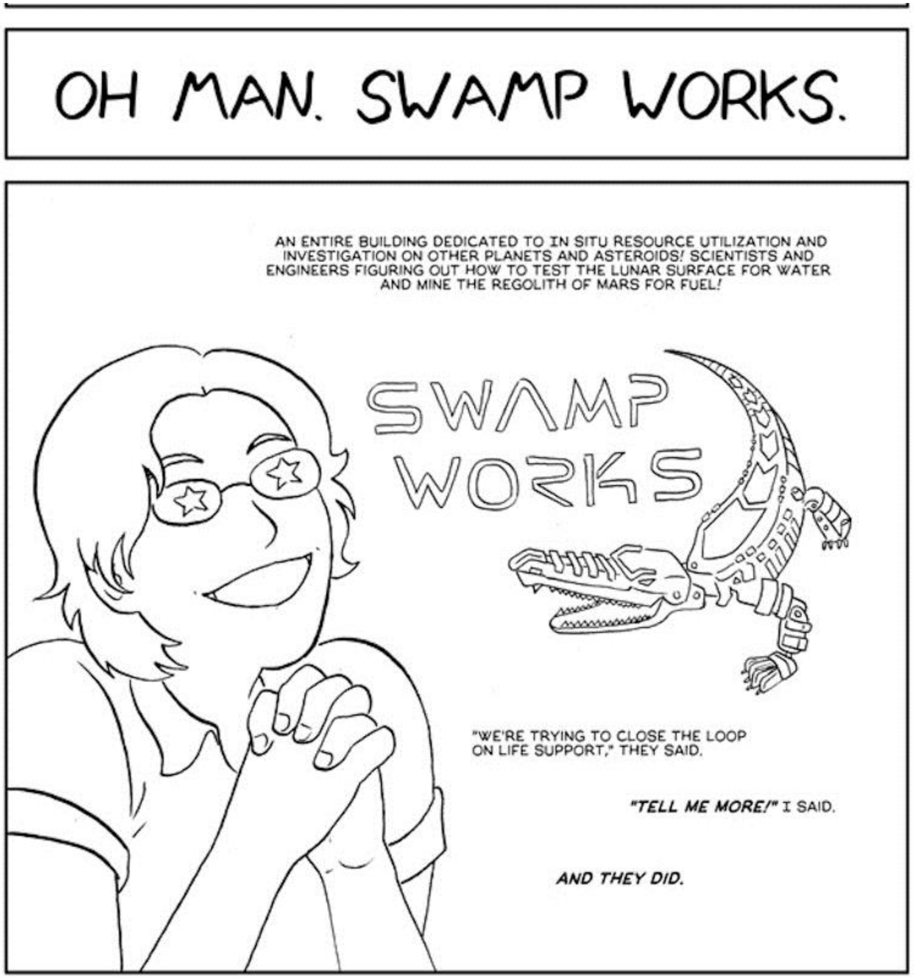
Kennedy Space Center – Swamp Works

Biography

- B.Sc. Mechanical Engineering, University of Miami
- M.S. Space Systems, Tech University of Delft, Netherlands
- M.B.A. Florida Institute of Technology
- ASCE Aerospace Division, Former National Chairman
- NASA Space Shuttle Engineer, ISS Engineer, Space Mission Architecture, Advanced Technology Development for Moon, Mars, Asteroids

  In-Situ Resource Utilization (ISRU) , Robotics for Construction
- 28 Years Experience at NASA KSC, JSC and JPL

Innovation Labs

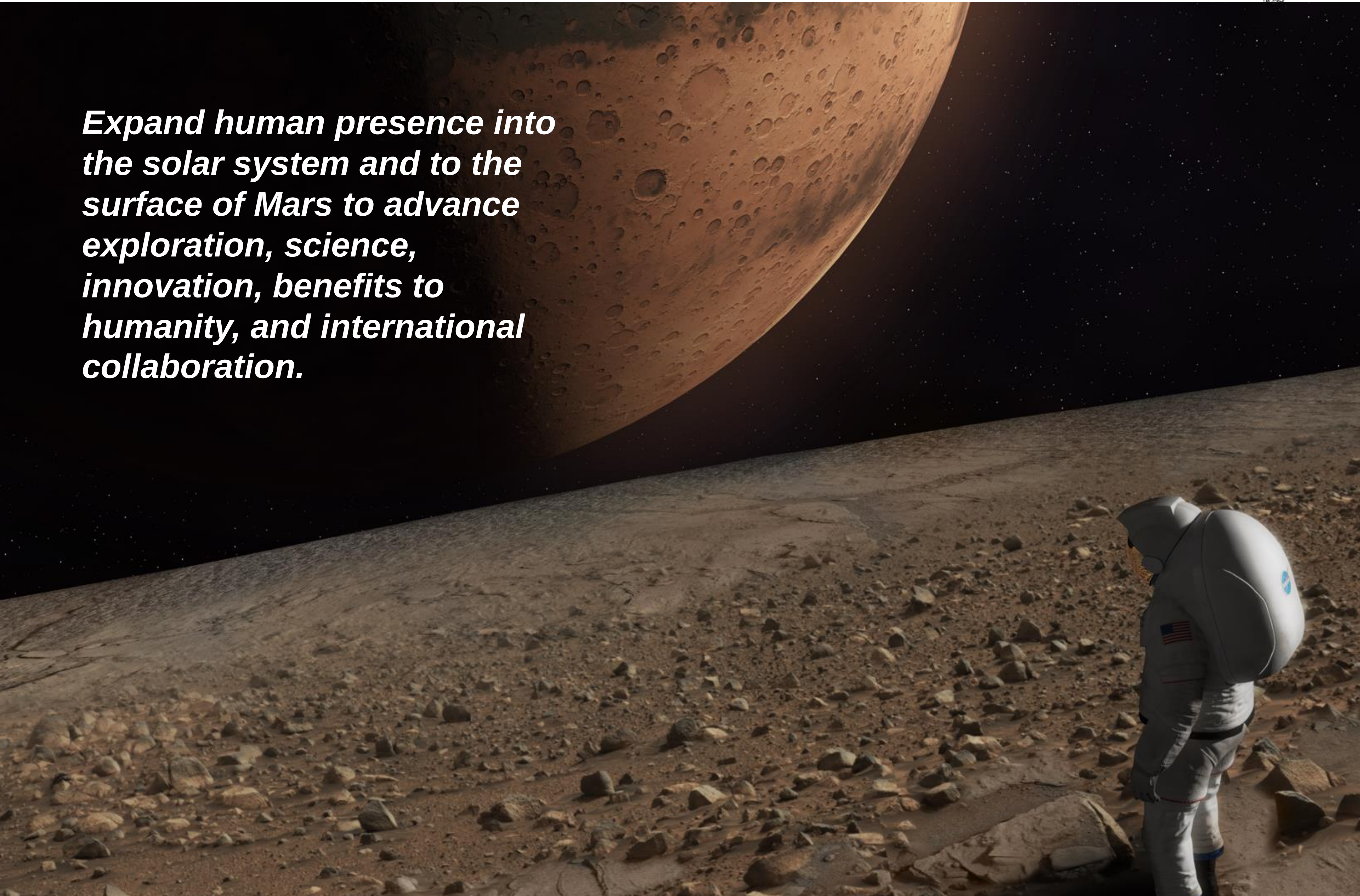


SWAMP WORKS
NASA KENNEDY SPACE CENTER

http://www.tor.com/stories/2013/07/nasa-comic-alison-wilgus

NASA Strategic Plan Objective 1.1

SWAMP WORKS
NASA KENNEDY SPACE CENTER



Expand human presence into the solar system and to the surface of Mars to advance exploration, science, innovation, benefits to humanity, and international collaboration.

Objectives

- Broad exposure to Planetary Surface Construction using regolith as a building material
- Regolith and indigenous materials
- Space Environments
- Infrastructure required for Surface Settlement
- Understand the robotic construction tasks required in various space environments
- Case Study 1: Robotic excavation of regolith
- Case Study 2: Paver Based VTVL Pad
- Case Study 2: 3D printing a habitat for humans

Pioneering in Space

Pioneering involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration

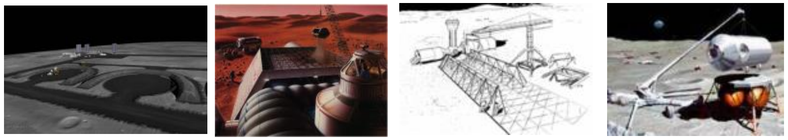
Five Major Areas of Pioneering

- ➢ **ISRU: Resource Characterization and Mapping**

  Physical, mineral/chemical, and volatile/water

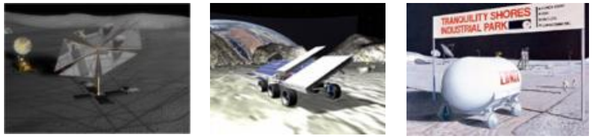
- ➢ **ISRU: Mission Consumable Production**

  Propellants, life support gases, fuel cell reactants, etc.



- ➢ **Civil Engineering & Surface Construction**

  Radiation shields, landing pads, roads, habitats, etc.



- **In-Situ Energy Generation, Storage & Transfer**

  Solar, electrical, thermal, chemical

- **In-Situ Manufacturing & Repair**

  Spare parts, wires, trusses, integrated structures, etc.

- ➢ **ISRU is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)
- ➢ **Pioneering does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.

Lunar and Mars Resources

Moon Resources

Regolith:

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)

Mars Resources

Regolith *
- Silicon Dioxide (43.5%)
- Iron Oxide (18.2%)
- Sulfur Trioxide (7.3%)
- Aluminum Oxide (7.3%)
- Magnesium Oxide (6.0%)
- Calcium Oxide (5.8%)
- Other (11.9%)
- Water (2 to >50%)^{XX}

* Based on Viking Data

XX Mars Odyssey Data

Atmosphere
- Carbon Dioxide (95..5%)
- Nitrogen (2.7%)
- Argon (1.6%)
- Oxygen (0.1%)
- Water (210 ppm)

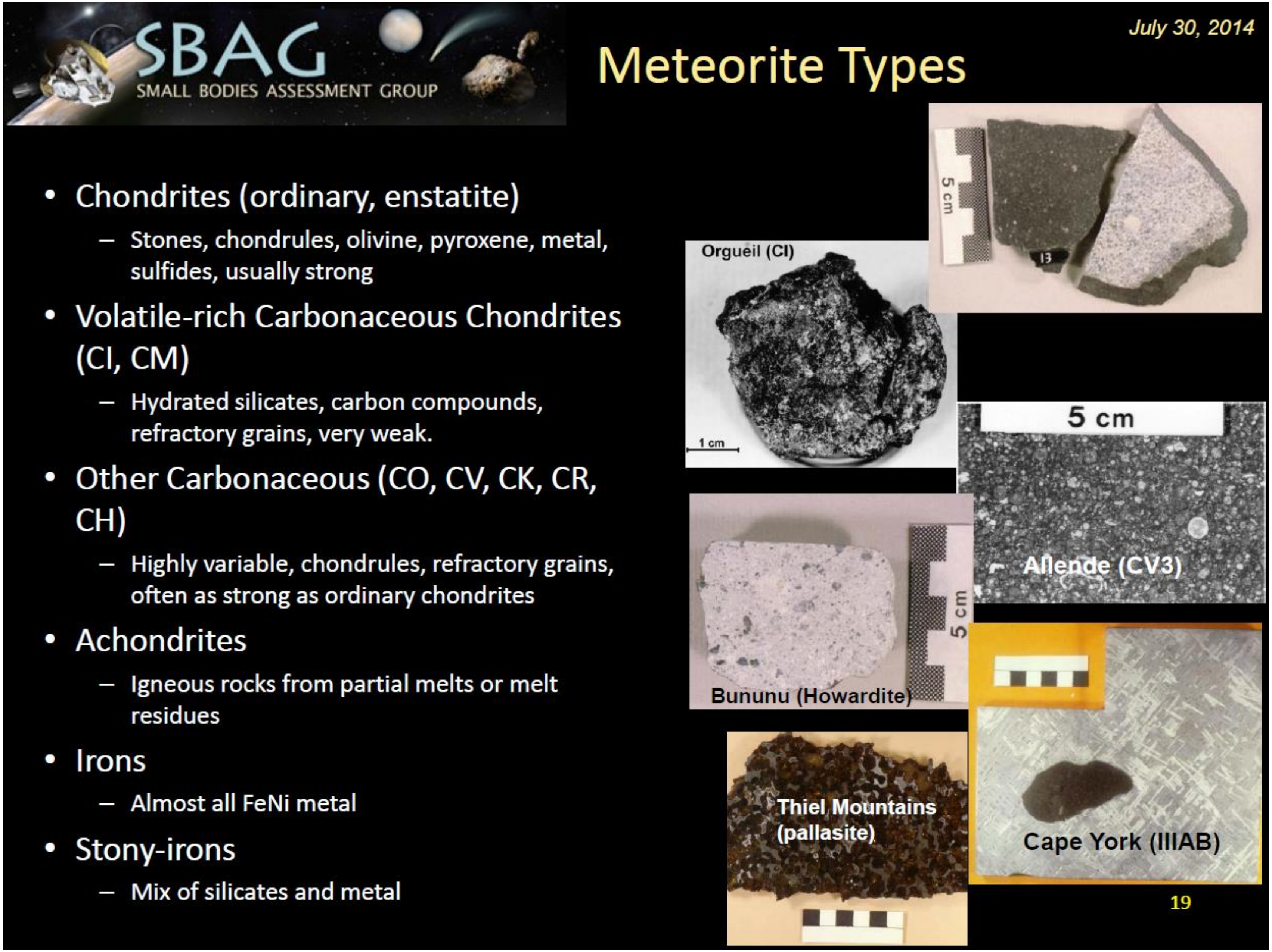
Lunar Resources

- Oxygen is the most abundant element on the Moon – 42% of the regolith
- 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

Mars Resources

- Atmospheric gases, and in particular carbon dioxide (95.5 %) , are available everywhere at 6 to 10 torr (0.1 psi)
- Viking and Mars Odyssey data shows that water is wide spread but spatial *distribution and form of water/ice is not well understood* (hydrated clays and salts, permafrost, liquid aquifers, and/or dirty ice)

Asteroid Resources



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SMALL BODIES ASSESSMENT GROUP

July 30, 2014

Meteorite Types

- Chondrites (ordinary, enstatite)
  - Stones, chondrules, olivine, pyroxene, metal, sulfides, usually strong
- Volatile-rich Carbonaceous Chondrites (CI, CM)
  - Hydrated silicates, carbon compounds, refractory grains, very weak.
- Other Carbonaceous (CO, CV, CK, CR, CH)
  - Highly variable, chondrules, refractory grains, often as strong as ordinary chondrites
- Achondrites
  - Igneous rocks from partial melts or melt residues
- Irons
  - Almost all FeNi metal
- Stony-irons
  - Mix of silicates and metal

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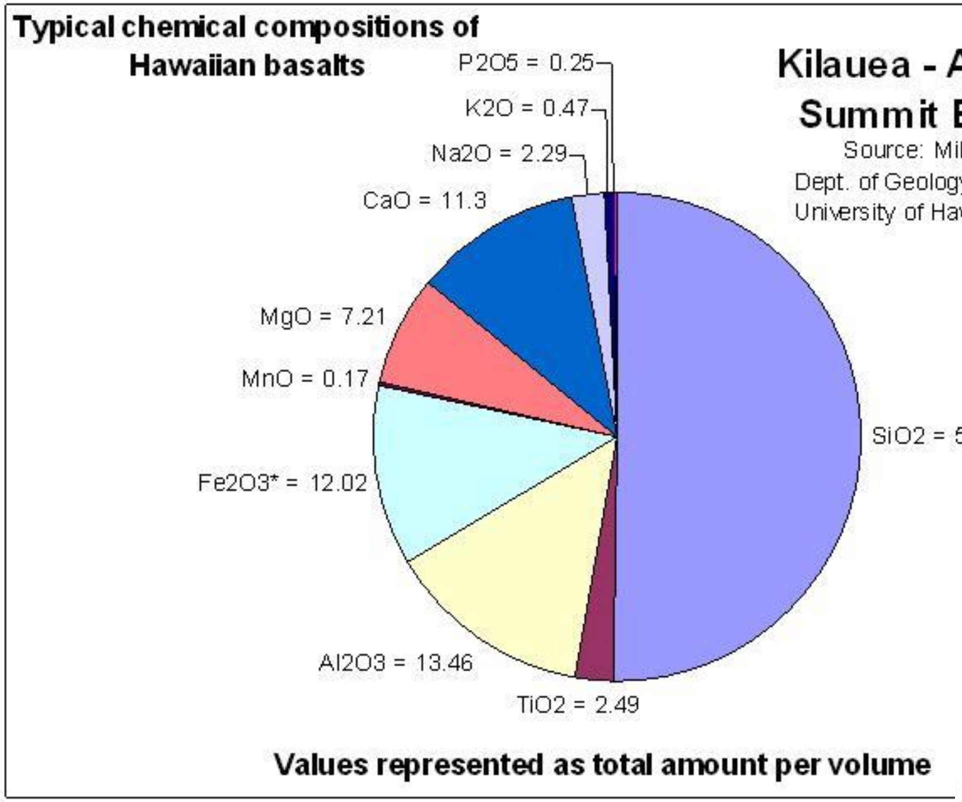
Some Regolith Resources and their Uses

- Lunar oxygen: propellant, life support
- Iron, aluminum, titanium: structural elements
- Magnesium: less strong structural elements
- Regolith: sintered blocks, concrete, glass
- Water: Ice blocks, molded ice

Potential Applications

- Structural beams, rods, plates, cables
- Cast shapes for anchors, fasteners, bricks, flywheels, furniture
- Solar cells, wires for power generation and distribution
- Pipes and storage vessels for fuel, water, and other fluids
- Roads, foundations, shielding
- Spray coatings or linings for buildings
- Powdered metals for rocket fuels, insulation
- Fabrication in large quantities can be a difficult engineering problem in terms of materials handling and heat dissipation

Basalt Rock



Kilauea - April 1982
Summit Eruption
Source: Mike Garcia
Dept. of Geology - Geophysics
University of Hawai`i at Manoa

