NASA Swamp Works at Kennedy Space Center

ADVANCED TECHNOLOGY DEVELOPMENT

II International Symposium of Cement and Concrete Technology

Universidad de Cuenca, Ecuador

October 8, 2019

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Florida, USA

NASA Photo

WHO WE ARE AND WHAT WE DO

SWAMP WORKS

Kennedy Space Center
Florida

GRANULAR MECHANICS AND REGOLITH OPERATIONS

- High bay lab area
- Lunar Regolith (moon dirt) Test Bin
- Technology incubator area – spaces for new project ideas to grow
- Innovation Space – loft area with white boards for brainstorming
- Machine Shop

NASA Photo

LUNAR SURFACE SIMULATION TEST BED

NASA Photo

Granular Mechanics & Regolith Operations Lab

- In-Situ Resource Utilization
  - Regolith Excavation & Transfer
  - Robotic Surface Support Equipment
- In-Situ Construction
  - Automated Additive Robotic Construction
  - Novel Sustainable Materials
- Rocket Plume Surface Interaction
  - Landing/Launch Pads
  - Debris Ejecta
- Cryobotics
  - Advanced mechanism for operating in cryogenic surface environments
  - Lunar & Mars Polar Regions
  - Permanently Shadowed Craters
  - Europa and other icy Moons, asteroids & Comets
- Regolith Simulants & Systems Testing
  - Simulating surface operations in harsh , dusty environments
  - Lifetime testing, mean time between failures

TECHNOLOGY READINESS

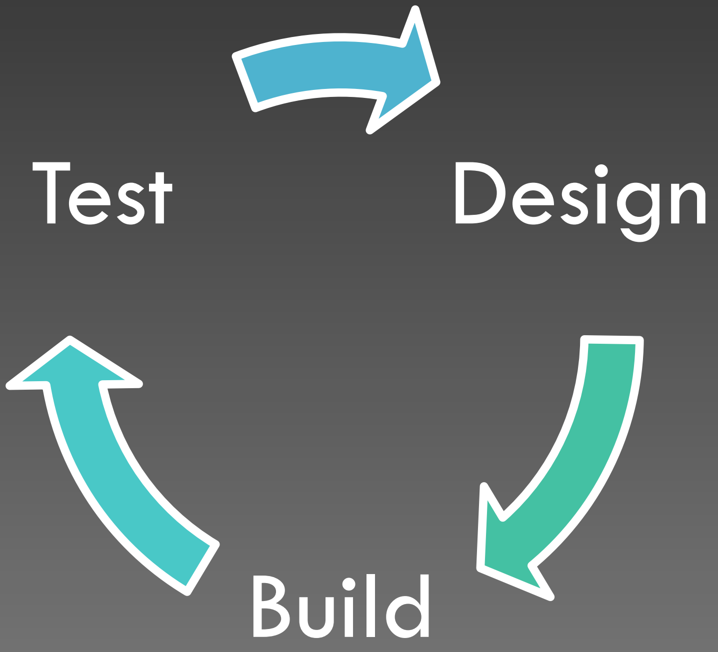
NASA has a scale to measure how far along a technology is in its development lifecycle. They call increments on the scale Technology Readiness Levels, or TRLs.

Swamp Works focuses on TRLs 1-5, with the occasional 6.

1. Transition from scientific research to applied research
2. Applied research
3. Proof-of-concept validation
4. Standalone prototyping implementation and test
5. Thorough prototype testing in relevant environment

