ISRU Construction & Excavation of Regolith

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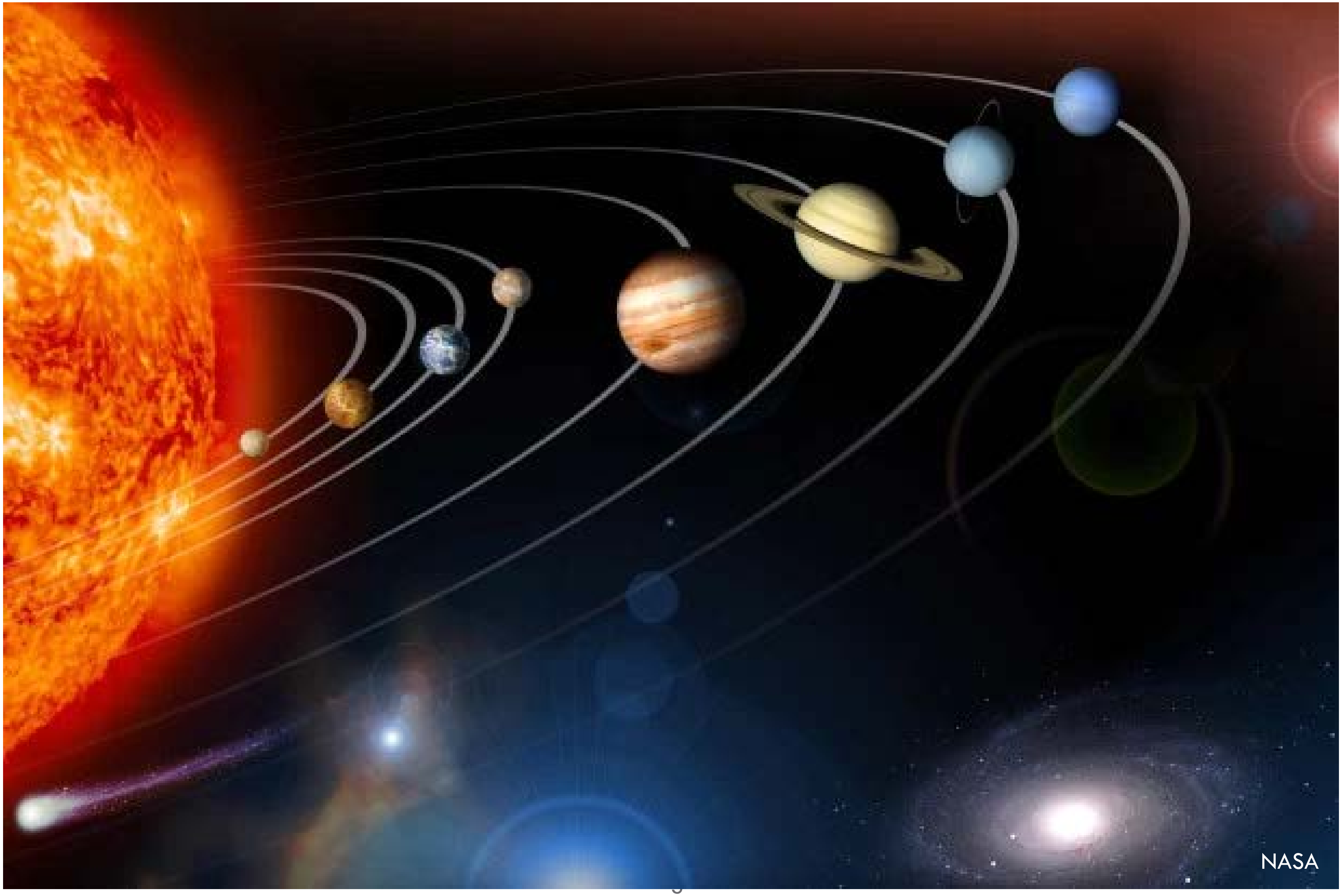
Space Environments

What are Space Resources?



Space Resources

- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.

- **Energy**
  - Thermal Energy Storage Using Modified Regolith
    - Thermal conductivity of unmodified lunar regolith is very low (~1 mW/m-K); good insulator.
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments

- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - Large Thermal Gradients
  - Atmosphere Drag

- **Location**
  - Stable Locations/'Real Estate':
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

In Situ Resource Utilization (ISRU)

Possible Destinations

Moon

Mars & Phobos

Near Earth Asteroids & Extinct Comets

Europa

Titan

Common Resources

Water
- Moon
- Mars
- Comets
- Asteroids
- Europa
- Titan
- Triton
- **Human Habitats**

Carbon
- Mars (atm)
- Asteroids
- Comets
- Titan
- **Human Habitats**

Metals & Oxides
- Moon
- Mars
- Asteroids

Helium-3
- Moon
- Jupiter
- Saturn
- Uranus
- Neptune

Core Building Blocks

- Atmosphere & Volatile Collection & Separation
- Regolith Processing to Extract O_2, Si, Metals
- Water & Carbon Dioxide Processing
- Fine-grained Regolith Excavation & Refining
- Drilling
- Volatile Furnaces & Fluidized Beds
- 0-g & Surface Cryogenic Liquefaction, Storage, & Transfer
- In-Situ Manufacture of Parts & Solar Cells

Core Technologies

- Microchannel Adsorption
- Constituent Freezing
- Molecular Sieves

- Hydrogen Reduction
- Carbothermal Reduction
- Molten Oxide Electrolysis

- Water Electrolysis
- CO_2 Electrolysis
- Sabatier Reactor
- RWGS Reactor
- Methane Reformer
- Microchannel Chem/thermal units