Chemical	Element as an oxide
SiO_2	Silicon
TiO_2	Titanium
Al_2O_3	Aluminum
Fe_2O_3*	Iron
MnO	Manganese
MgO	Magnesium
CaO	Calcium
Na_2O	Sodium
K_2O	Potassium
P_2O_5	Phosphorus

Basalt, a mafic extrusive rock, is the most widespread of all igneous rocks, and comprises more than 90% of all volcanic rocks – it is commonly found on the Moon and Mars

Source: www.geocaching.com

Terrestrial Concrete vs Basalt

Typical properties of normal strength Portland cement concrete are:

- Density : *2500 - 2900 kg/m^3 (140 - 150 lb/ft^3)*
- Compressive strength : *~20 - 40 MPa (~3000 - 6000 psi)*

Typical properties of Basalt rock are:

- Density : *2630 +/- 140 kg/m^3 (164 lb/ft^3)*
- Compressive strength : *~144 - 292 MPa (20,885 – 42,351 psi)*

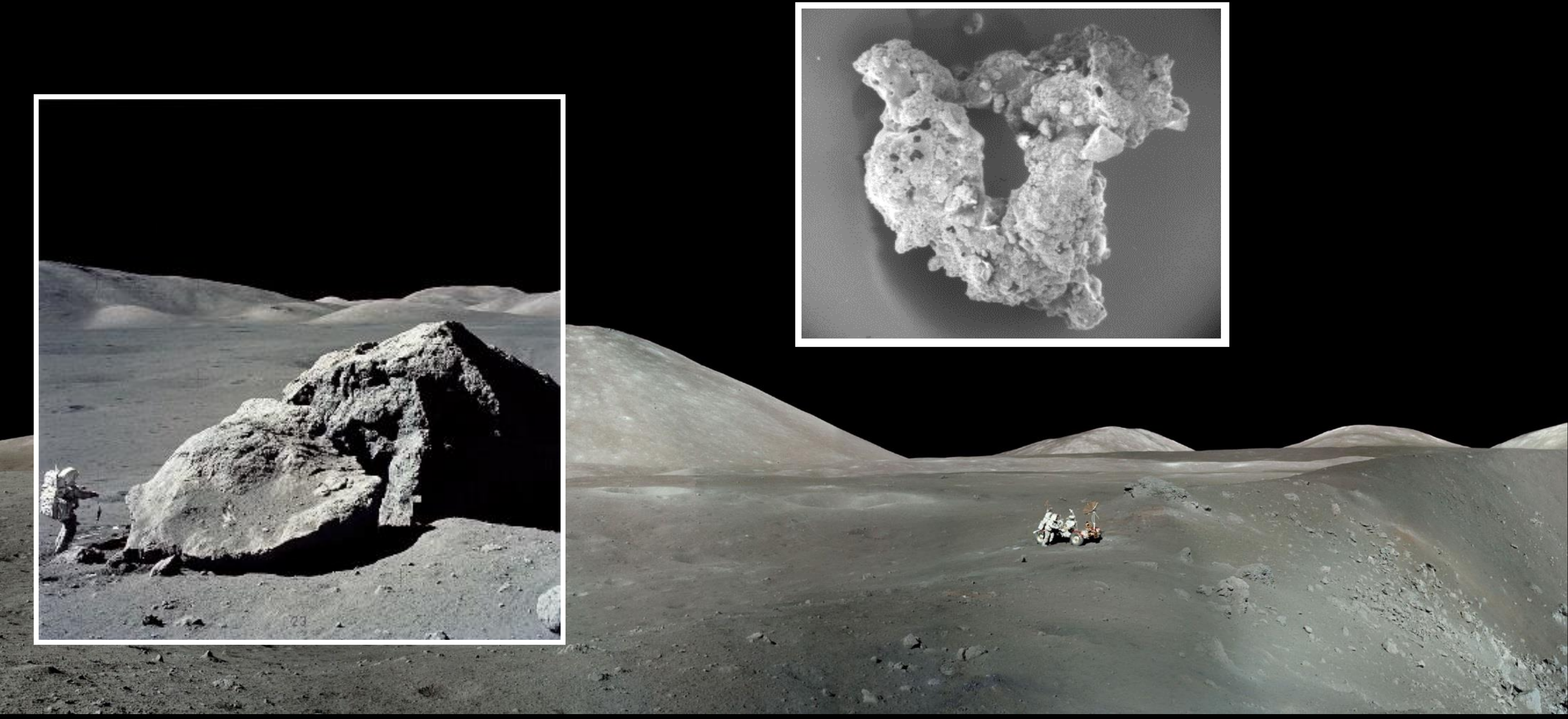
Basalt rock can be 4-7 X stronger in compression than normal Portland cement concrete typically used on Earth.

How can basalt rock be formed to be comparable to concrete as a construction material?

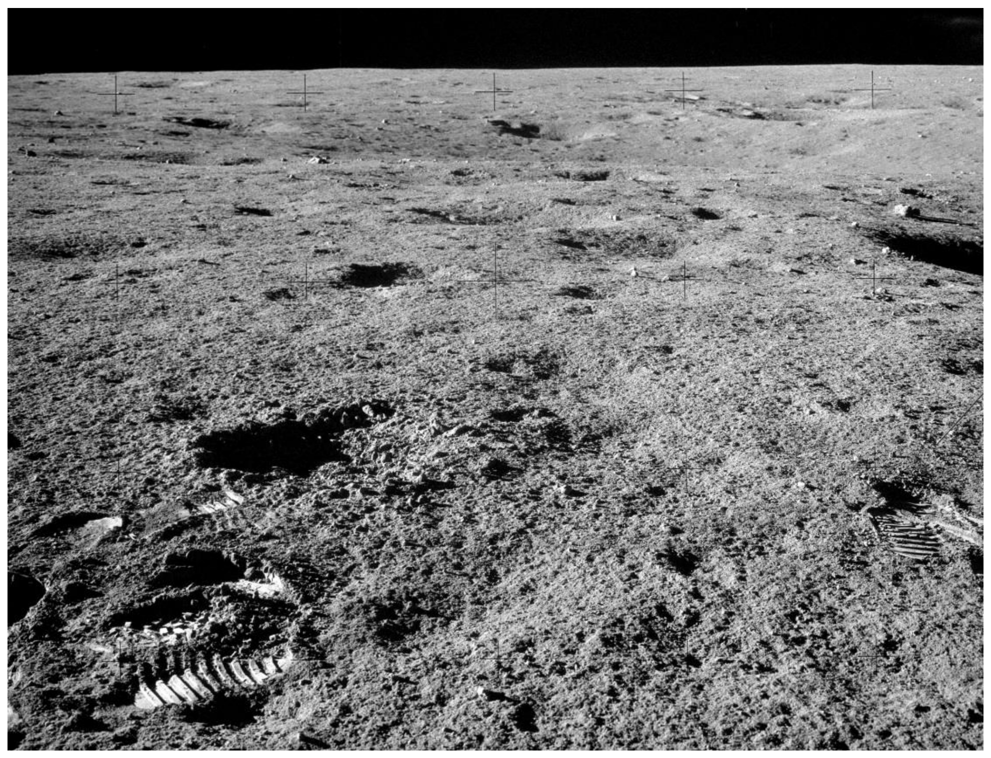
Sintered basalt regolith has achieved ***206 Mpa (30,000 psi) in compression tests*** (ref: KSC Swamp Works with PISCES, Hawaii collaboration)
5X stronger than Portland Cement concrete – ***turning regolith into rock!***

Lunar Regolith Definition

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.



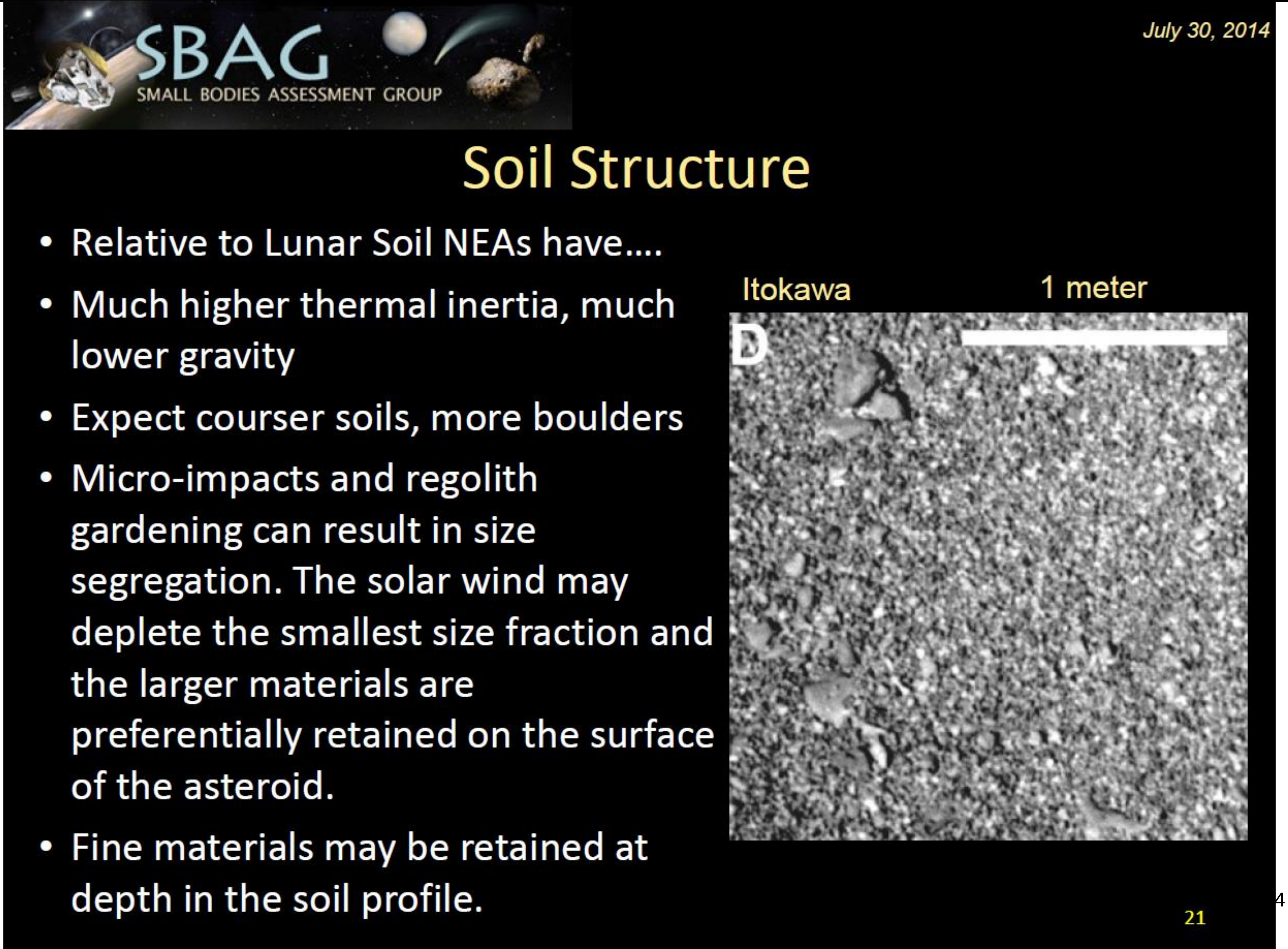
Basalt Granular Material = Construction Material



APOLLO 12

APOLLO 16

Asteroid Regolith Fines



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Soil Structure

- Relative to Lunar Soil NEAs have….
- Much higher thermal inertia, much lower gravity
- Expect courser soils, more boulders
- Micro-impacts and regolith gardening can result in size segregation. The solar wind may deplete the smallest size fraction and the larger materials are preferentially retained on the surface of the asteroid.
- Fine materials may be retained at depth in the soil profile.

Mars is full of Regolith Fines

The Moon

- Gravity ~1/6 of Earth G
- Hard vacuum (1x 10^{-12} torr)
- Large temperature swings (especially at Equator)
- Long night (~14 Earth-days)
- Very dusty
- Sharp, angular soil with high glass content
  - Very abrasive, electrostatically charged, 100 micron and less
- Soil very compacted below top 2-3 cm layer
  - But we don't know about compaction in the polar craters
- Unprotected from space particle radiation
- Solar flux same as at Earth
- Heating comes almost entirely from the Sun (at night the lunar surface is warmed slightly by Earth).

Near Earth Asteroids

- Gravity negligible (1/1000th of Earth G)
- Hard vacuum
- May be “rubble piles”
- Might have regolith
- Regolith may be denuded of fine particles at the surface; may be gravelly with boulders
- Different types of asteroids
- Unprotected from particle radiation
- Solar flux same as at Earth

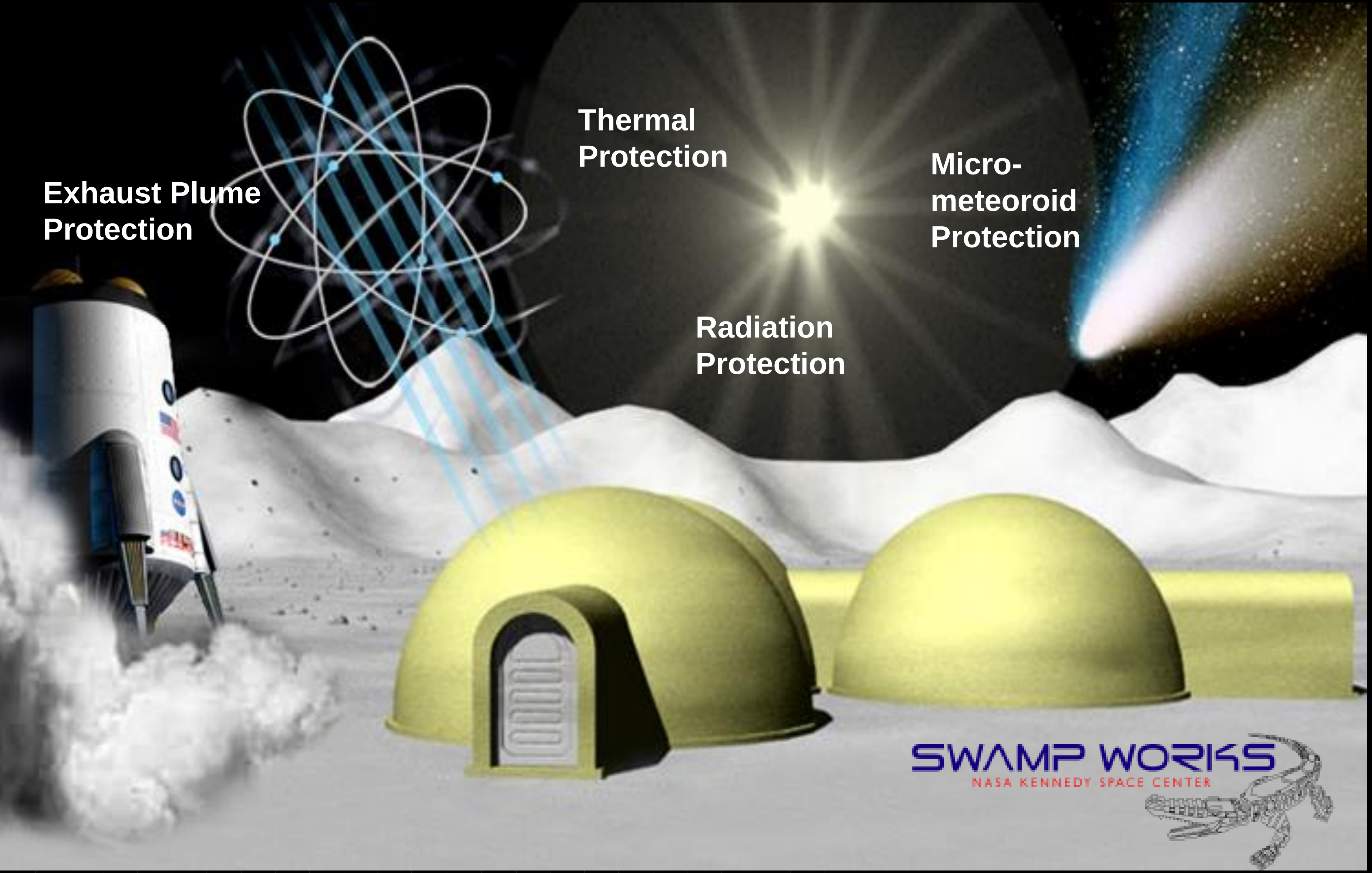
Mars

- Gravity ~3/8 of Earth G
- Atmospheric pressure ~1% of Earth’s, but varies seasonally by 30% as it freezes and unfreezes from the polar caps
- Wind only has 1% of force as Earth’s wind
- Mars has CO_2 frost & snow
- Sand carried by wind still abrades like on Earth
- Atmosphere mostly carbon dioxide
- Very dusty atmosphere; dust storms, dust devils

Mars, continued

- Radiation environment on the surface is bad
- Soil is weathered, behaves like terrestrial soil
- Soil is diverse
- Geology is complex
- Little is known about subsurface geology
- Mixture of CO2 and water ice and clathrates
  - Varying mechanical strength
  - Ice is on the surface at high latitudes
  - Ice is near the surface at moderate latitudes
  - Ice is deep beneath the surface at low latitudes