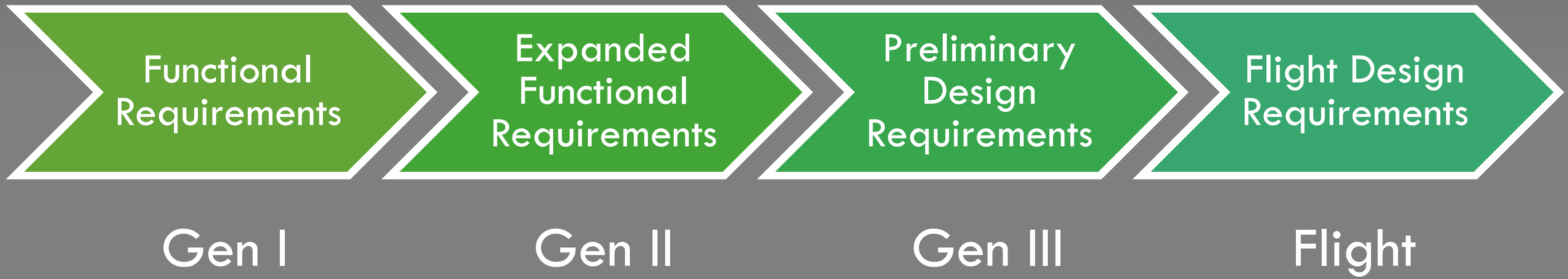
6. Prototyping on full-scale realistic problems
7. System functions in operational environment
8. System completed and "mission qualified"
9. Mission/ground operations

Design-build-test conducted iteratively with increasing knowledge of the operating environment will result in an end product that optimizes safety and performance.



Begin with a clear vision of what the technology will do and won’t do

By the Preliminary Design Review (PDR), we will know exactly what we want, how we’re going to build it, and how we’re going to operate it



Credit: Astronaut Mike Gernhardt, NASA JSC

IN-SITU RESOURCE UTILIZATION

LIVING OFF THE LAND ...IN SPACE

NASA Photo

Like explorers before us, we don't need to carry everything with us. In-situ resource utilization, or ISRU, is the idea of harnessing resources available at our destination, whether it is Mars, the Moon, an asteroid, or elsewhere.

Why does NASA need ISRU?

- Launch costs (~$4,000/kg)
- Payload volume does not allow enough space and mass to send supplies, return propellants and equipment

What are the unique challenges?

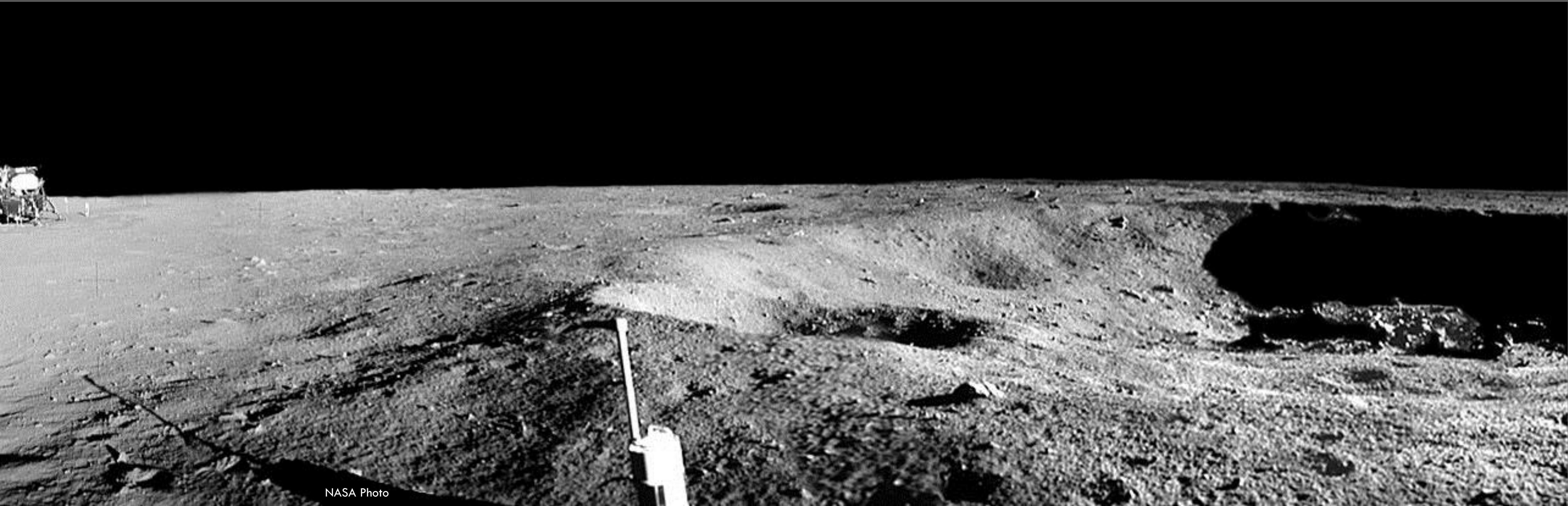
- Various surface conditions
- Reduced gravity
- Extreme temperatures
- Hard ice