- Scoopers/buckets
- Conveyors/augers
- No fluid drilling

- Thermal/Microwave Heaters
- Heat Exchangers
- Liquid Vaporizers

- O_2 & Fuel Low Heatleak Tanks (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings

Lunar and Mars Resources

Moon Resources

Ilmenite - 15%
- $FeO \cdot TiO_2$ (98.5%)

Pyroxene - 50%
- $CaO \cdot SiO_2$ (36.7%)
- $MgO \cdot SiO_2$ (29.2%)
- $FeO \cdot SiO_2$ (17.6%)
- $Al_2O_3 \cdot SiO_2$ (9.6%)
- $TiO_2 \cdot SiO_2$ (6.9%)

Olivine - 15%
- $2MgO \cdot SiO_2$ (56.6%)
- $2FeO \cdot SiO_2$ (42.7%)

Anorthite - 20%
- $CaO \cdot Al_2O_3 \cdot SiO_2$ (97.7%)

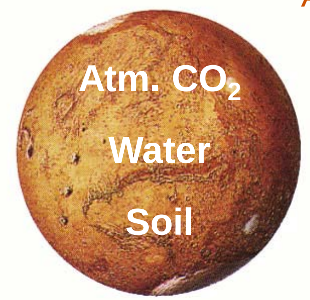
Water (?, >1000 ppm)

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)

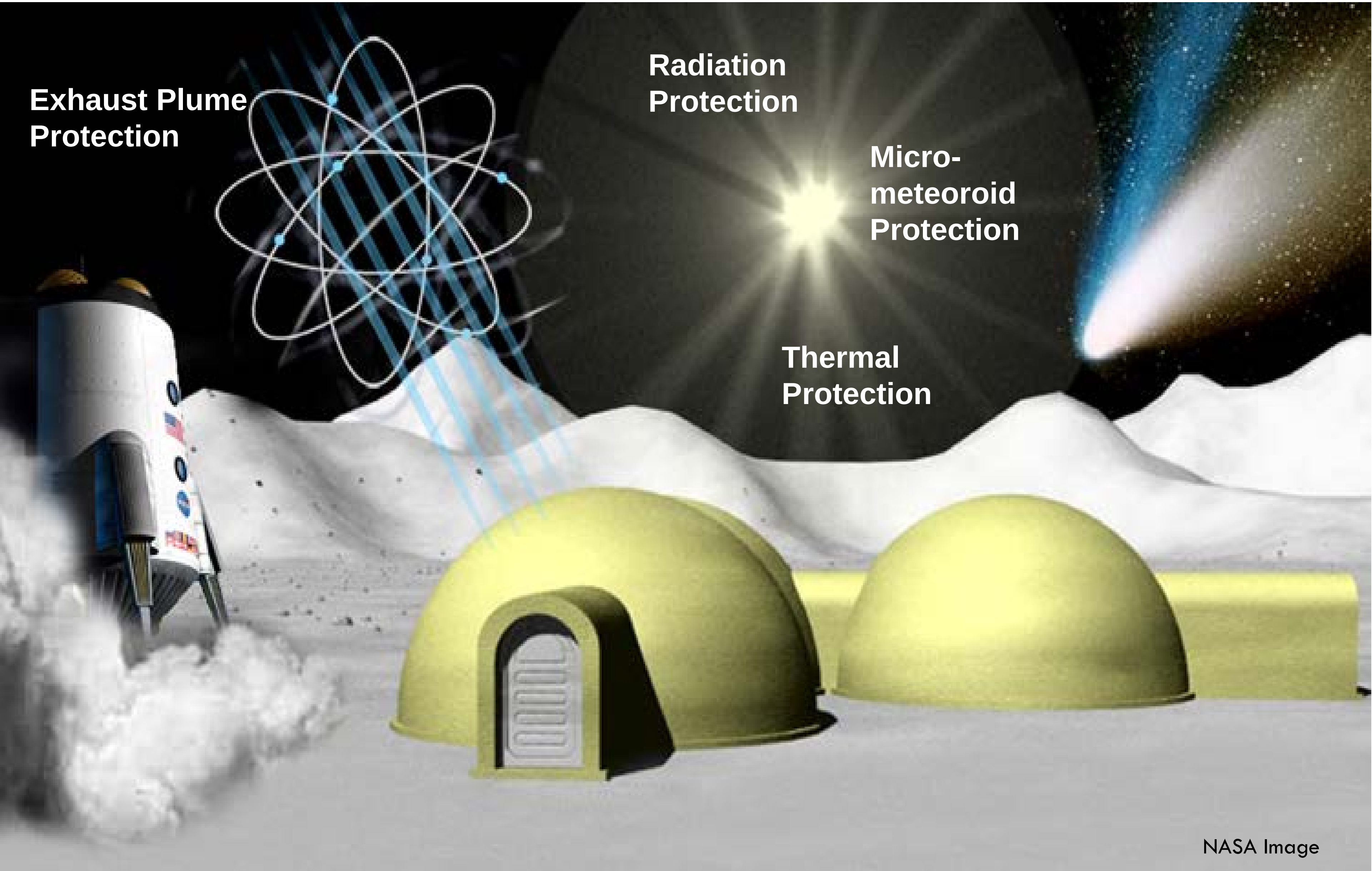
Lunar Resources

- Oxygen is the most abundant element on the Moon: 42% of the regolith mass
- Solar wind deposited volatile elements are available at low concentrations
- Metals and silicon are abundant
- Water ice & other volatiles may be available at poles but we need more ground truth data
- 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)