Multiple Sheltering Aspects Needed



Thermal Protection

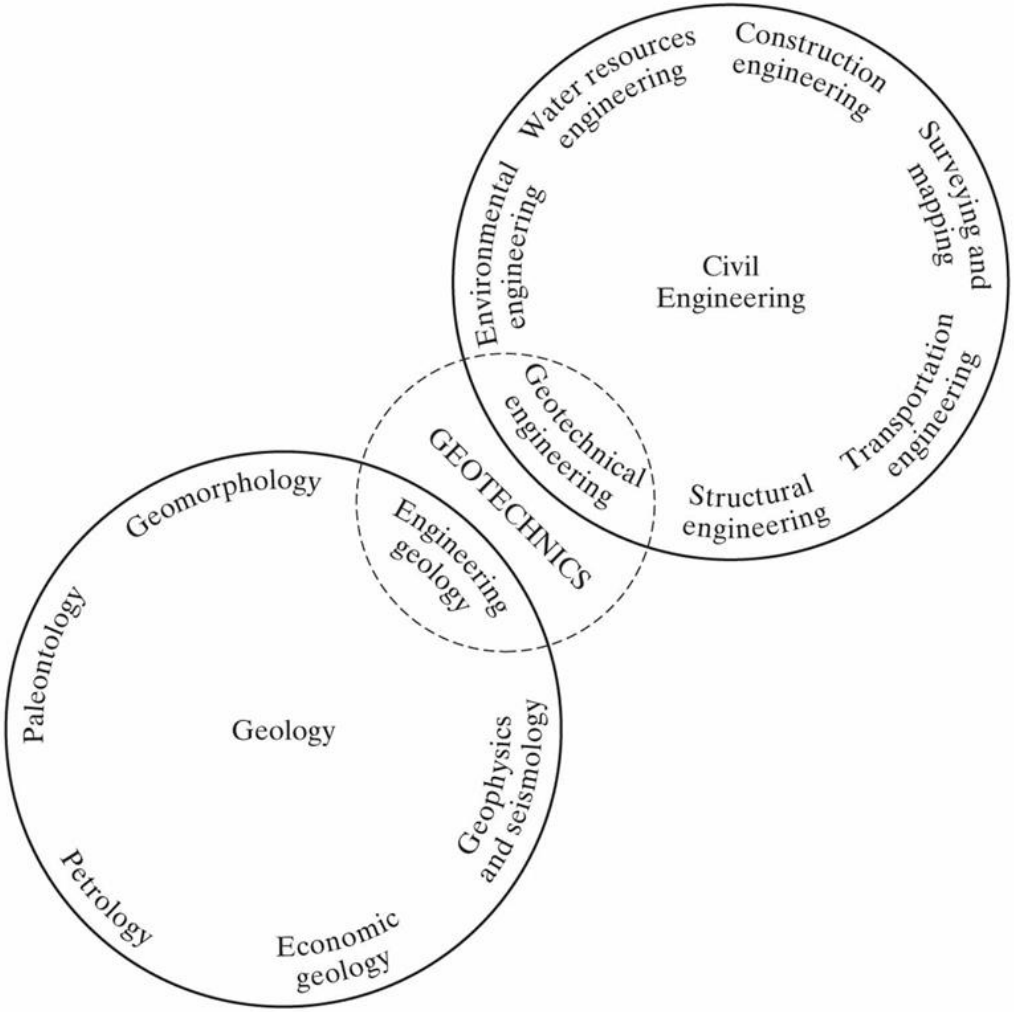
Exhaust Plume Protection

Micro-meteoroid Protection

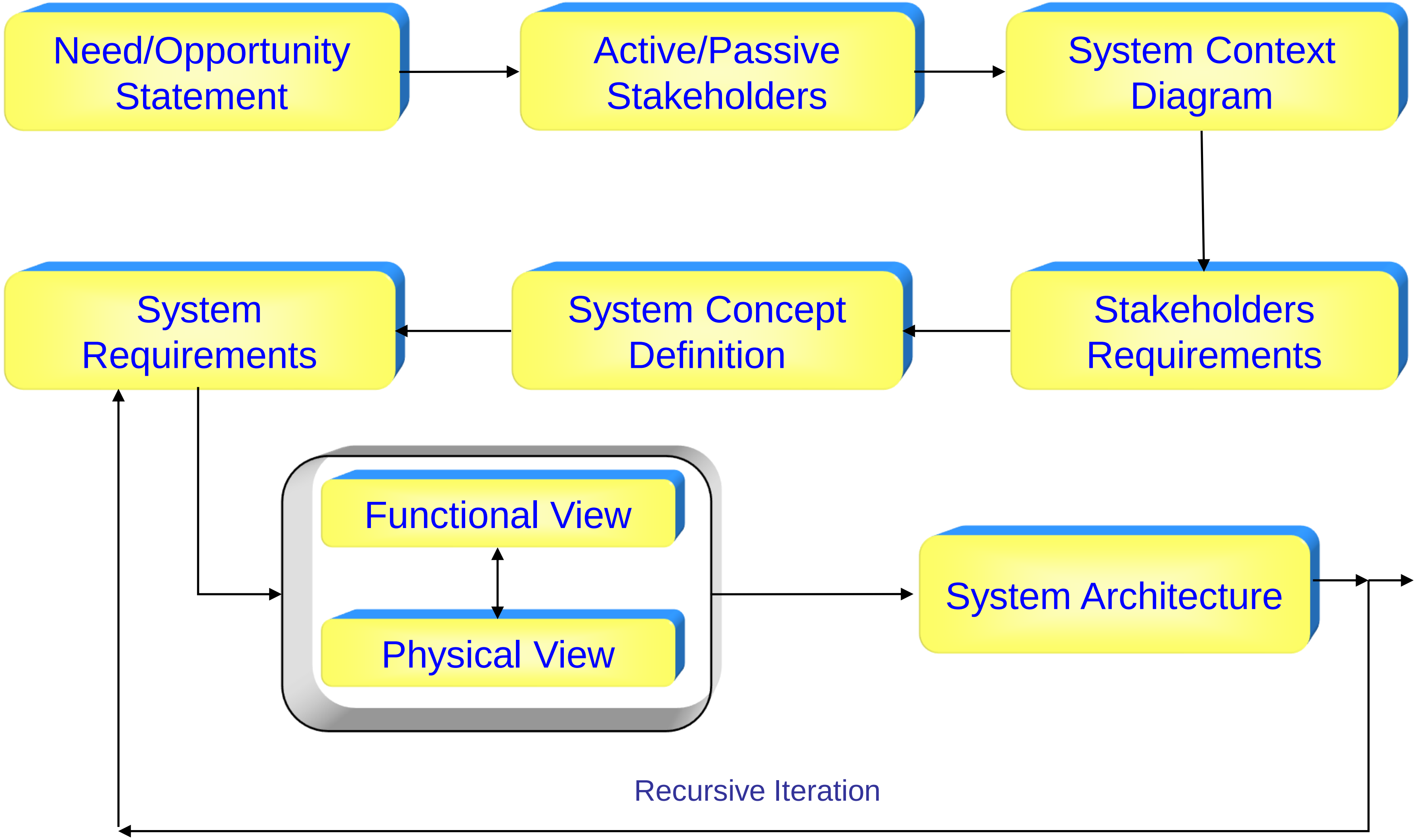
Radiation Protection

Geotechnical Engineering

- Geotechnical engineering falls within Civil Engineering but very closely aligned with Geological sciences and engineering, as shown below:



Typical Systems Engineering Process



Need/Opportunity Statement

Active/Passive Stakeholders

System Context Diagram

Stakeholders Requirements

System Concept Definition

System Requirements

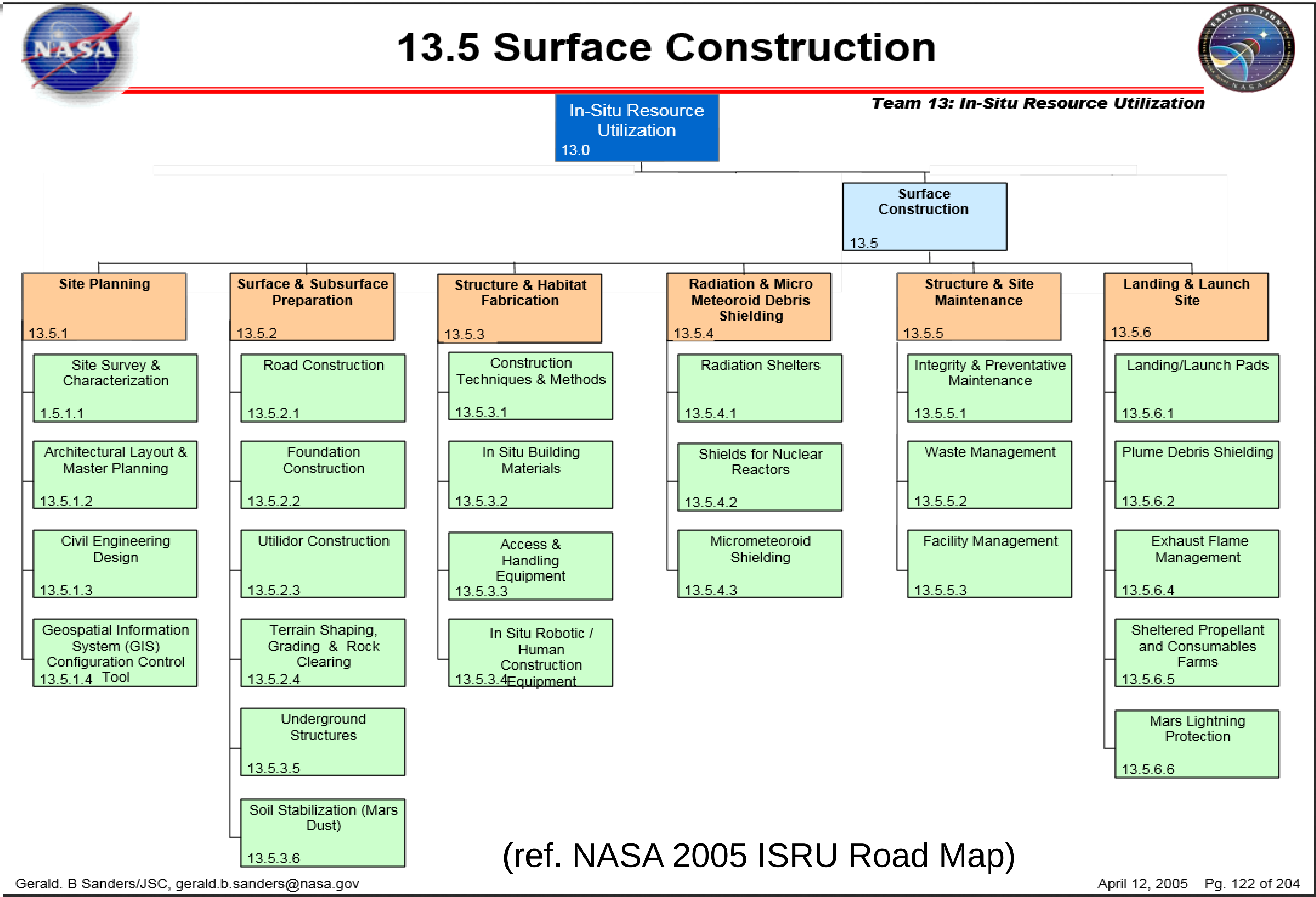
Functional View

Physical View

System Architecture

Recursive Iteration

Mars Site Planning: Functional Requirements



13.5 Surface Construction

Team 13: In-Situ Resource Utilization

- In-Situ Resource Utilization 13.0
  - **Surface Construction** 13.5
    - **Site Planning** 13.5.1
      - Site Survey & Characterization 1.5.1.1
      - Architectural Layout & Master Planning 13.5.1.2
      - Civil Engineering Design 13.5.1.3
      - Geospatial Information System (GIS) Configuration Control Tool 13.5.1.4
    - **Surface & Subsurface Preparation** 13.5.2
      - Road Construction 13.5.2.1
      - Foundation Construction 13.5.2.2
      - Utilidor Construction 13.5.2.3
      - Terrain Shaping, Grading & Rock Clearing 13.5.2.4
      - Underground Structures 13.5.3.5
      - Soil Stabilization (Mars Dust) 13.5.3.6
    - **Structure & Habitat Fabrication** 13.5.3
      - Construction Techniques & Methods 13.5.3.1
      - In Situ Building Materials 13.5.3.2
      - Access & Handling Equipment 13.5.3.3
      - In Situ Robotic / Human Construction Equipment 13.5.3.4
    - **Radiation & Micro Meteoroid Debris Shielding** 13.5.4
      - Radiation Shelters 13.5.4.1
      - Shields for Nuclear Reactors 13.5.4.2
      - Micrometeoroid Shielding 13.5.4.3
    - **Structure & Site Maintenance** 13.5.5
      - Integrity & Preventative Maintenance 13.5.5.1
      - Waste Management 13.5.5.2
      - Facility Management 13.5.5.3
    - **Landing & Launch Site** 13.5.6
      - Landing/Launch Pads 13.5.6.1
      - Plume Debris Shielding 13.5.6.2
      - Exhaust Flame Management 13.5.6.4
      - Sheltered Propellant and Consumables Farms 13.5.6.5
      - Mars Lightning Protection 13.5.6.6

(ref. NASA 2005 ISRU Road Map)

Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov

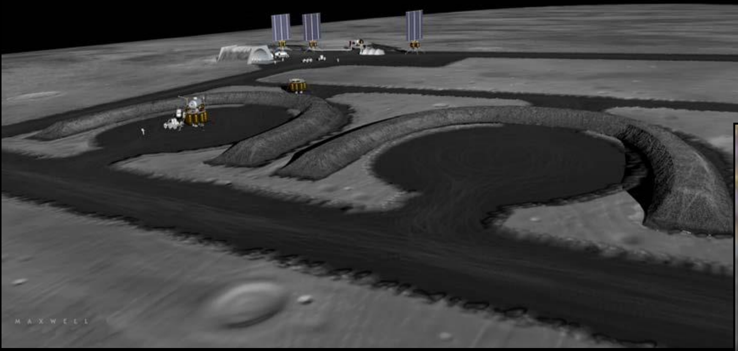
April 12, 2005 Pg. 122 of 204

Lunar Mission Space Civil Engineering Capability Concepts

Resource Prospecting – Looking for Resources

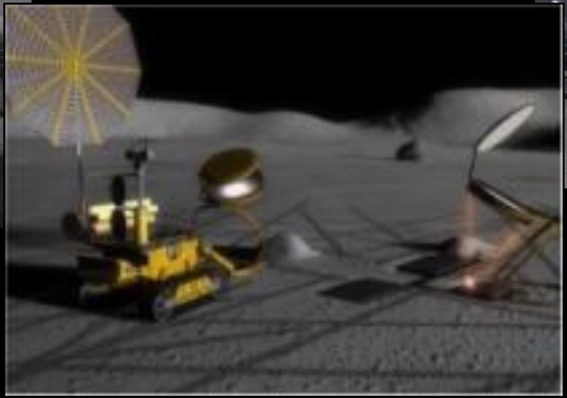
Excavation & Regolith Processing for H_2 & O_2 Production, Binders & Aggregates

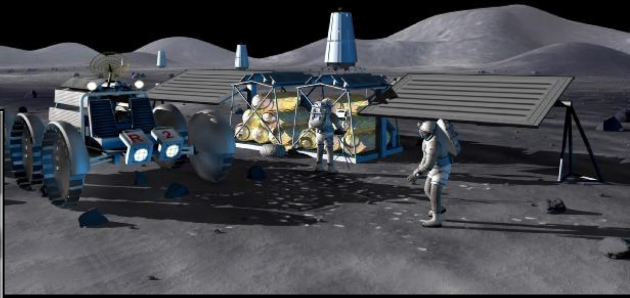
Propellant Processing with Lander & Pad Infrastructure



Habitat, Hangars, Dust Free Zones, Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction





Construction of Consumables Depots for Crew & Power (O_2, H_2)

Planetary Surface Construction Tasks

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

Ablative Regolith Atmospheric Entry Heat Shields

Radiation Shielding for Fission Power Plants

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

Radiation shielding panels for spacecraft

Regolith Mining for O_2 Production

H_2O Ice/Regolith Mining from Shadowed Craters

Specific Examples: Types of Structures

Habitats

- Landed self-contained structures
- Rigid modules (prefabricated/*in situ*)
- Inflatable modules/membranes (prefabricated/*in situ*)
- Tunneling/coring/ trenches/underground
- Exploited caverns/ lava tubes

Storage Facilities/Shelters

- Open tensile (tents/awning)
- Interlocking Elements with standard interfaces
- Modules (rigid/inflatable)
- Trenches/underground
- Ceramic/masonry (arches/tubes)
- Mobile
- Shells

Supporting Infrastructure

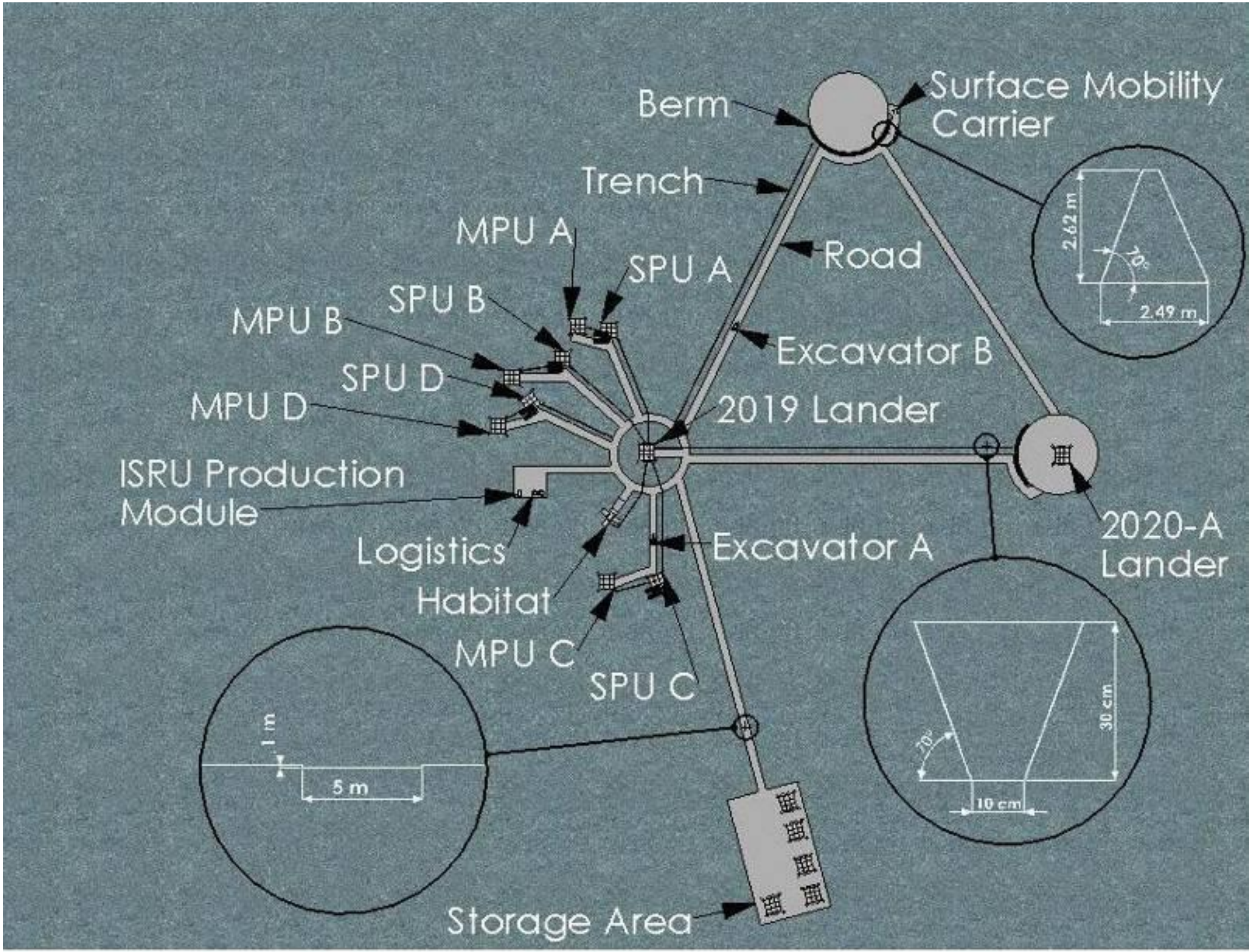
- Slabs / foundations (melts/compaction/additives)
- Trusses/frames
- Berms for rocket blast protection