REGOLITH AS A RESOURCE

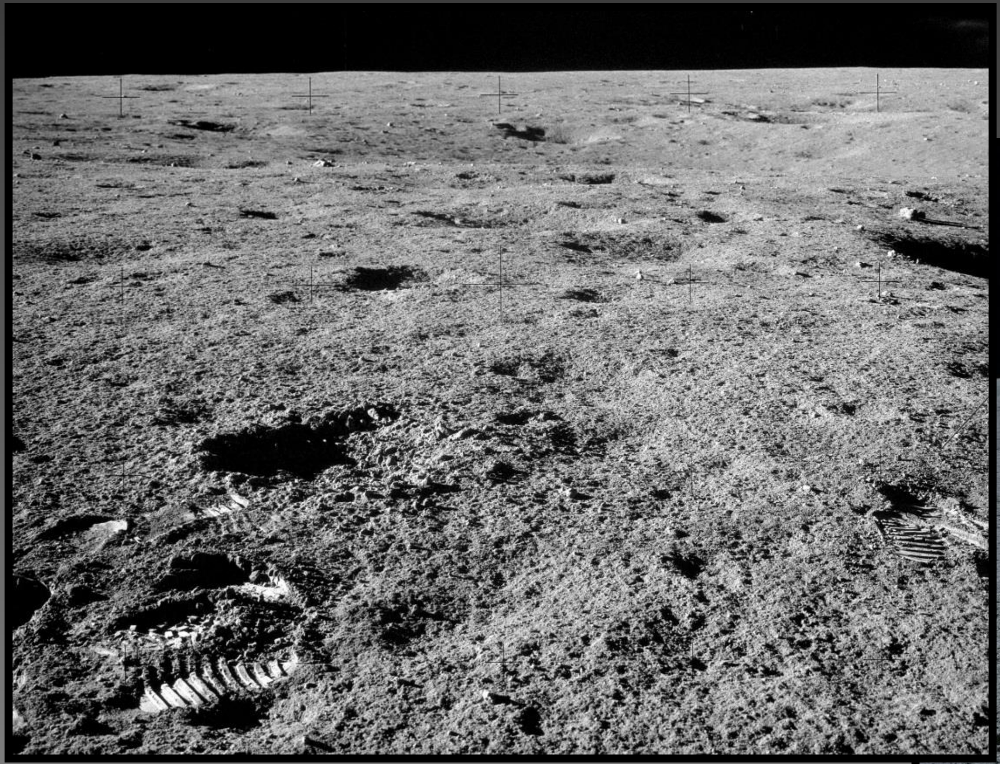
Regolith is the surface layer of loose material that sits on top of bedrock. It includes all the rocks, gravel, and dust – from large boulders to tiny particles. It exists on Earth, other planets, moons, and asteroids.

Swamp Works is exploring ways to exploit the regolith for as many uses as possible. We take one of two approaches:

1. Extracting resources out of the regolith, usually with chemical processes
2. Using the regolith as a raw material for building structures