3D Printed Infrastructure: Multiple Sheltering Aspects Needed in Space



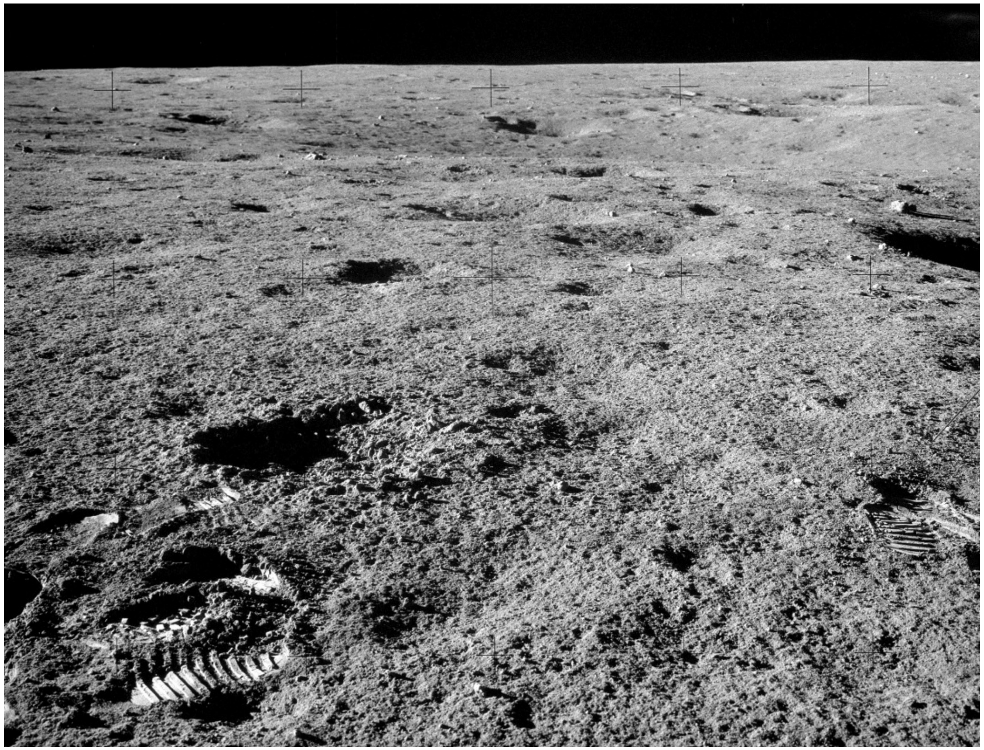
Reduced Gravity & Extreme Environmental Issues

- Reduced gravity means structural loads are lower on un-pressurized structures (e.g. Hangars, berms, walls etc.)
- Vacuum means that pressurized structures have higher loads than on Earth (14.7 psi)
- Radiation shielding for human crew and equipment can be achieved by emplacing several meters thickness of regolith covering over the habitat / hangar
- Burrowing or using natural features (lava tubes, caves) could provide shielding
- Ballistic loads must be endured from statistically possible micro-meteorites
- Seismic activity is possible and structures must be designed to account for it
- Rocket engine blast plume can eject regolith particles at 2,000 m/s during launch & landing
- Regolith is fine rock dust that is highly abrasive, electrostatically charged and clings
- Granular material angle of repose and flow dynamics are very different in reduced G

Reduced Gravity & Extreme Environmental Issues

- Lunar thermal swings of +127 C to -173 C from day to night conditions and in shadows
- Lunar days are 14 Earth days and lunar nights are 14 Earth days: surviving the night?
- Lunar Permanently Shadowed Craters (PSC) at the poles are as cold as 40 K (-233.15 C)
- Excavation machinery has low weight so traction and reaction force are limited
- Construction machinery motion inertias do not change but weight is reduced: tipping hazard
- Solid foundations are a requirement for any structure – sub-surface must be understood
- Geographical location (poles vs equatorial) can influence regolith type, lighting, temperatures (and even weather on Mars) while also impacting orbital dynamics and propellant needs
- The harsh and extreme environment in space implies that robotic construction is necessary
- Water is a precious resource and my have non-construction priority use (e.g. humans, plants)
- Infrastructure must be designed with psychological and physical human health needs i.e. (quality of life/health in extreme environmental conditions)