Top Space Regolith Construction Technical Challenges*

- Strength of In-situ derived regolith concrete materials
- New construction methods & equipment
- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Energy re-charging and work flow scheduling
- Encountering sub surface rock obstacles
- Long life cycle (5-10 years) and high reliability required
- Spare parts logistics, manufacturing and repair
- Unknown water ice / regolith composition and deep digging
- Extended lunar night time operation and power storage
- Thermal management
- Robust communications

*(no specific order)

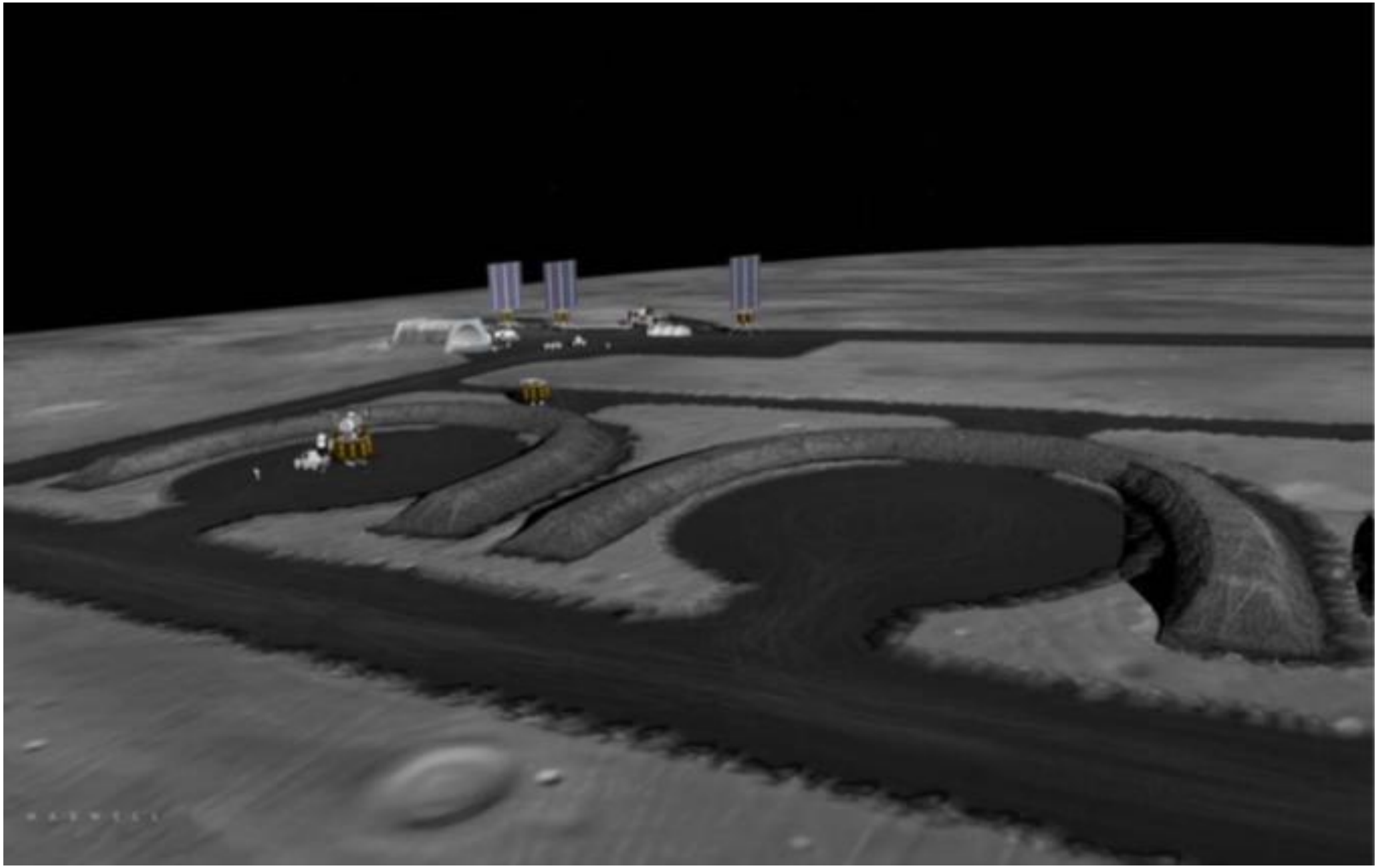
Lunar Master Site Planning Considerations: Example



Mueller & King, 2007

Lunar Base Construction

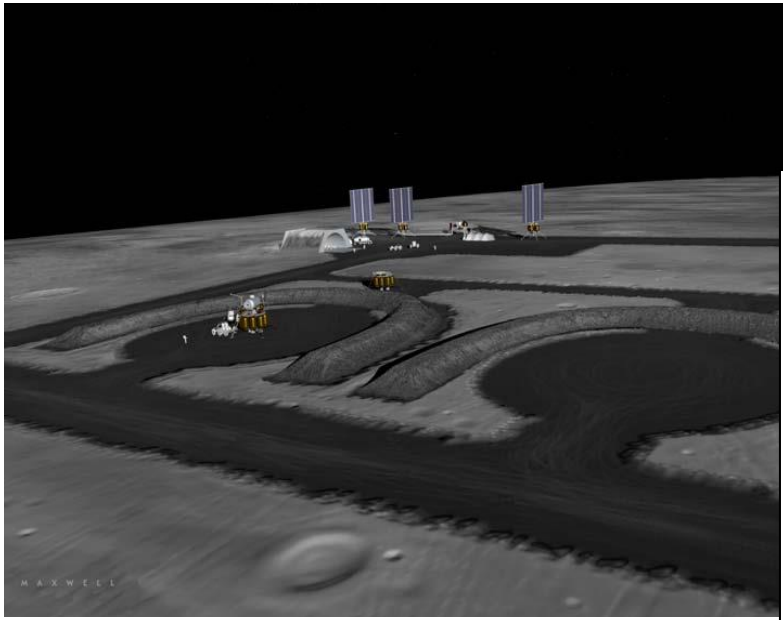
Build Regolith Based Landing Pads and Berms for safe Vertical Take Off & Vertical Landing (VTVL) Operations

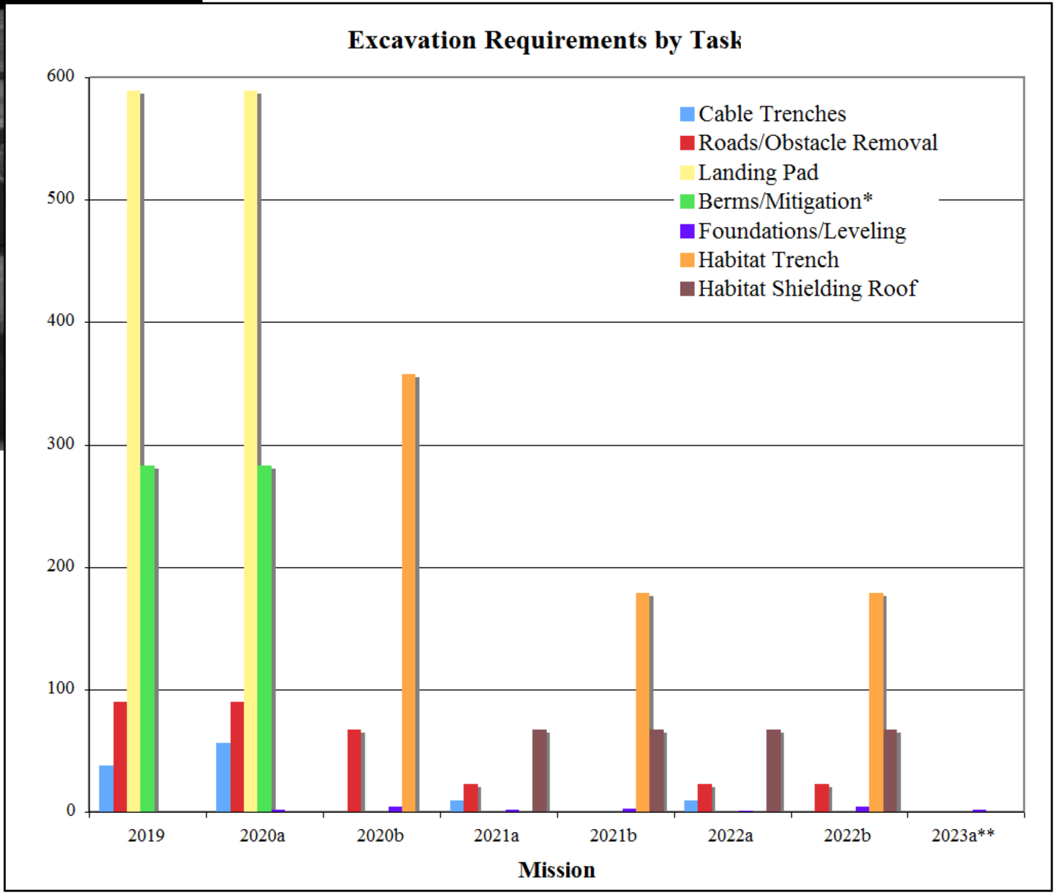


NASA Artwork by Maxwell

Lunar Surface Construction Tasks

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

Robotic Functional Decomposition

TA4.0 Robotics, Tele-Robotics & Autonomous (RTA) Systems

TA4.1 Sensing & Perception

TA4.1.1
3-D Perception

TA4.1.2
Relative Position & Velocity Estimation

TA4.1.3
Terrain Mapping, Classification & Characterization

TA4.1.4
Natural & Man-made Object Recognition

TA4.1.5
Sensor Fusion for Sampling & Manipulation

TA4.1.6
Onboard Science Data Analysis

TA4.2 Mobility

TA4.2.1
Extreme Terrain Mobility

TA4.2.2
Below-Surface Mobility

TA4.2.3
Above-Surface Mobility

TA4.2.4
Small Body / Microgravity Mobility

TA4.3 Manipulation

TA4.3.1
Robot Arms

TA4.3.2
Dexterous Manipulators

TA4.3.3
Modeling of Contact Dynamics

TA4.3.4
Mobile Manipulation

TA4.3.5
Collaborative Manipulation

TA4.3.6
Robotic Drilling & Sample Processing

TA4.4 Human-Systems Int.

TA4.4.1
Multi-Modal Human-Systems Interaction

TA4.4.2
Supervisory Control

TA4.4.3
Robot-to-Suit Interfaces

TA4.4.4
Intent Recognition & Reaction

TA4.4.5
Distributed Collaboration

TA4.4.6
Common Human-Systems Interfaces

TA4.4.7
Safety, Trust, & Interfacing of Robotic/Human Proximity Operations

TA4.5 Autonomy

TA4.5.1
Vehicle System Management & FDIR

TA4.5.2
Dynamic Planning & Sequencing Tools

TA4.5.3
Autonomous Guidance & Control

TA4.5.4
Multi-Agent Coordination

TA4.5.5
Adjustable Autonomy

TA4.5.6
Terrain Relative Navigation

TA4.5.7
Path & Motion Planning with Uncertainty

TA4.6 Autonomous Rendezvous & Docking

TA4.6.1
Relative Navigation Sensors (long-, mid-, near-range)

TA4.6.2
Guidance Algorithms

TA4.6.3
Docking & Capture Mechanisms/ Interfaces

TA4.6.4
Mission/System Managers for Autonomy/ Automation

TA4.7 RTA Systems Engineering

TA4.7.1
Modularity / Commonality

TA4.7.2
Verification & Validation of Complex Adaptive Systems

TA4.7.3
Onboard Computing

NASA Roadmap 2012

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)

Lunar Excavation System Concepts

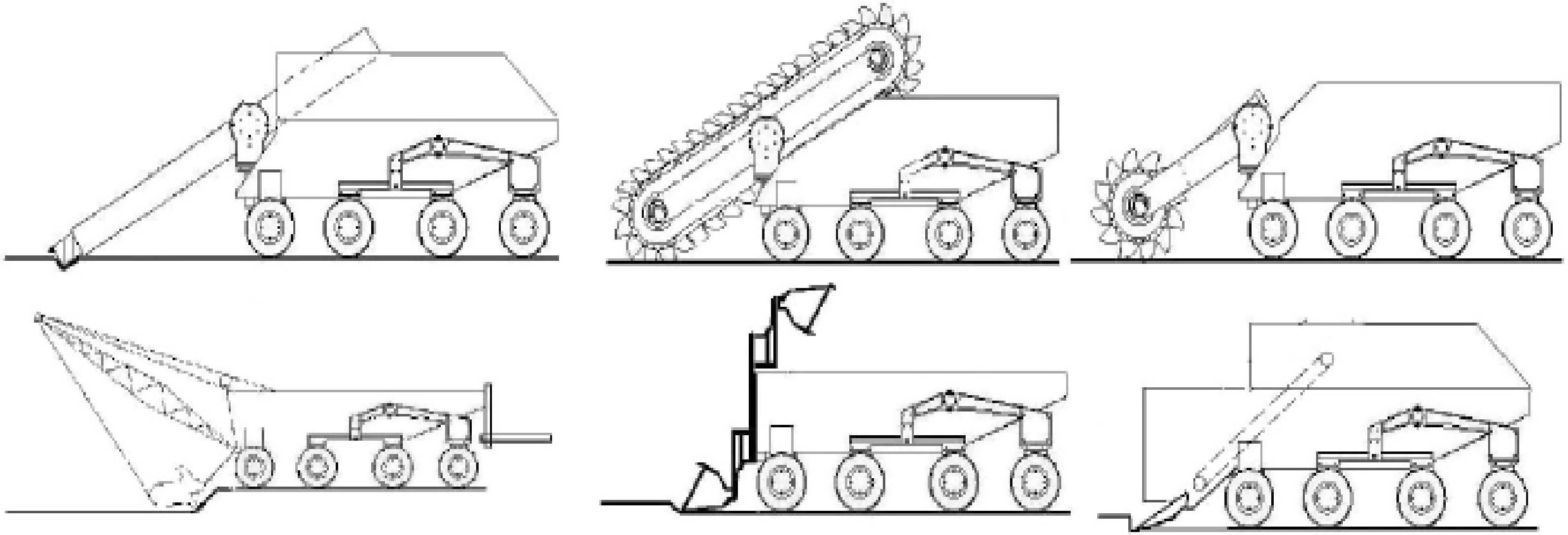


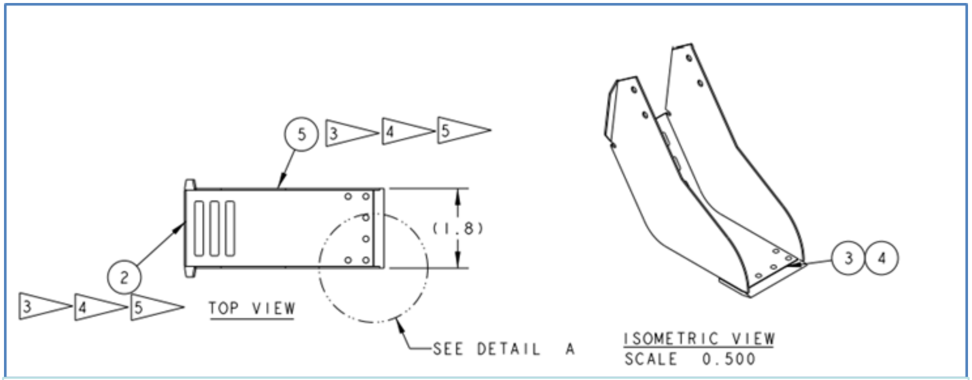
FIGURE 3. Additional Concepts From Top Left to Bottom Right: Auger, Bucket Ladder, Bucket Wheel or Bucket Drum, Dragline, Overshot Loader, and Scraper.

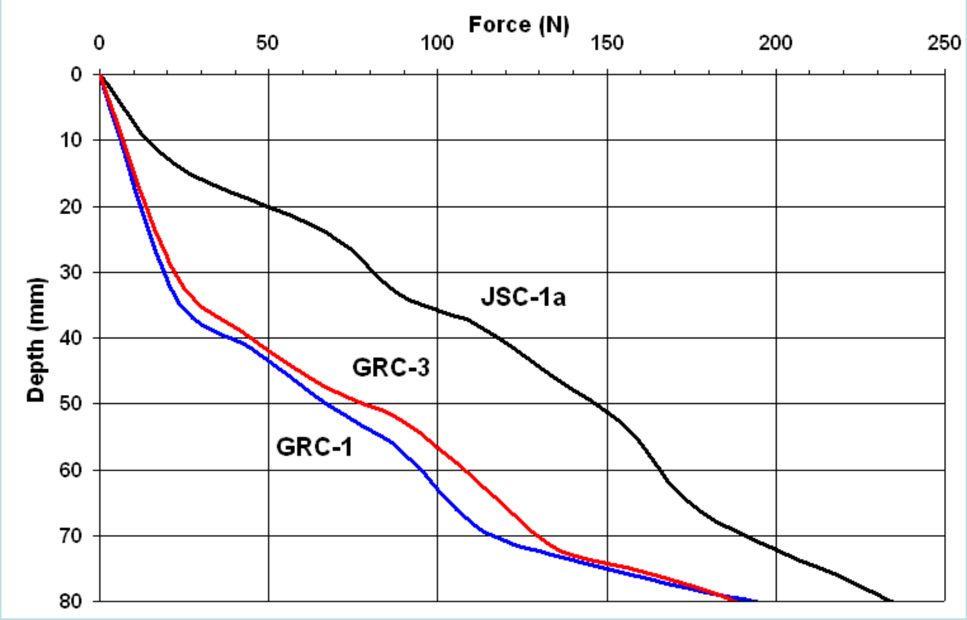
TABLE 4. Summary Estimated Specifications for the Additional Concepts.

	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

60 Kg Excavator with Small Scoop





Replica of NASA Lunar Surveyor Scoop & Test results in regolith simulants

Regolith Excavator Design

Design Options:

- Increase Traction (Heavier, grousers on wheels)
- Decrease Excavation Forces (Smaller scoops, less depth of cut)

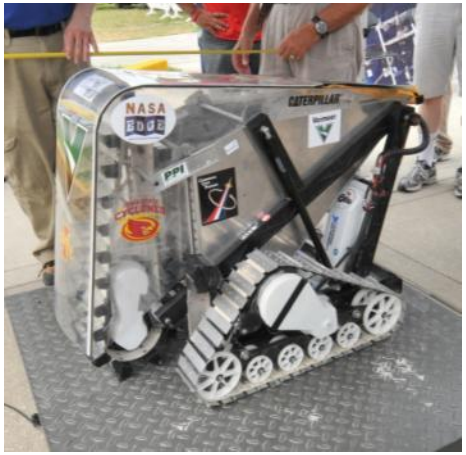
- If a traditional small / lightweight excavator is designed, then the design solution must excavate many small scoops quickly to meet traction constraints and still meet production goals

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

2009: Paul's Robotics WPI

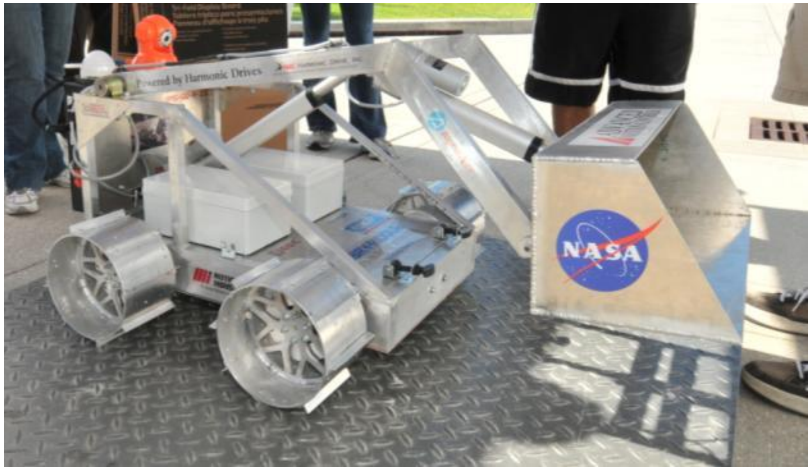
2010: Montana State U

2011: Laurentian University



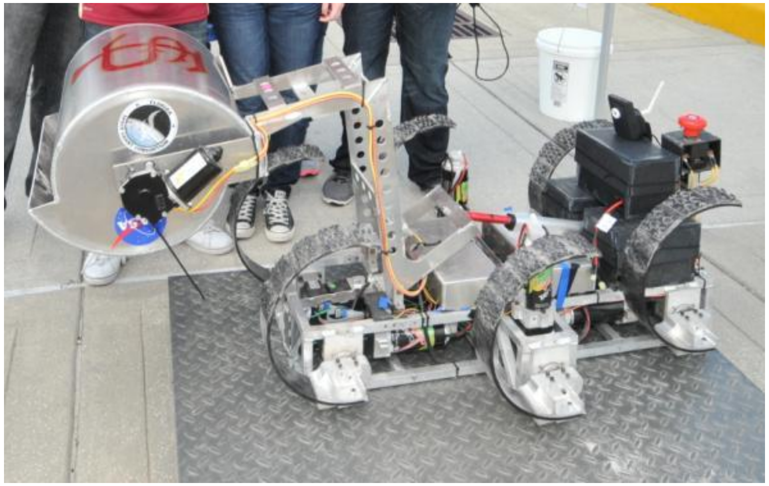
2012: Iowa State U

Or are these designs better?



2012: Embry Riddle Daytona AU

2011: U North Dakota



2012: FAMU/ Florida State U

2012: Montana State U

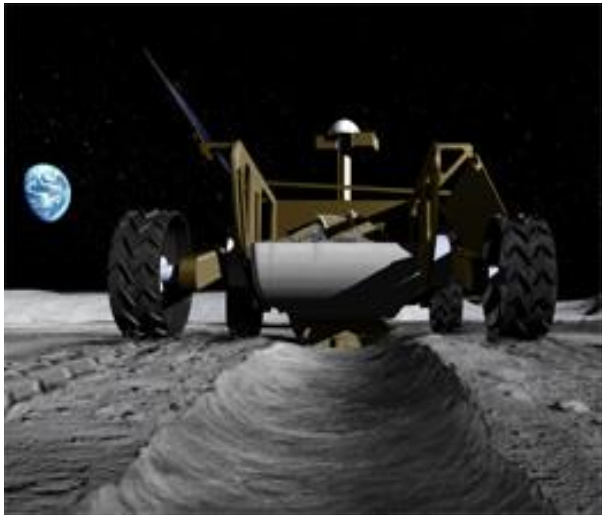
Regolith Excavation Mechanisms

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

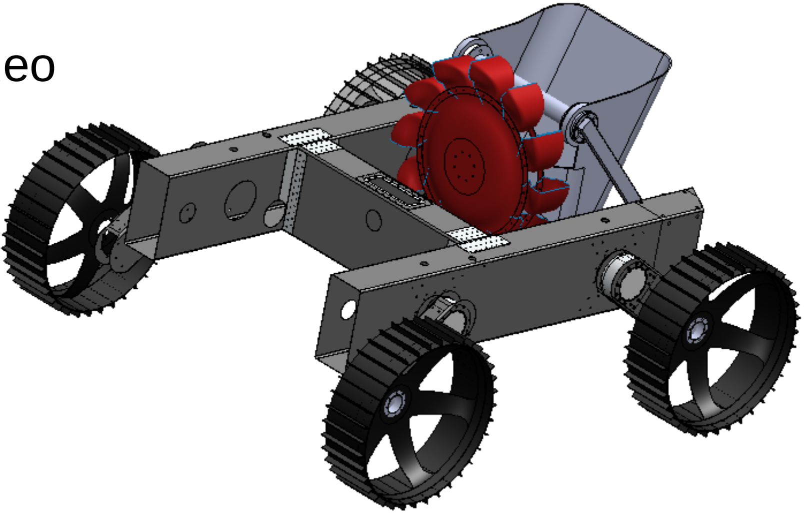
Regolith Excavation Mechanism	# of machines employing excavation mechanism
Bucket ladder (two chains)	29
Bucket belt	10
Bulldozer	10
Scraper	8
Auger plus conveyor belt / impeller	4
Backhoe	4
Bucket ladder (one chain)	4
Bucket wheel	4
Bucket drum	3
Claw / gripper scoop	2
Drums with metal plates (street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

Astrobotic Technology inc. Lunar Mining Concepts NASA SBIR 2010-2012

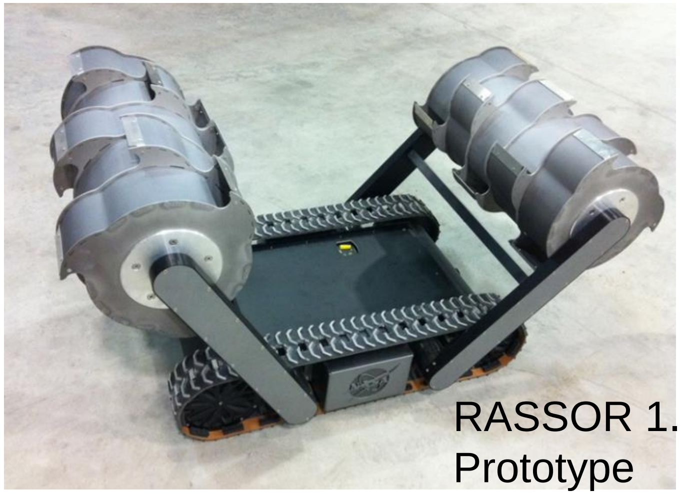
ASTROBOTIC



Video



NASA KSC Swamp Works
Regolith Advanced Surface Systems Operations Robot (RASSOR)



RASSOR 1.0
Prototype

RASSOR 1.5
Prototype

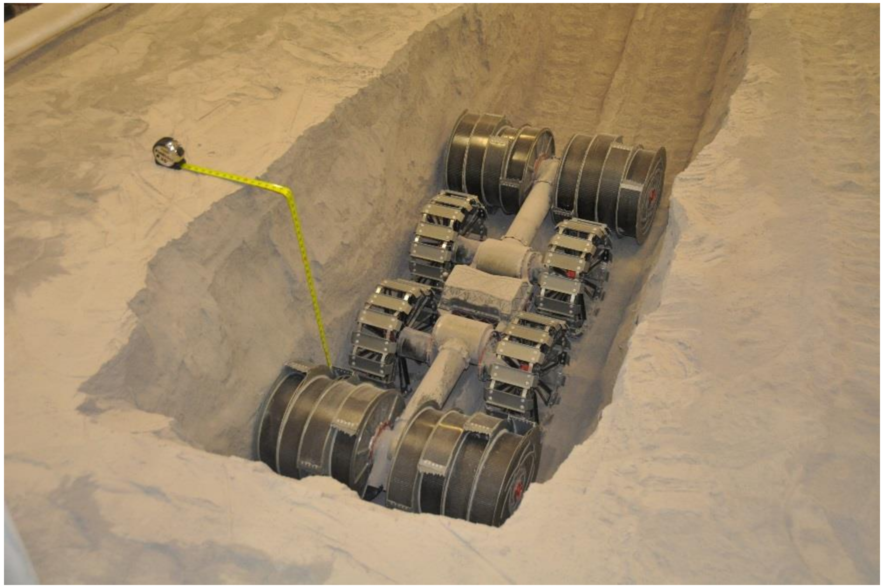
SWAMP WORKS
NASA KENNEDY SPACE CENTER

Video

RASSOR 2.0 Prototype
Dry Mass ~ 66 Kg
Regolith Payload = 80 Kg
ounter-Rotating Bucket Drums = Zero Net Reaction Forc

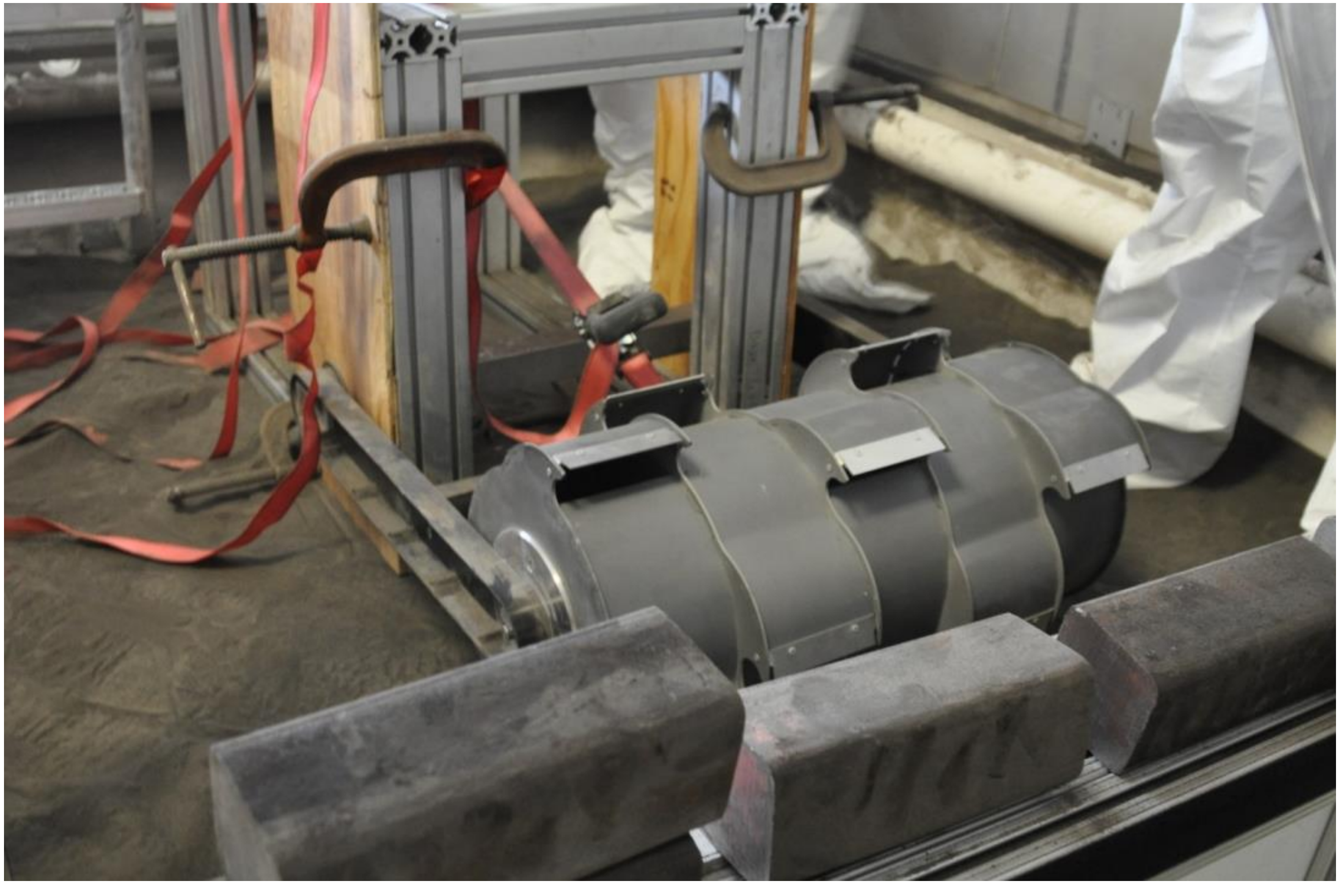
Excavator: RASSOR 2.0

Excavator: RASSOR 2.0



Video

Bucket drum torque test setup



Bucket Drum Torque Test (N m).

Cutting Depth (cm)	Test 1	Test 2	Test 3	Test 4	Avg.	Force (N)
2.66	47.45	33.89	40.67	33.89	38.98	220.09
1.77	20.34	20.34	20.34	13.56	18.64	105.26

~275 N Digging Force @ 4 cm depth

Launch / Landing Pad Construction

NASA Photo: Morpheus Project

Construct a Launch/Landing Pad using In Situ Regolith for rocket plume impingement mitigation

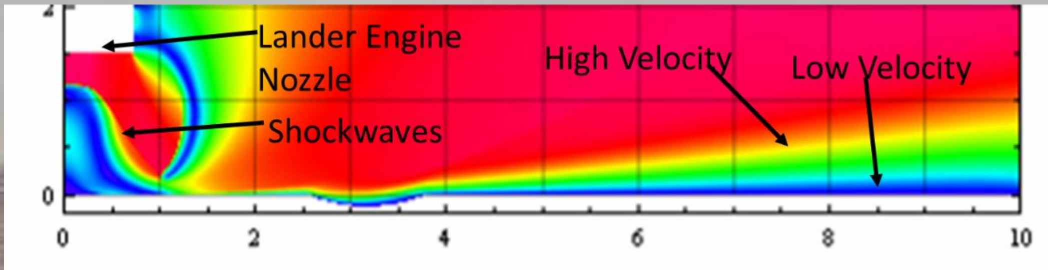


Photo Credits: PISCES /NASA ACME

NASA/ PISCES Paver Laying Robot

Hawaii PISCES Rover on Mauna Kea with Payloads

ISRU Process Waste

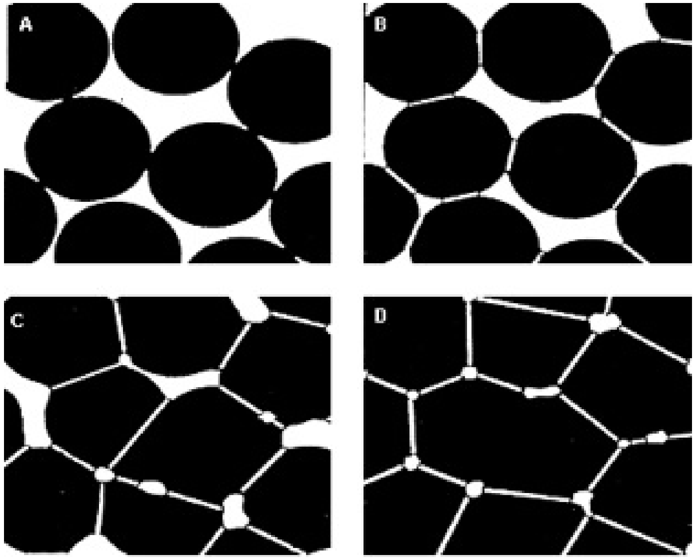
Use of waste stream from In-Situ Resource Utilization (ISRU) processes.

- Hot regolith can be poured into a heat shield mold.
- Saves energy by combining processes.

Hot Hawaiian tephra output from the ROxygen generation I oxygen production reactor.