Lunar Mare Basalt Granular Material = Regolith Construction Material



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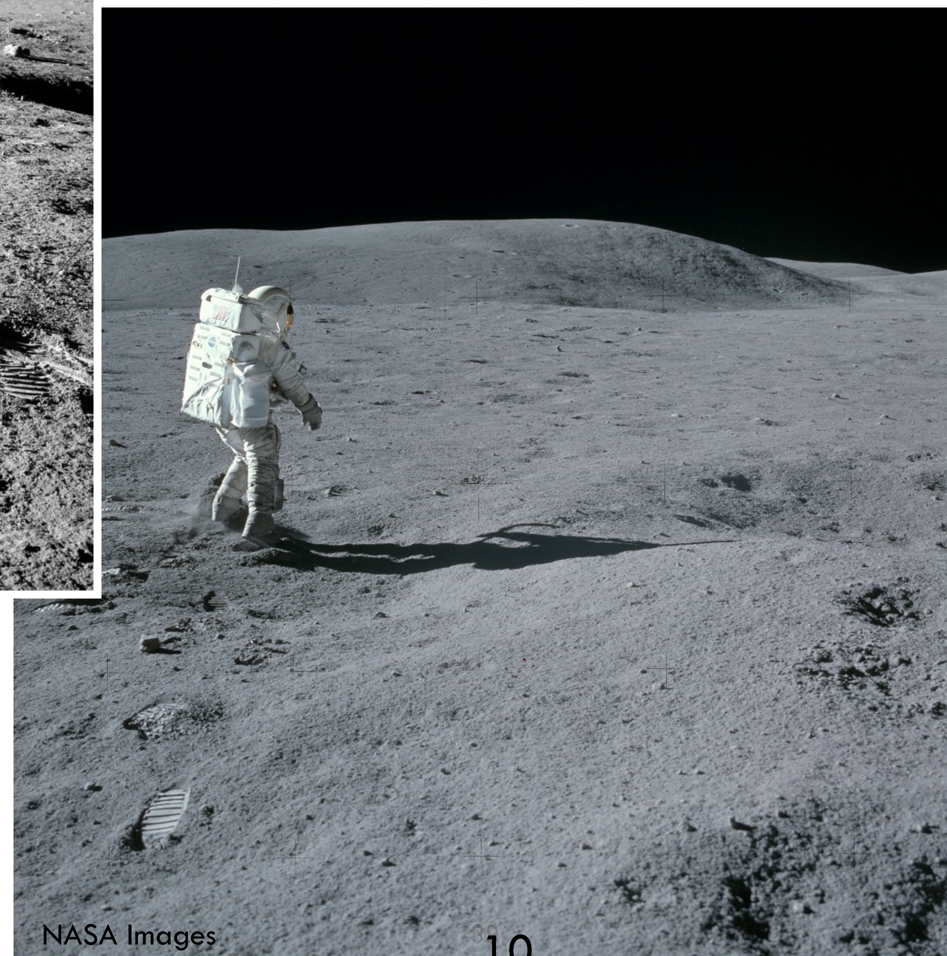

NASA Images

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

Excavation / Construction Machines

Earth:

- Steel
- High mass (1,000's kg)
- Robust
- Large (e.g. Cat D10: 70,170 kg)
- Multiple machines
- "Human on Board" operated

Mars Today:

- Aluminum
- Low mass (100's kg)
- Fragile – Science based
- Car –sized (e.g. MSL: 899 kg)
- Single robot
- Delayed commands sent

Future Space:

- Toughened Composites
- Very low mass (10's kg)
- Robust – dig/build
- Medium to Small (e.g. RASSOR: 69 kg)
- Robot Swarms?
- Autonomous

https://www.cat.com/en_US/products/new/equipment/dozers/large-dozers/18500099.html

NASA image

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Robotic Construction of a Foundation / Landing Pad
Hilo, Hawaii

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PISCES

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Robotic Grading

Robotic Compaction

Robotic Paver Laying

HONEYBEE ROBOTICS

Argo
XTREME TERRAIN ROBOTICS

Foundation / Landing Pad

NASA Images

Tele-Robotically Assembled
Sintered Basalt Paver Pad

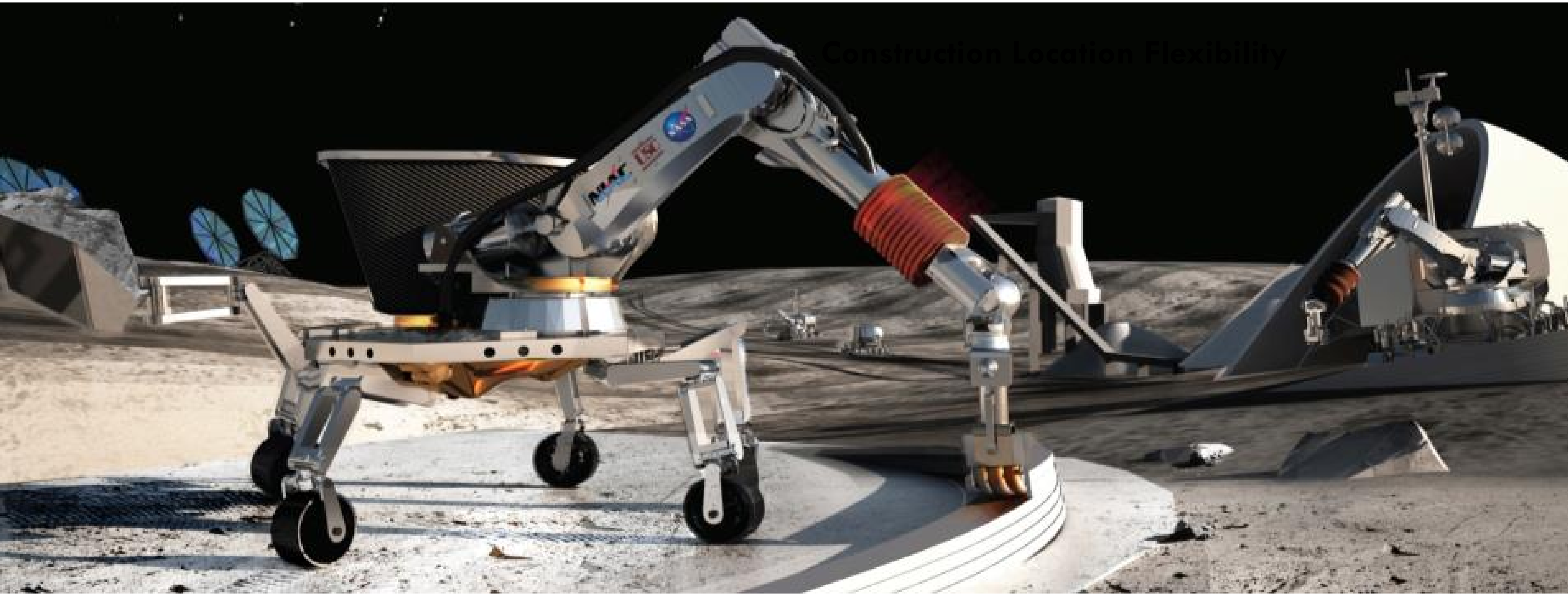
U.S. Army Corps of Engineers: B-Hut

The USACE had the following objectives for construction of a Barracks B-hut in a forward base:

- Reduce construction time from 4-5 days to 1 day per structure
- Reduce construction personnel requirements from 8 to 3 per structure
- Reduced logistics impacts associated with materials shipped, personnel, and resources to sustain the structures and personnel
- Decrease material shipped from out of theater from 5 tons to less than 2.5 tons
- Improved energy performance of the envelope from less than R1 to greater than R15
- Reduced sustainment (logistics) and operations/maintenance personnel
- Reduce construction waste from 1 ton to less than 500 pounds
- Improved security during construction
- Improved local population acceptance by mimicking local construction

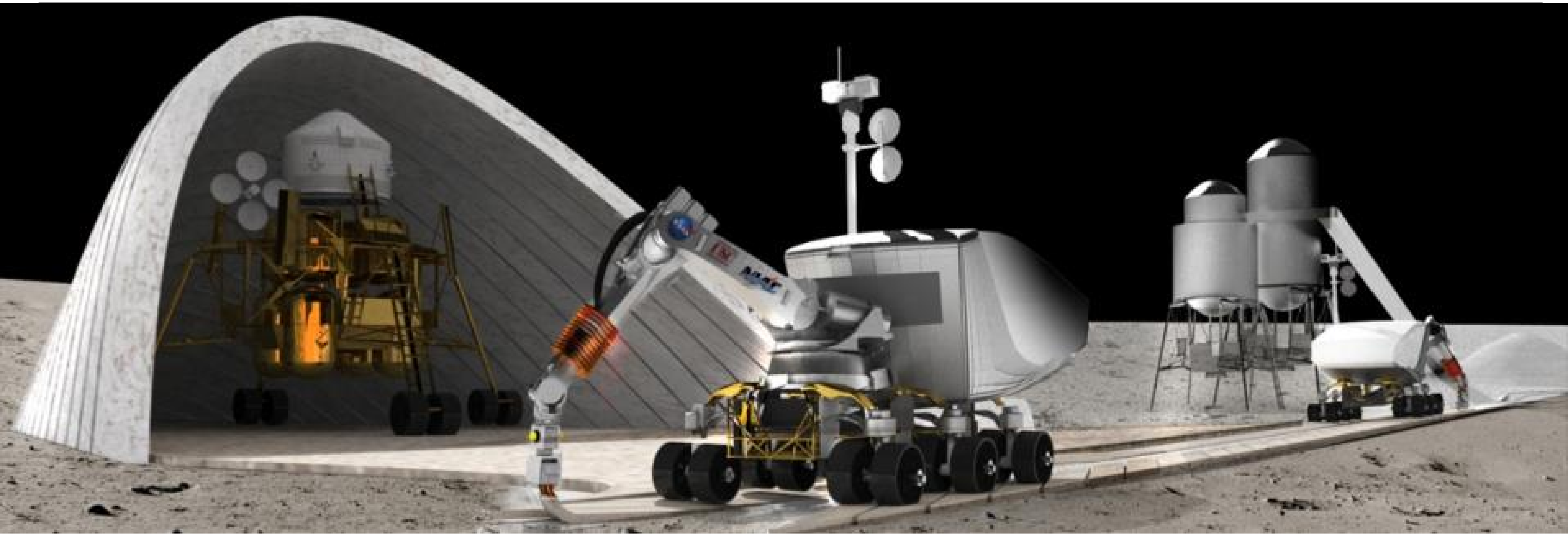
Key Performance Parameters			
Performance Parameter	**State of the Art**	**Threshold Value**	**Project Goal**
KPP-1 Construction Material	Contour crafting with water-based concrete	Use in-situ regolith materials for manufacturing feedstock using imported binders	Use in-situ regolith materials for manufacturing feedstock using no imported feedstock materials
KPP-2 Emplacement	Subscale gantry mechanisms that are fixed in locations	Full scale gantry mechanisms in fixed locations	Mobile-ready print system
KPP-3 Construction Scale	Small concrete dome: ~1m high	In-situ regolith structure pad and curved wall; subscale optimized planetary structure	In-situ regolith structure pad and curved wall; full scale optimized planetary structure
KPP-4 Print Head Construction Speed (1cm thick layers material)	30cm/minute	60cm/minute	100cm/minute

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



Images Courtesy of Dr. B. Khoshnevis, Contour Crafting, LLC

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

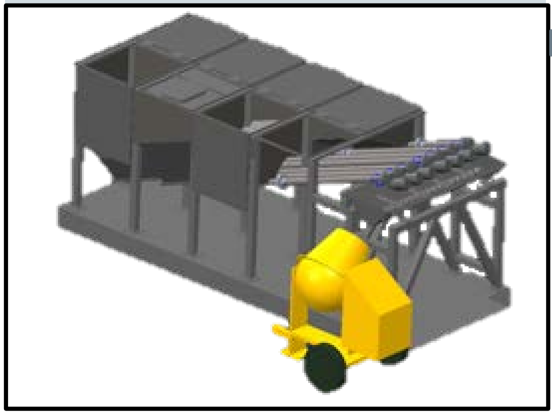


Images Courtesy of Dr. B. Khoshnevis, Contour Crafting, LLC

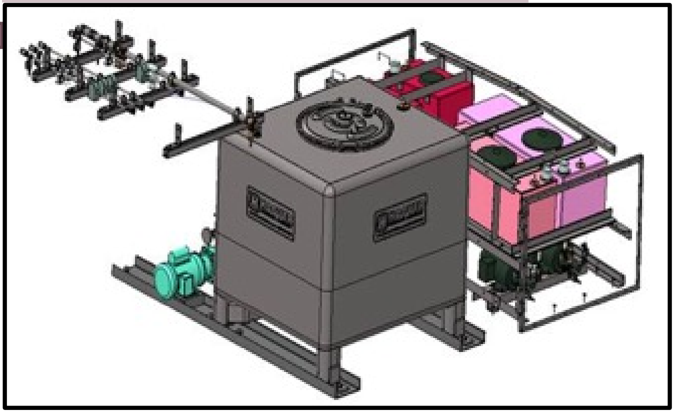
Complex Tool Path Development Allows Interior Walls