This basalt regolith material can be used to make parts and pavers for lunar structures

Regolith Sintering Process

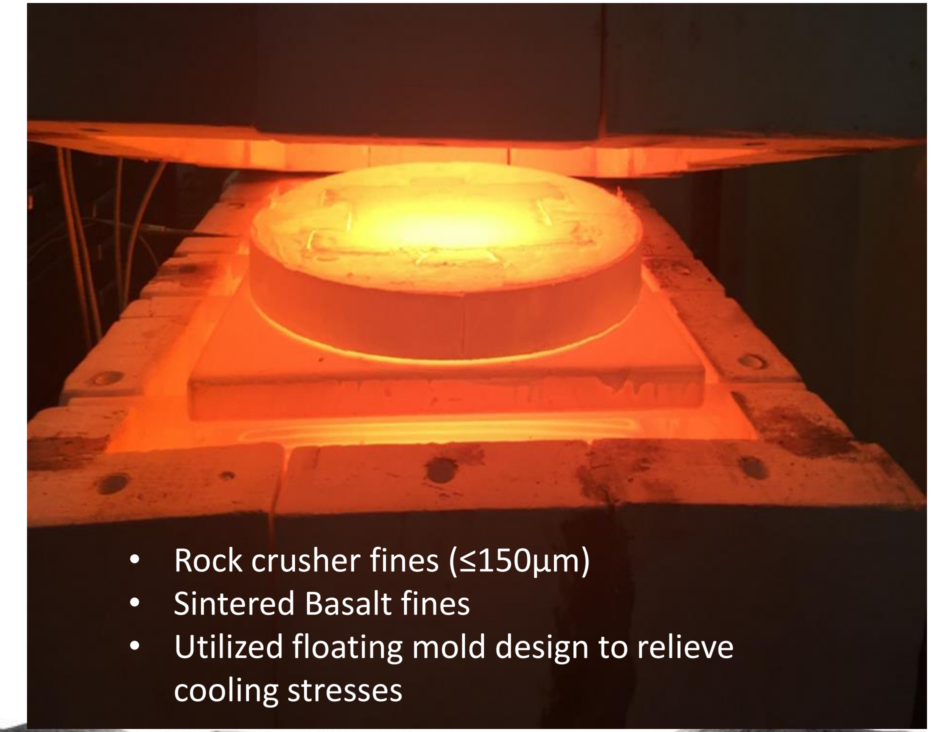


Temperature and heating time are crucial factors in resulting structure.

Sintered Basalt Regolith results in a high temperature resistant material that can be used for launch/landing pad materials

JSC-1A sintered tiles that have been exposed to a rocket plume for a lander vehicle
(Courtesy Swamp Works, NASA KSC)

Sintered Basalt Pavers



- Rock crusher fines (≤150µm)
- Sintered Basalt fines
- Utilized floating mold design to relieve cooling stresses

PISCES Rover, Helelani: Multi Purpose Vehicle.
Mobile Platform Base: Alpha Argo Rover

Grading & Leveling Blade

1,270 mm x 406 mm Steel Blade

Compactor Roller

1200 mm x 450mm (diam) Roller ($1.9m^3$)

Paver Deployment Mechanism

PISCES

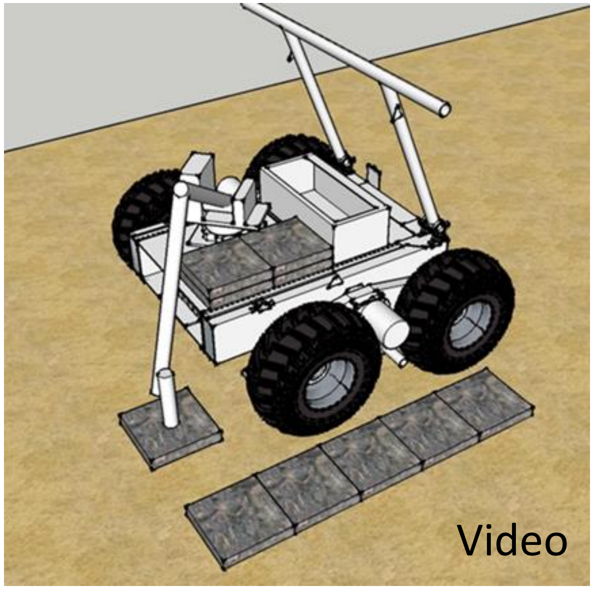
PACIFIC INTERNATIONAL SPACE CENTER FOR
EXPLORATION SYSTEMS | PISCES.HAWAII.GOV

SWAMP WORKS
NASA KENNEDY SPACE CENTER

Argo

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

Launch / Landing Pad Construction



Video

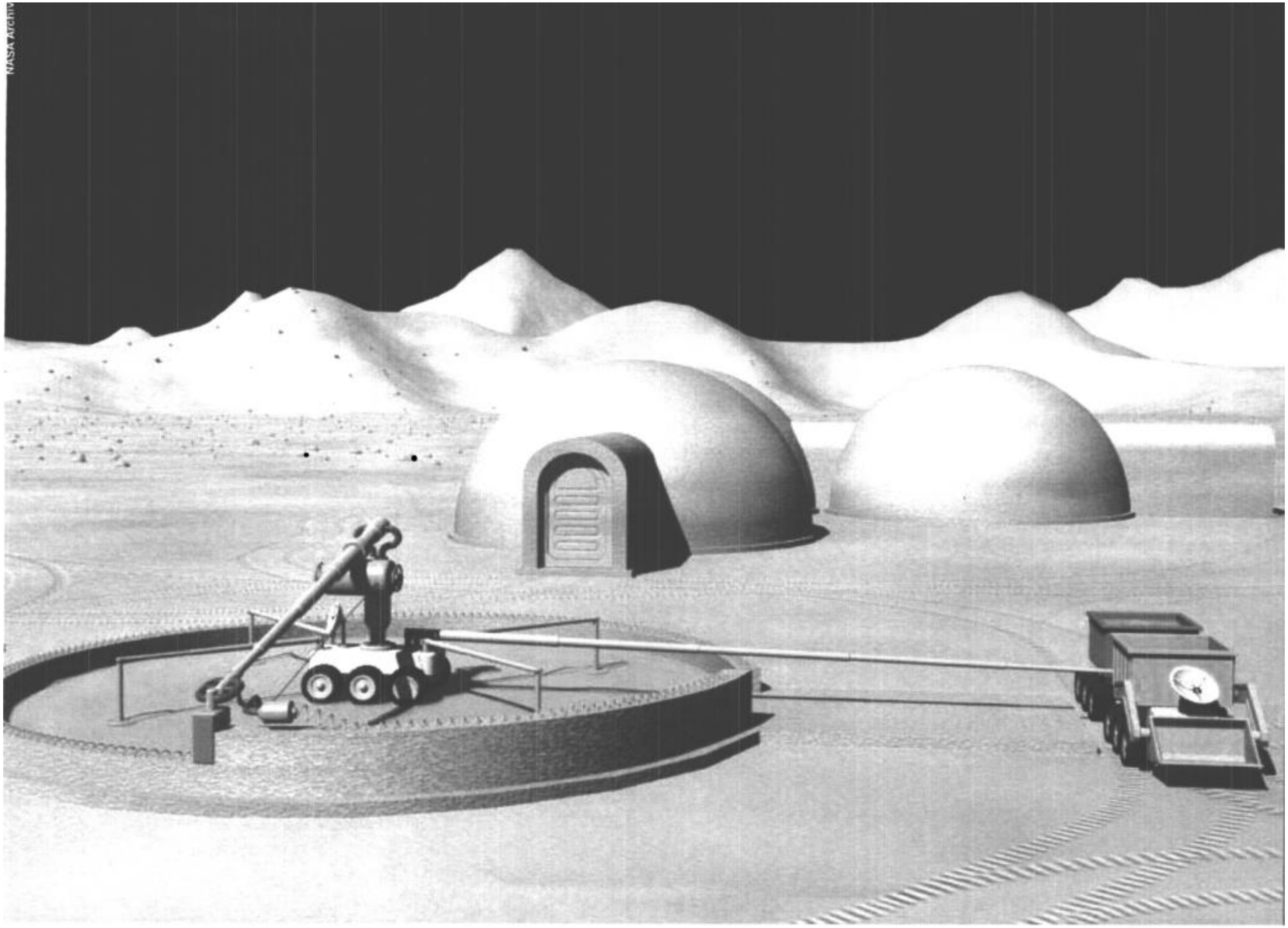
Photo Credits: PISCES / NASA ACME

Hawaiian Hot Fire Test!

Photo Credits: PISCES / NASA ACME

~1,000 lbf Thrust, “M” Class Solid Rocket Motor Firing in test stand
Paver cracking led to new, improved sintered basalt material being developed

Robotic 3D Additive Construction using Regolith Concrete

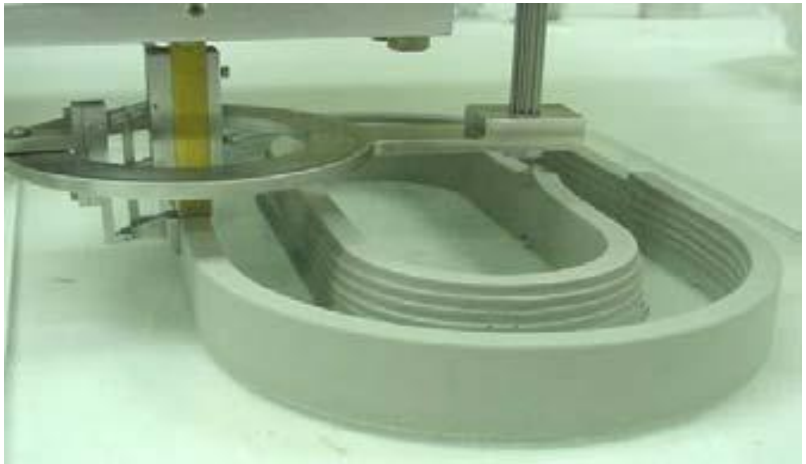


2005 Concept: NASA / Marshall Space Flight Center

3D Additive Construction with Regolith Concrete

Construction Location Flexibility

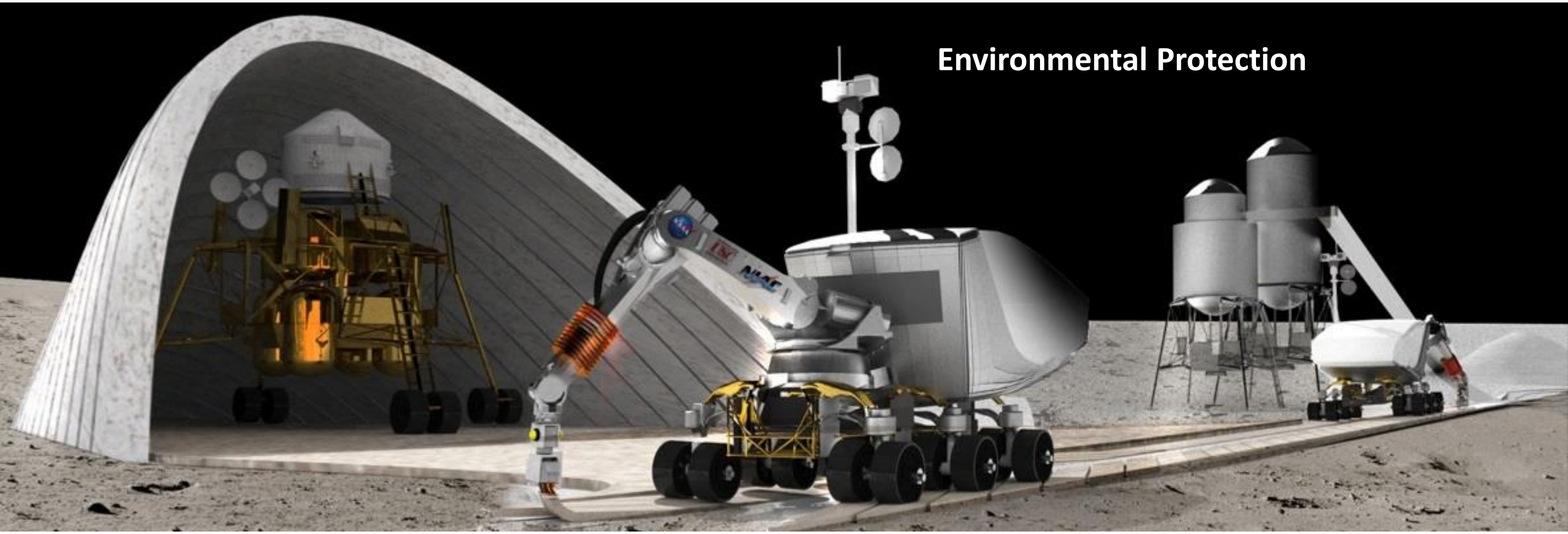
Multi-axis print head



Curved wall tool path development

Images Courtesy
of Dr. B. Khoshnevis,
Contour Crafting, LLC
for NASA NIAC

3D Additive Construction Elements Using In-Situ Materials (Basalt)



Environmental Protection

Images Courtesy
of Dr. B. Khoshnevis,
Contour Crafting, LLC for NASA NIAC

Complex Tool Path Development Allows Interior Walls

NASA / USC Additive Construction with Mobile Emplacement (ACME)

CRAFT Center - USC

Rendering courtesy of Behnaz Farahi and Connor Wingfield

Bench Top Test Results

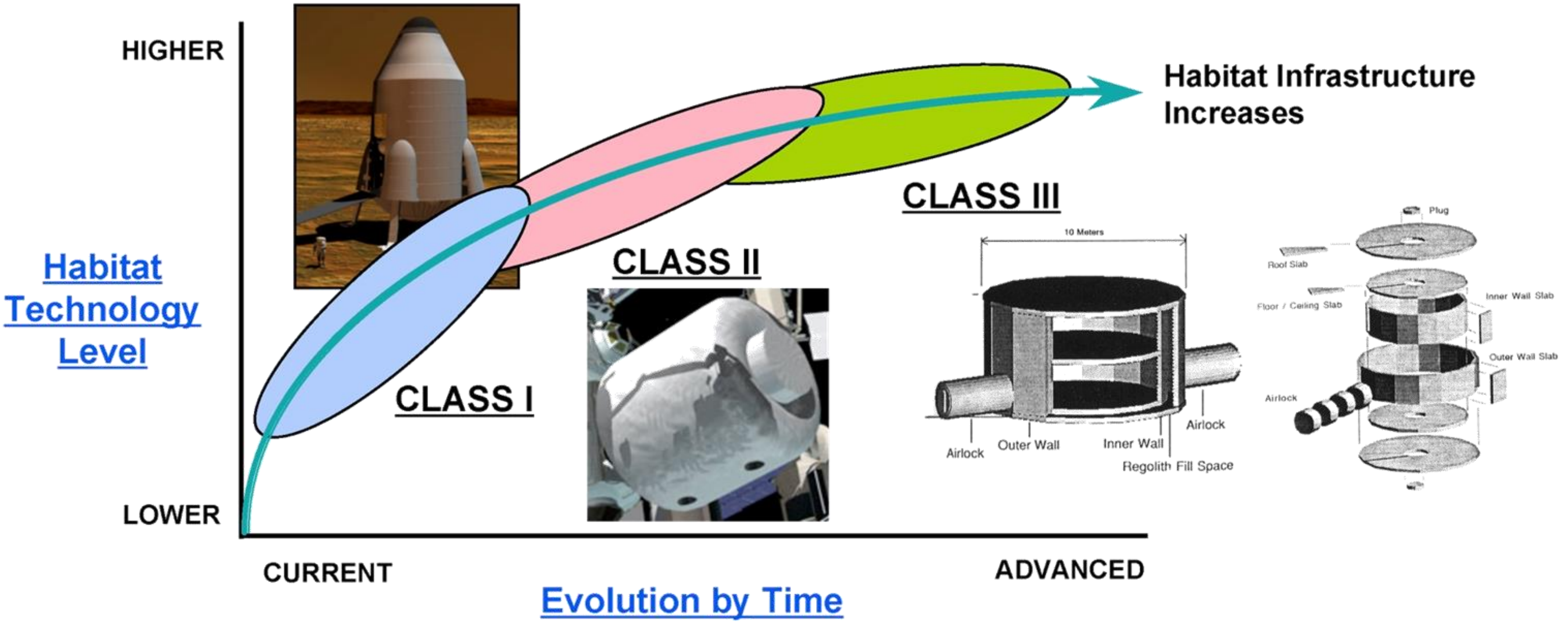
Successful laser based fabrication of test materials and bench-top scale freestanding structures was achieved with several types of regolith simulant including:

- Black Point -1 (BP-1), Lunar Regolith Basalt Simulant – NASA KSC
- JSC-1A, Lunar Mare Simulant – NASA Johnson Space Center (JSC)
- NU-LHT-2M, Lunar Highland Type Simulant (2 Medium) – NASA USGS
- Hawaiian Basaltic Tephra from Mauna Kea Volcano, Hai Wahine Valley
- Standard White Construction Sand with 30% by weight added BP-1
- Cape Canaveral “Jetty Park” Beach Sand with 30% by weight added BP-1

Figure 2. Bench-top scale freestanding structures created by Swamp Works 3D Regolith Construction process: **A) BP-1 Hollow Cone Structure; B) BP-1 Hollow Ogive Dome Structure**

Phased Approach to Space Construction

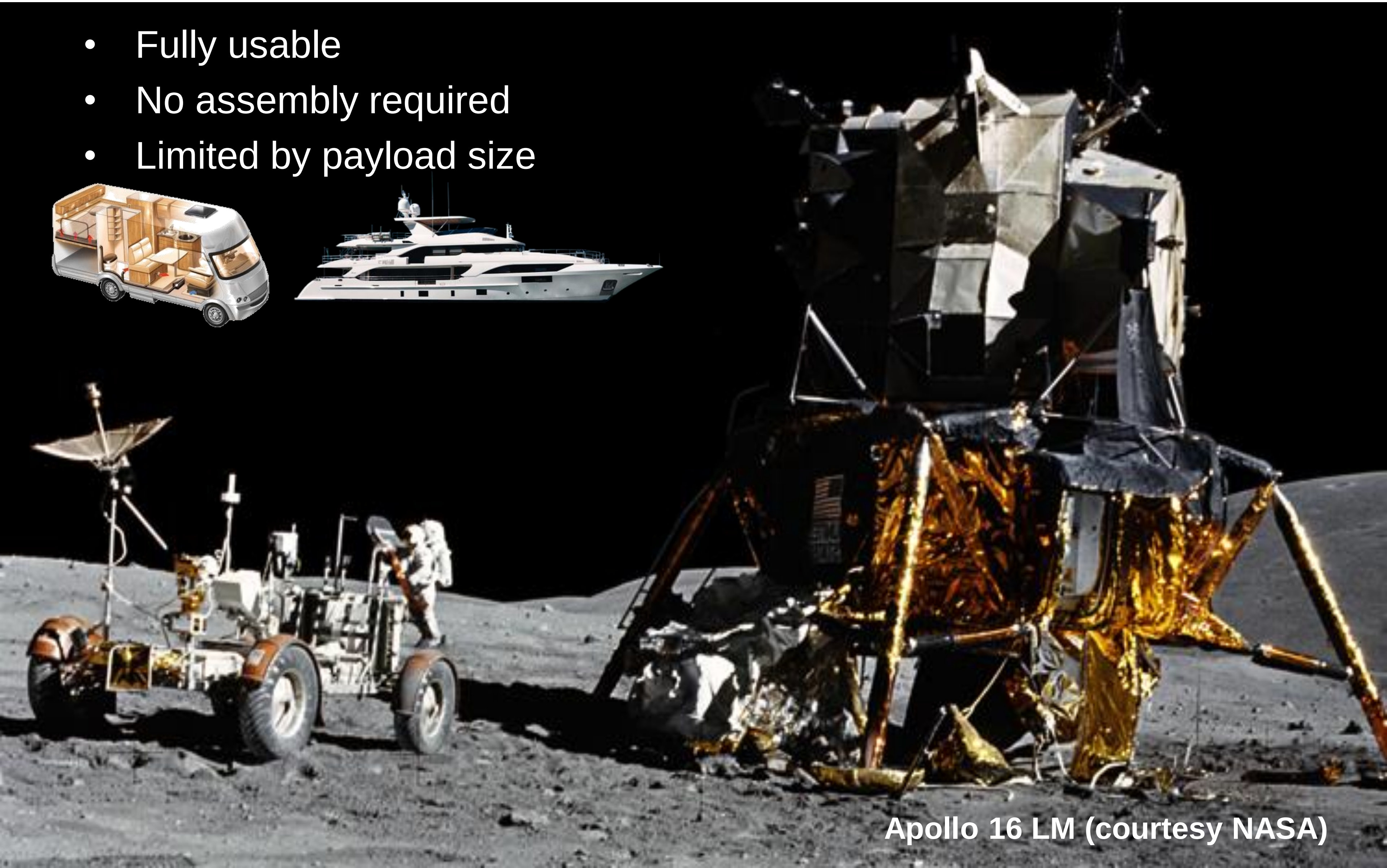
- CLASS I:
  - Preintegrated, Hard Shell Module
- CLASS II:
  - Prefabricated, Surface Assembled
- CLASS III:
  - ISRU Derived Structure w/ Integrated Earth components



Credit: Scott Howe, JPL

Class I: Pre-integrated Construction

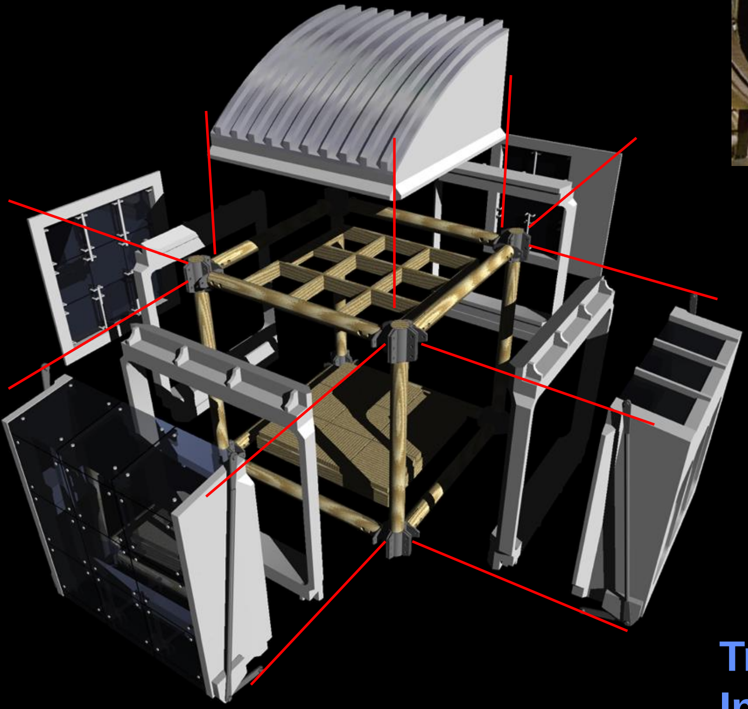
- Fully usable
- No assembly required
- Limited by payload size

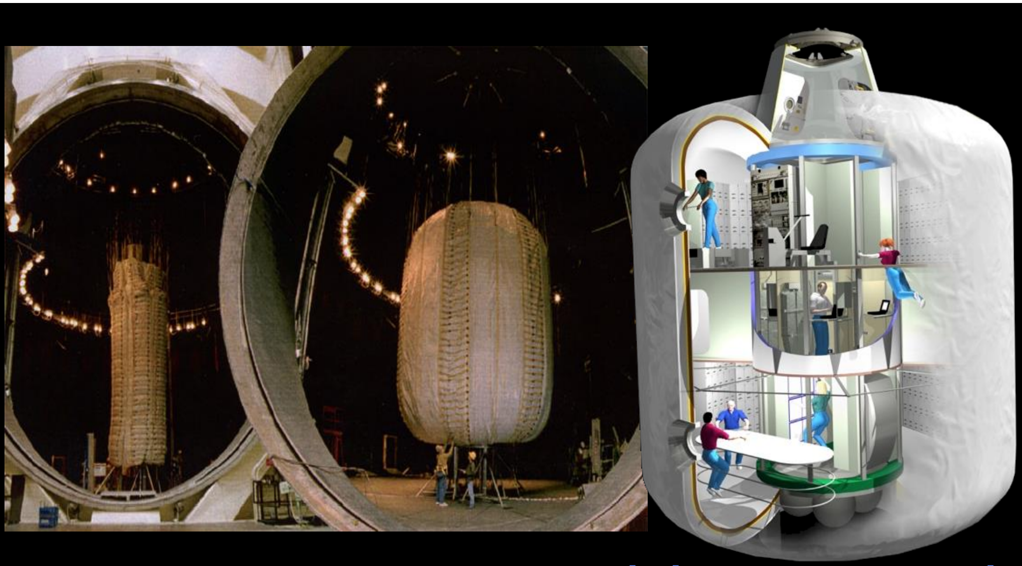


Apollo 16 LM (courtesy NASA)

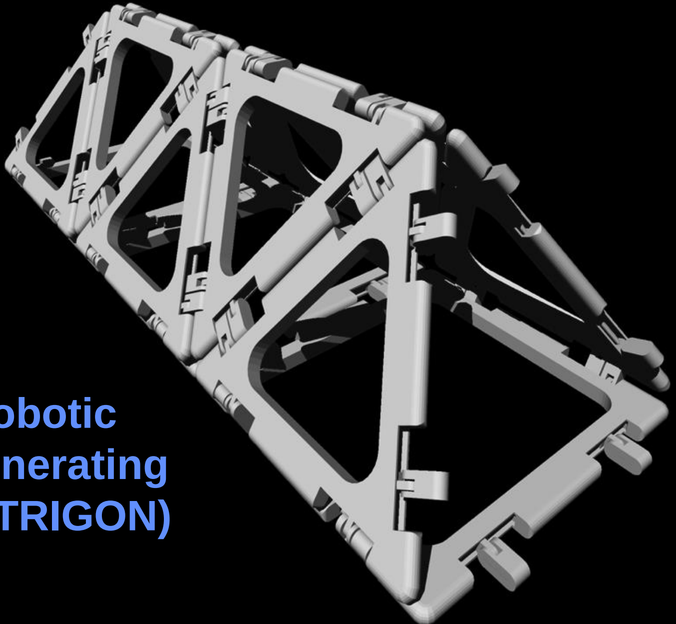
Class II: Pre-fabricated Construction

- Assembled onsite
- Robust joints
- Replacable
- No size limit





TransHab (courtesy NASA)



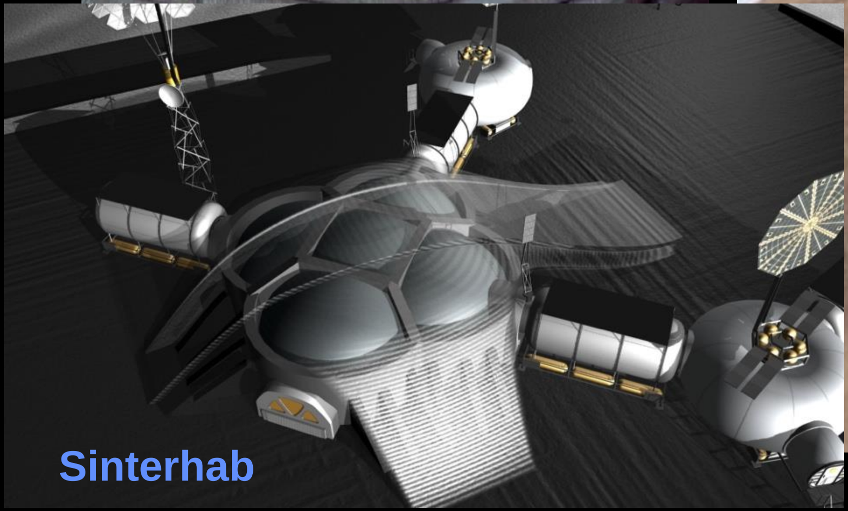
Transformable Robotic Infrastructure-Generating Object Network (TRIGON)

Class II Execution: Robotic Assembly

Credit: Scott Howe, JPL

Class III: In-situ Construction

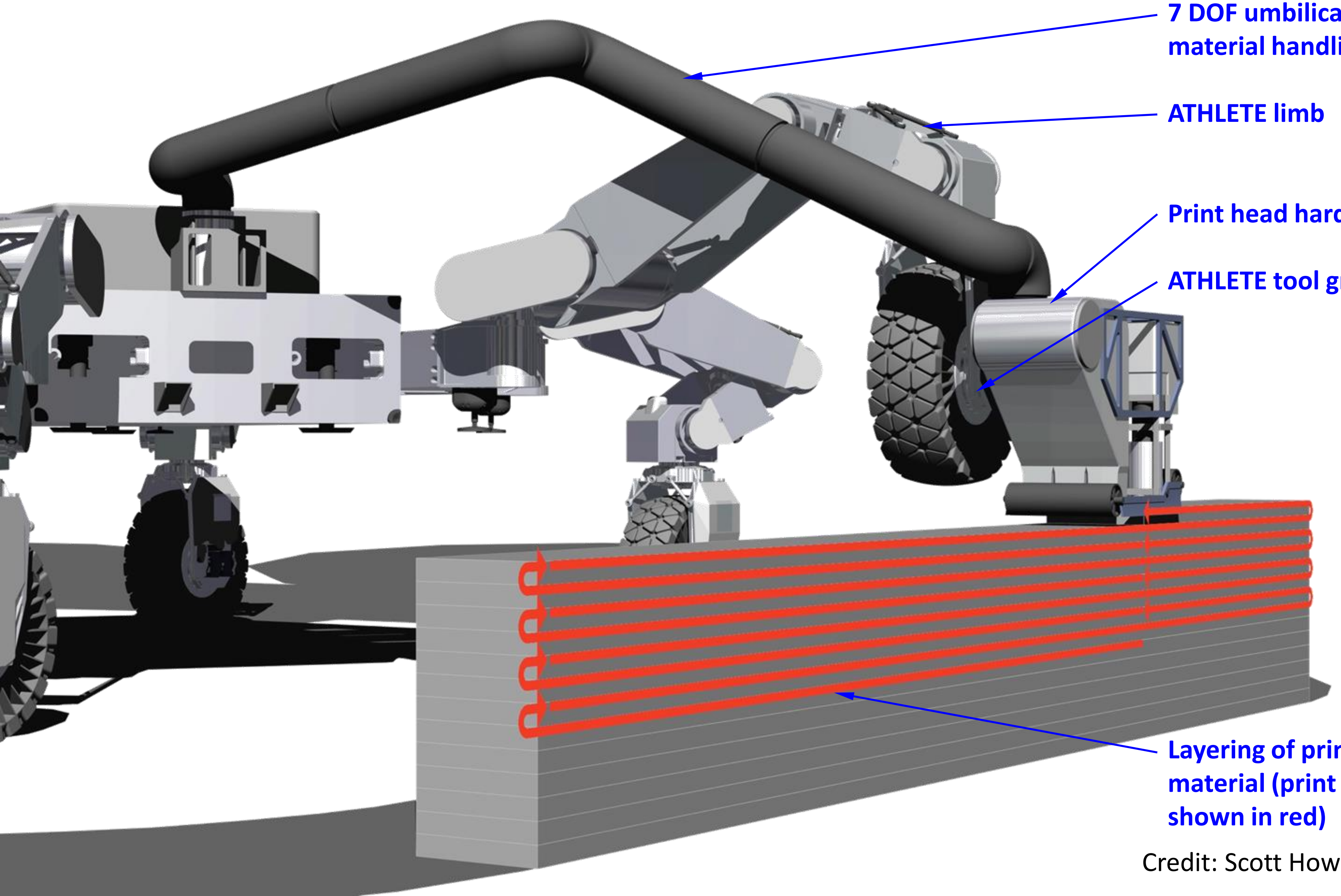
- Need up-front technology
- Onsite effort
- Unlimited resources
- Sustainable



Sinterhab

Sandbag domes (courtesy CalEarth)

Class III Concepts: 3D Additive Construction



7 DOF umbilical / material handling

ATHLETE limb

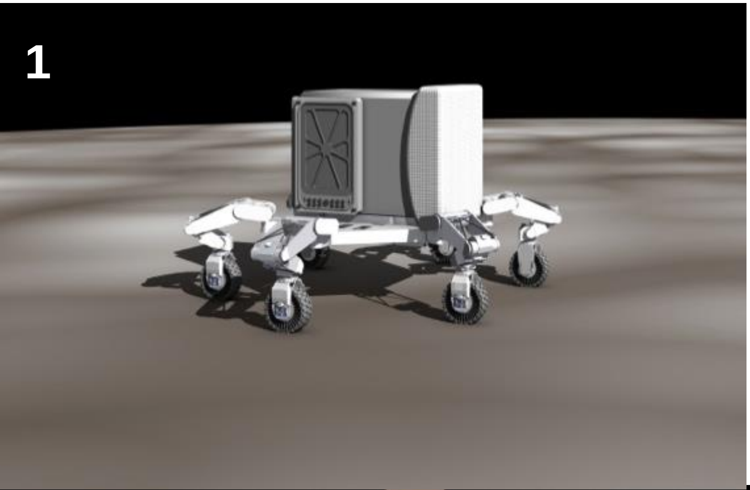
Print head hardware

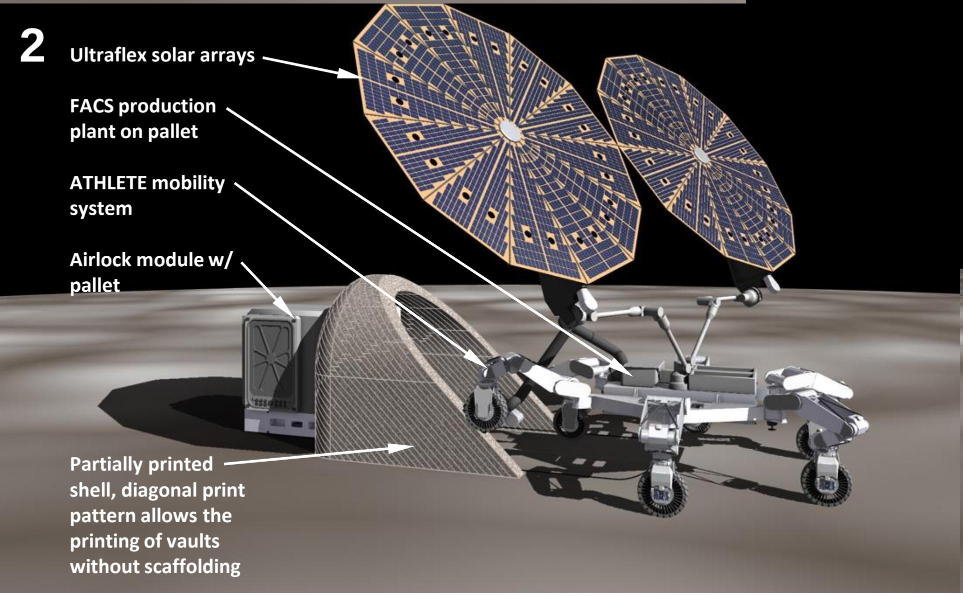
ATHLETE tool grasp

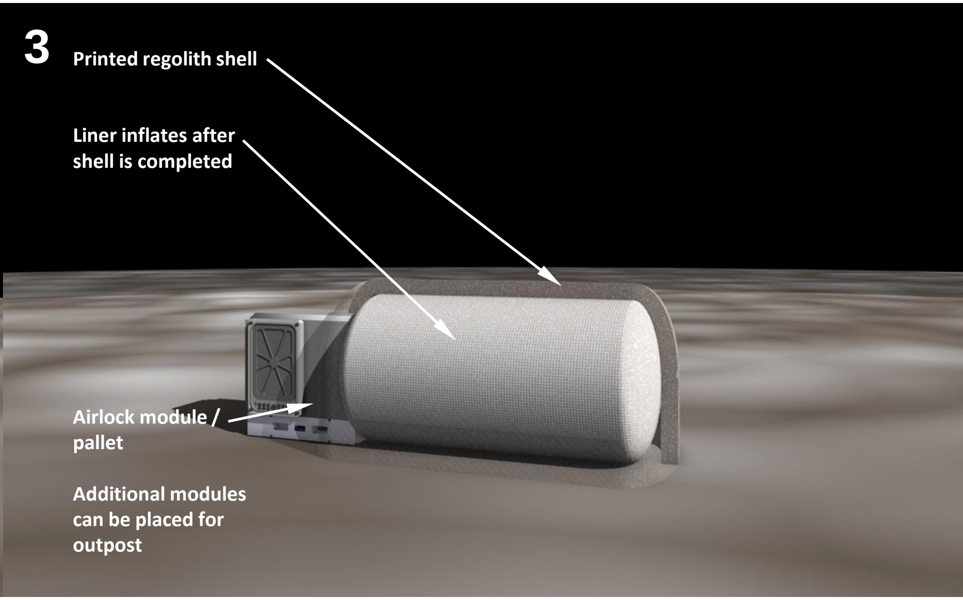
Layering of printed material (print path shown in red)