ACES 3 System

Dry Good Storage Subsystem

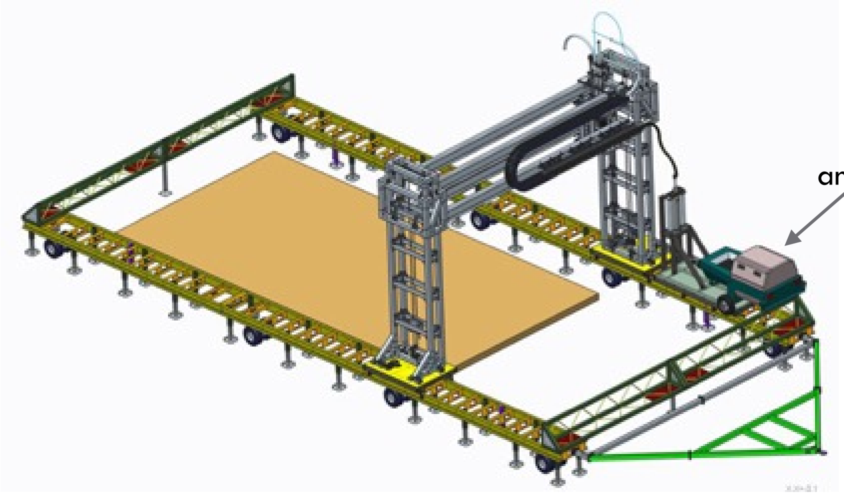


Liquid Storage Subsystem



Continuous Feedstock Mixing Delivery Subsystem (CFDMS)

- Accumulator
- Pump Trolley
- Gantry
- Hose Management
- Nozzle
- Electrical & Software