Credit: Scott Howe, JPL

Class III Concept: Shells Structures

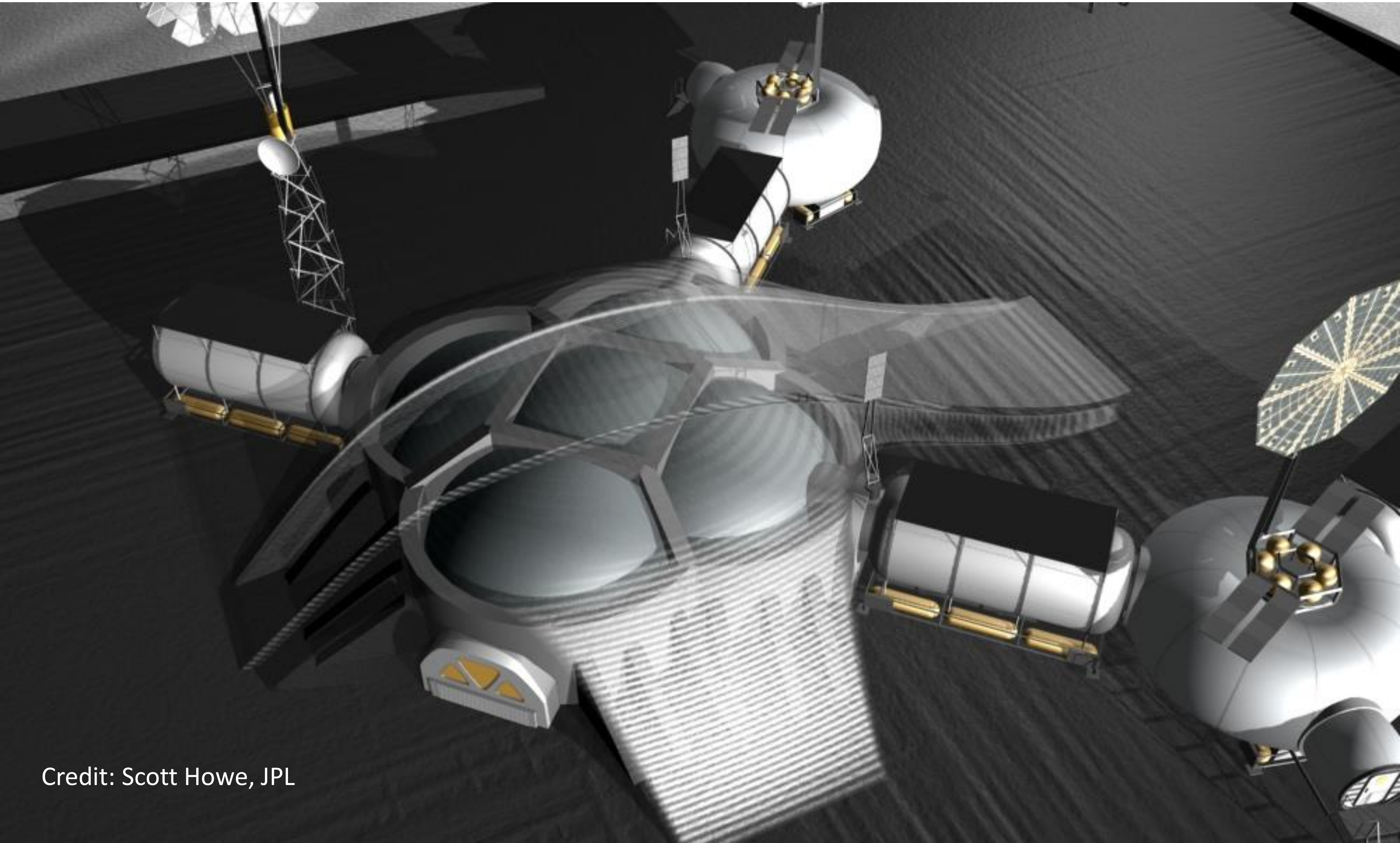






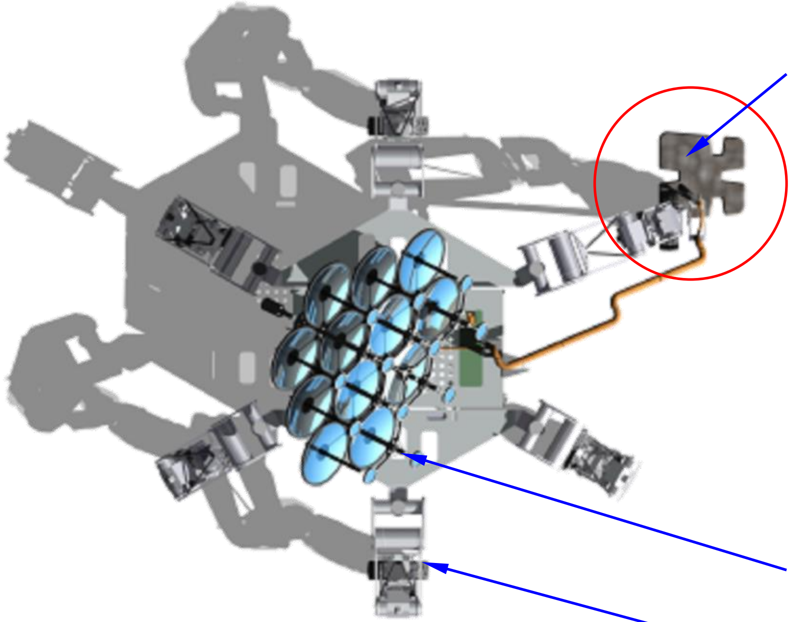
Credit: Scott Howe, JPL

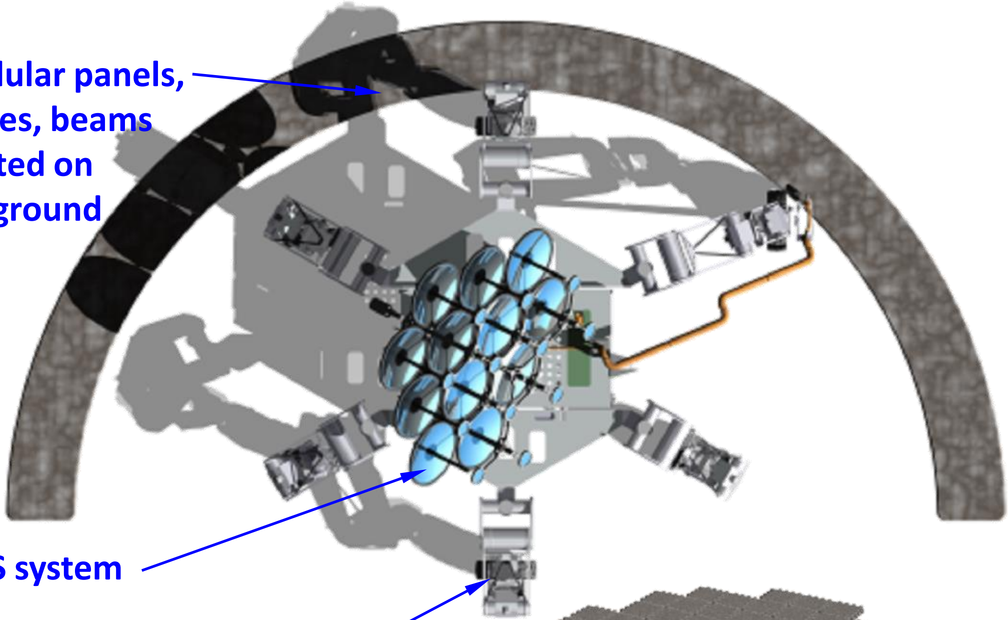
Application: Printed Habitat Shells: "Sinterhab"



Credit: Scott Howe, JPL

Class III Concept: In-situ Assembly

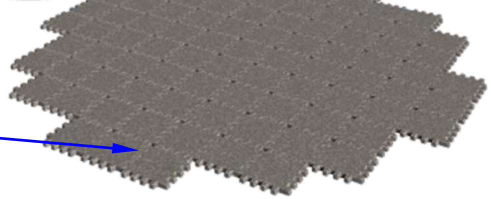




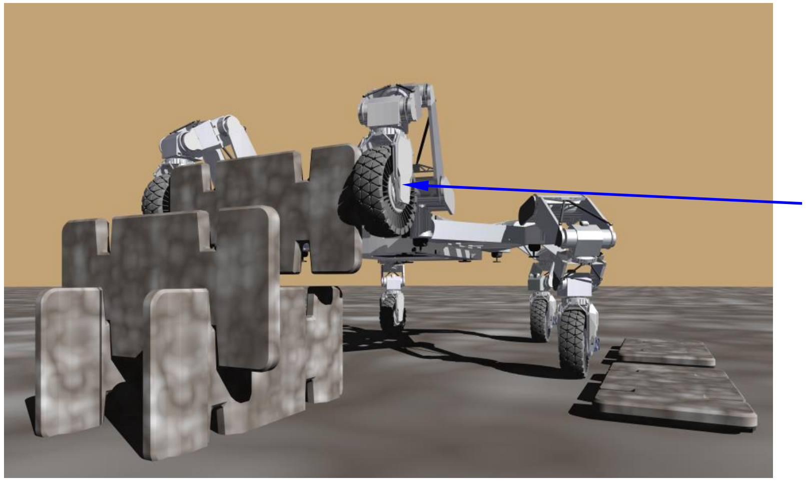
Modular panels, arches, beams printed on the ground

FACS system

ATHLETE mobility system



In-situ printed paving blocks for lander pads

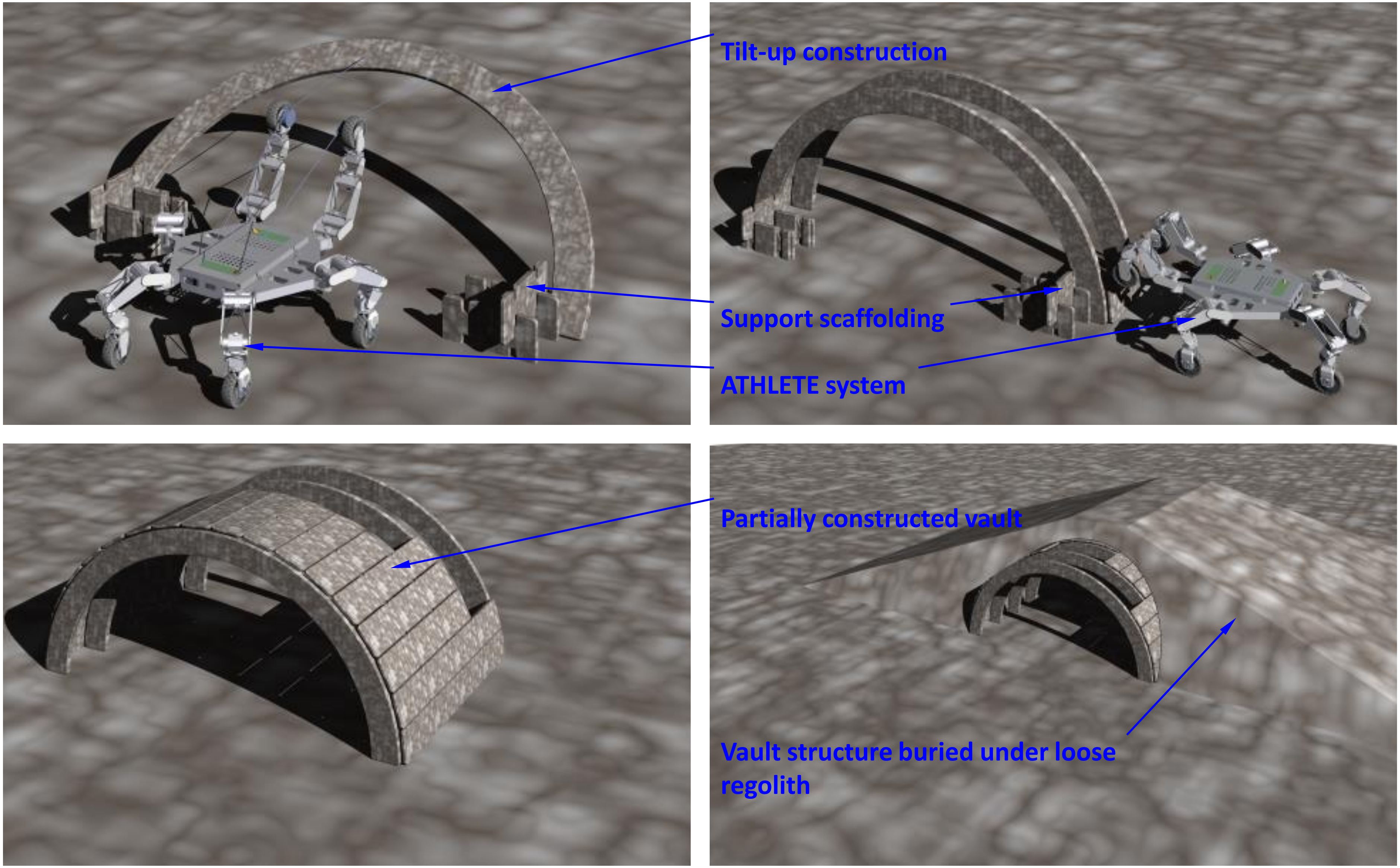


ATHLETE can lift and manipulate panels into in-situ structure

Modular archways and scaffolding assembled from in-situ printed panels

Credit: Scott Howe, JPL

Class III Concept: In-situ Assembly



Tilt-up construction

Support scaffolding

ATHLETE system

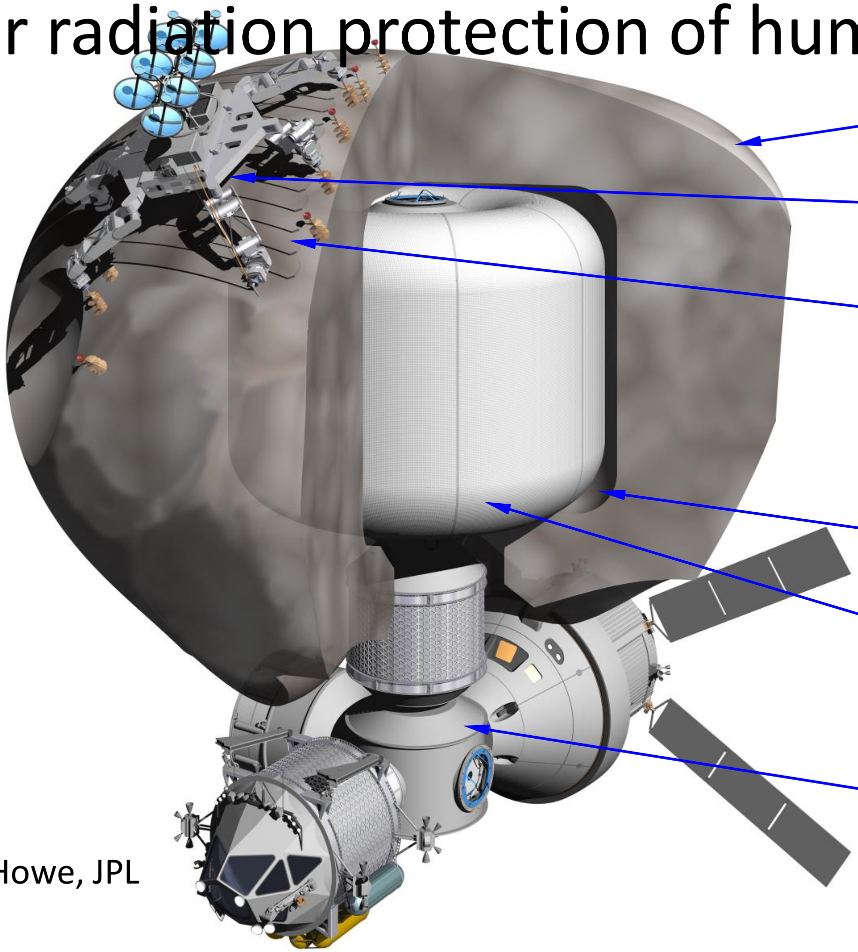
Partially constructed vault

Vault structure buried under loose regolith

Credit: Scott Howe, JPL

Asteroid Habitat Concept

- Microgravity Technology Demonstration: Stabilizing the surface of an asteroid that can be hollowed out for radiation protection of human habitats



Asteroid with powder regolith surface

Robotic mobility system placing grid of anchors

3D Automated Additive Construction technology hardens and stabilizes surface

Asteroid is partially hollowed out

Inflatable habitat inserted and inflated

Docking nodes, propulsion systems

Credit: Scott Howe, JPL

Vision for AAC

Time Frame (years)	Resource Utilization	Humans Off-planet	Automated Additive Construction Technology	Energy	Byproducts
10	Terrestrial demonstration of regolith processing / separation; Extraterrestrial prospecting	Trips to Moon / Mars / asteroids	Demonstrate terrestrial 3D printing with sintering / melting, print landing pads / shelters	All systems Earth manufactured	Volatile collection demonstration
25	Harness bulk regolith; Test regolith separation in space; Mars cyclers for radiation shielding	Habitation / outposts on Moon/Mars	Autonomous construction with bulk in-situ resources; 3D construction of landing pads, shelters in space	Exporting solar cells from Earth; manufacture concentrators in-situ	In-space collection of water separation into constituent gasses
50	Autonomous materials processing into desired elements / compounds; Cu/Fe extraction	Colonies; financially self-sustaining industries off-planet	Partial self-replicating factories; habitats/structures made in-situ	Sustainable off-world energy sources: solar concentrators, photovoltaics manufactured in-situ	Limited off-Earth fuel production: hydrocarbon, oxygen
100	Resource independence; terraforming asteroids; enclosed lunar / Martian cities	Communities on Mars / Moon / asteroids	3D additive industry; silicon / biologically based self-replicating factories	Communities independent of Earth resources; harness off-planet resources to create energy sources and storage	Sustainable off-Earth fuel production

Centennial Challenge: 3D Print a Habitat

Challenge Sponsors:

Challenge Sponsors:

NASA 3D Additive Construction
2015 Centennial Challenge – Top 3

Summary

- There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth
- Shelter for fragile humans will be required
- Space faring humans will need planetary bases which will require planetary surface construction
- New technologies are developing rapidly, allowing for robotic automated construction
- Much more work is needed before Planetary Surface Construction becomes viable, but *the first commercial space companies are emerging today*
- Government labs are already developing prototypes
- *It's your future – make it happen*