Dry Goods & Liquid Goods parked on side and mix in trolley

Dry Goods Delivery System

Automated Dispensing of Gravel, Coarse Sand, Fine Sand & Cements

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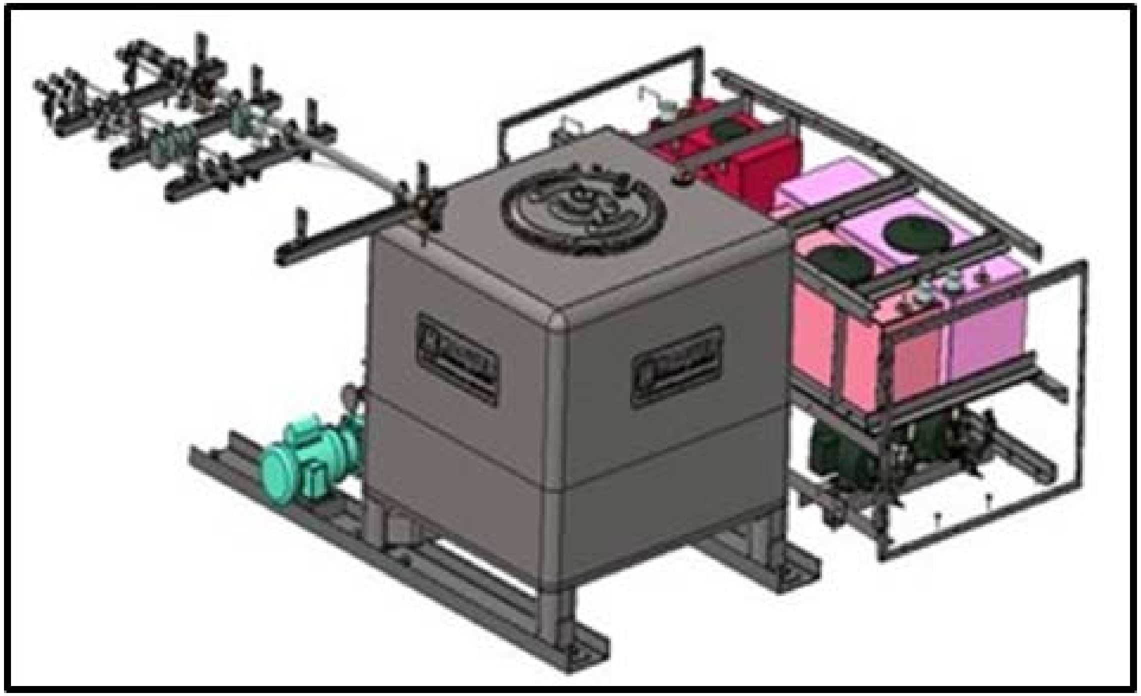
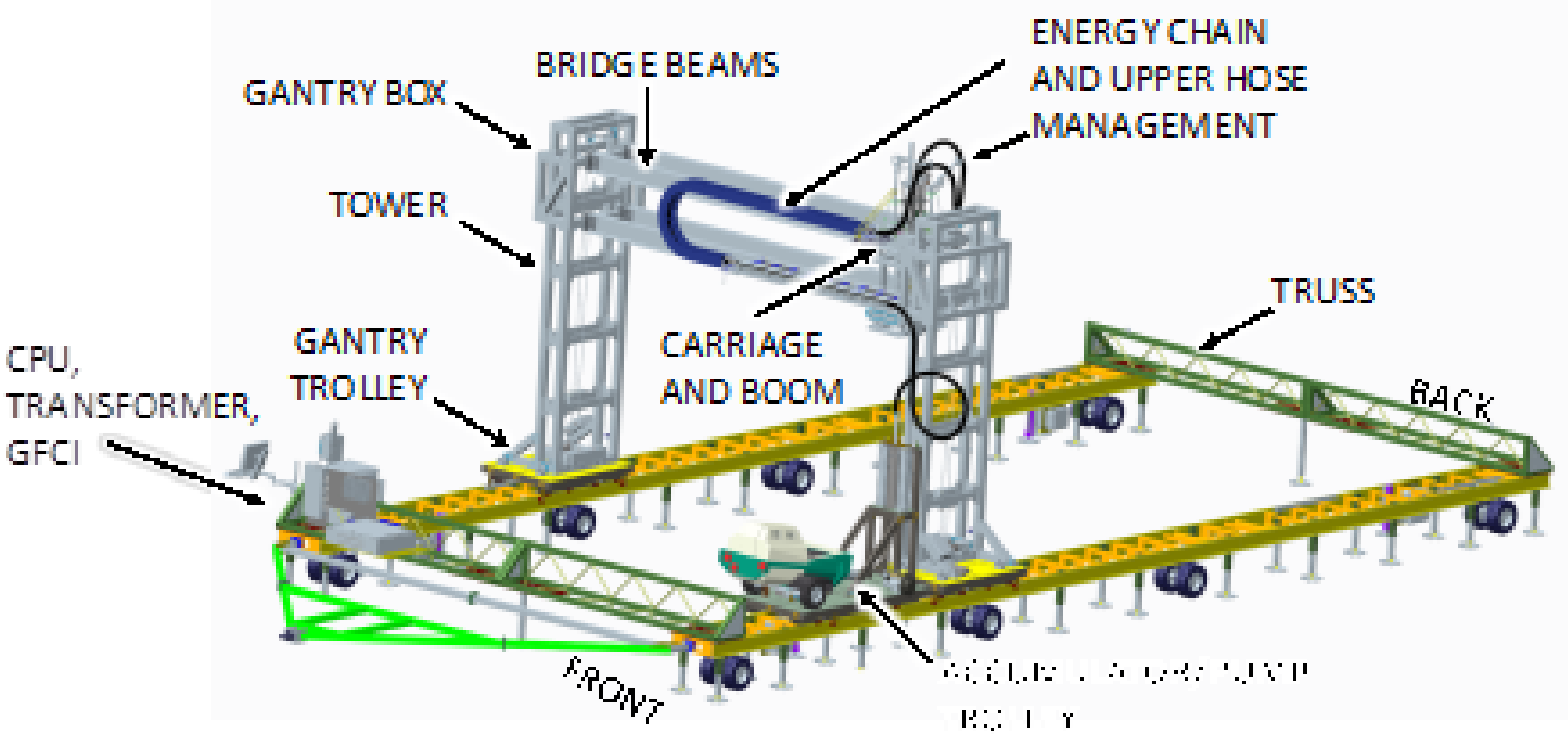
Liquid Goods Delivery System



Gantry 3D Printer Concept



Marshall Space Flight Center

Robotic Gantry 3D Printer: As Built

Completed 3D Printed Barracks "B-Hut"

US Army Photo

32' L x 16' W x 8.5' H

Video

NASA Centennial Challenge: 3D Print a Habitat

$2.5 Million Prize Money

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3DPH - Structure of the Competition

The goal of the 3D-Printed Habitat Challenge is to foster the development of new technologies necessary to additively manufacture a habitat using local indigenous materials.

- ☐ **Design Competition (Phase 1)** - focused on developing innovative habitat architectural concepts that take advantage of the unique capabilities that 3D-Printing offers.

- ☐ **Structural Member Competition (Phase 2)** - focused on the core 3D-Printing fabrication technologies and material properties needed to manufacture structural components from indigenous materials combined with recyclables, or indigenous materials alone.

- ☐ **On-Site Habitat Competition (Phase 3)** - focused on 3D-Printing of a scaled habitat design, using indigenous materials combined with recyclables, or indigenous materials alone.

NASA 3D Additive Construction Phase 1 Centennial Challenge – Top 3 Concepts

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First Place: Team Space Exploration Architecture and Clouds Architecture

Second Place: Team Gamma

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Third Place: Team LavaHive.

Phase 2: Structural Member Competition

Best Material Properties:

26,200 psi material flexural strength

44x stronger than typical PC concrete

Thermoplastic Concrete

Geo-Polymer Concrete

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Phase 3: 3D Print a 1.5 m Diameter Dome

Foster & Partners | Branch Technology
1st Place

$250,000 Prize

Thermoplastic Polymer / Basalt Concrete

Figure 6: 3D view of the dome structure to be printed at the Head to Head Competition

Penn State University
2nd Place

$150,000 Prize

Metakaolin Based Binder / Basalt Concrete

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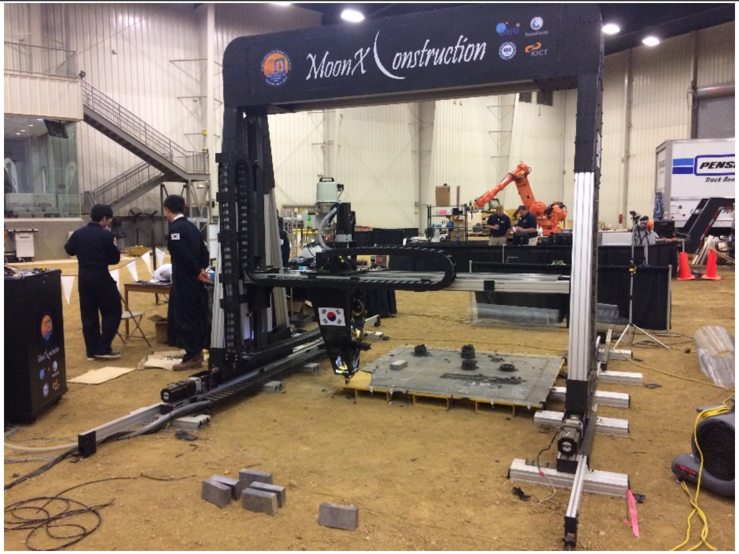
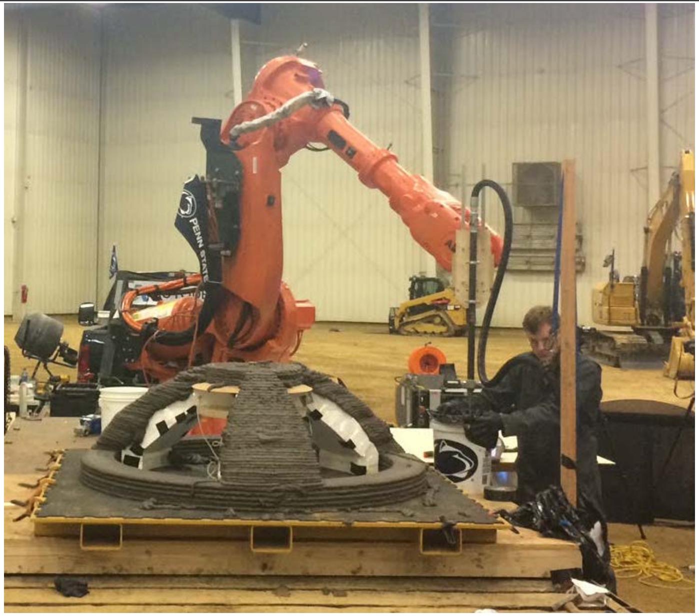
Phase 3 Robots: On-Site Competition



Moon X Construction
South Korea

Foster & Partners | Branch Tech. USA



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Penn State University, USA

Crushing Domes – Caterpillar, Peoria, Illinois

NASA Image

Foster & Partners | Branch Tech
1st Place

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F+P | Branch Technologies

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Technical Accomplishments

Zero Launch Mass (ZLM) Print Head

- Extrudes a mixture of 70 % Basalt regolith simulant and 30 % polymer mixtures.
- BP-1 Basalt powder regolith and Polyethelene materials was used with real time mixing in ZLM Print Head
- Successfully 3D printed a beam for ASTM C78 bending tests and a cylinder for C39 compression testing
- Switched to 70 % Basalt Glass and 30 % PETG polymer 3mm pellets: Centennial Challenge tech. infusion
- Successful KSC Swamp Works 3D printing of a polymer concrete 1 m ogive dome structure with 26,200 psi material flexural strength – 44X stronger than typical PC concrete

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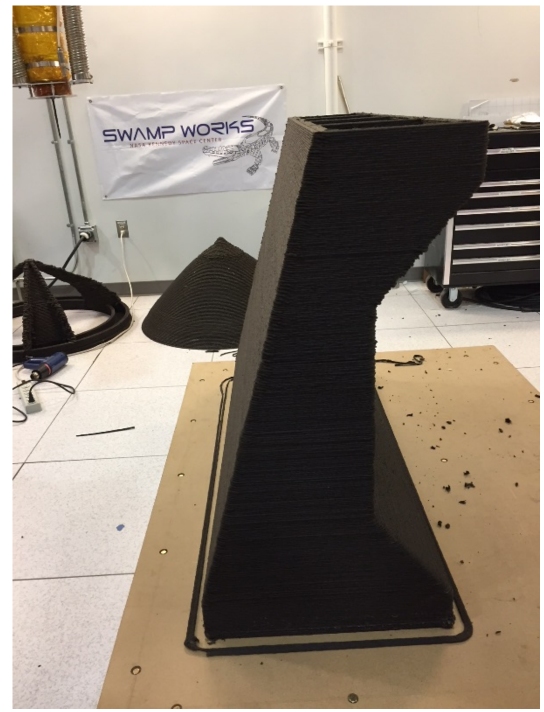
3D Printed Ogive:
Basalt Glass with PETG Binder

U.S. Army Checkpoint Vehicle Barrier Technology Demonstration



NASA Photos

Conclusions

- 3D Printing with Portland Cement Concrete is feasible
- Need to develop reinforcements equivalent or better than steel re-bar
- Need to increase the speed of deposition and curing
- Need to scale up the size of the 3D printed structure
- Improved nozzle control and finishing are under development

- A US Army B-Hut prototype was successfully 3D printed and the next generation B-Hut print is being developed which will be better

- Printing with concrete slurry may not be the best solution
- New ways of extruding concrete are being investigated

- New Materials are being developed e.g. polymer concrete, geopolymer concretes which are promising and can use recycled plastics from the waste stream
- Synthetic Biology may be able to produce binder materials in space
- 100% sintered regolith may eliminate binders

- Scaling has been a bigger issue than anticipated
- Development is continuing in industry, government and academia