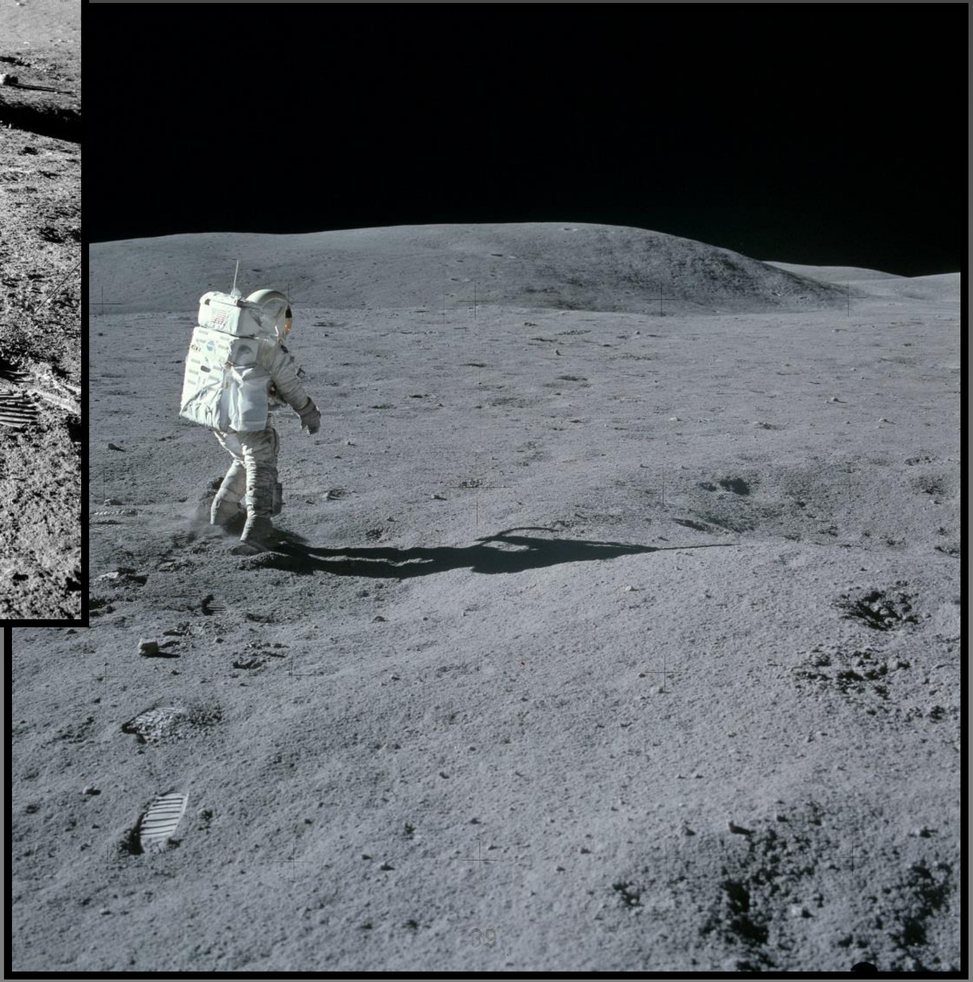


Basalt Granular Material = Construction Aggregate



APOLLO 12

APOLLO 16

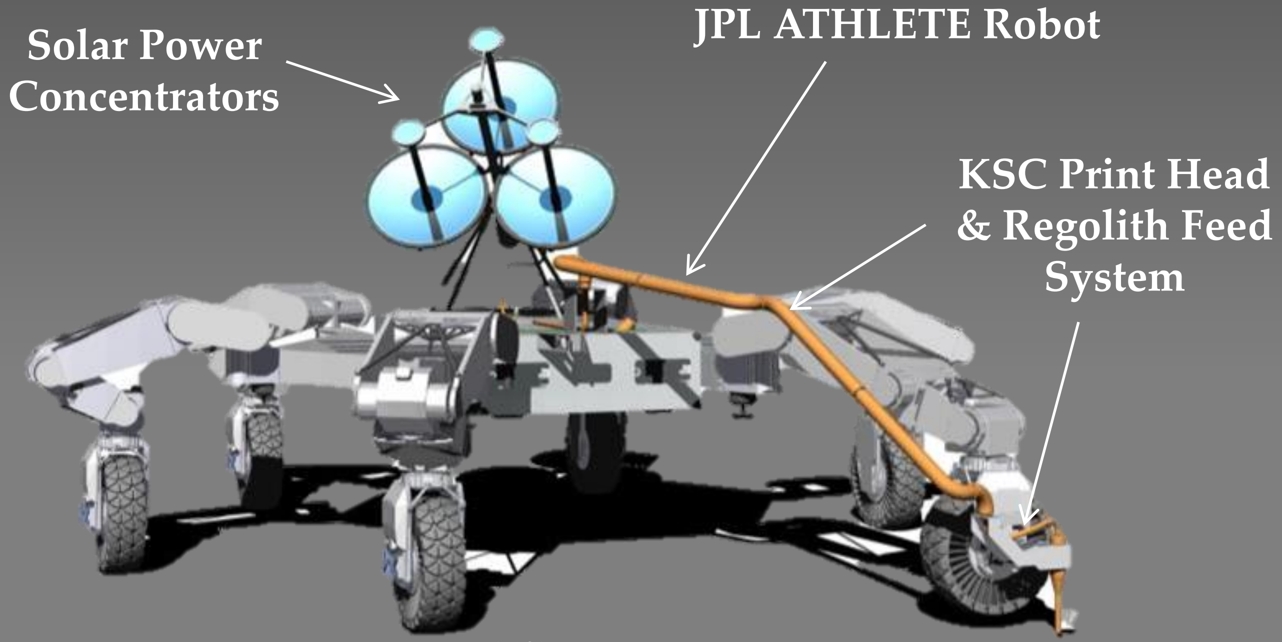


Shelter from the deep space environment is the top goal for ACME technology development

NASA Image / MSFC

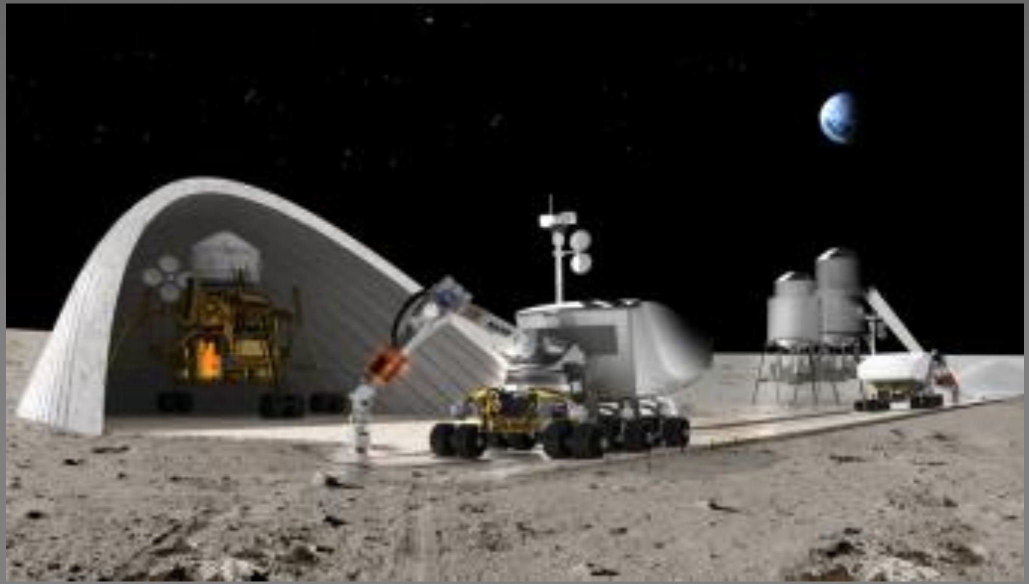
3D AUTOMATED ADDITIVE CONSTRUCTION (3DAAC)

Swamp Works is investigating methods of using robotic construction technologies to build structures using Lunar and Marian regolith.



NASA Image

NASA Innovative Advanced Concept (NIAC), Contour Crafting Image



NASA Innovative Advanced Concept (NIAC), Contour Crafting Image

3D Printing Concrete for Construction

- **3D Printing (or Additive Manufacturing)** is the process of constructing a 3D object by depositing material layer by layer based on a digital part file

- **Advantages of 3D Automated Additive Construction (3DAAC):**
  - Removes design constraints ("manufacturing for design")
  - Enables building and testing earlier in project lifecycle
  - Ability to work with new material formulations
  - Maximize use of in situ resources (planetary surface)

Photo by Mike Jazdyk, U.S. Army Engineer Research and Development Center

Additive Construction with Mobile Emplacement (ACME)

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

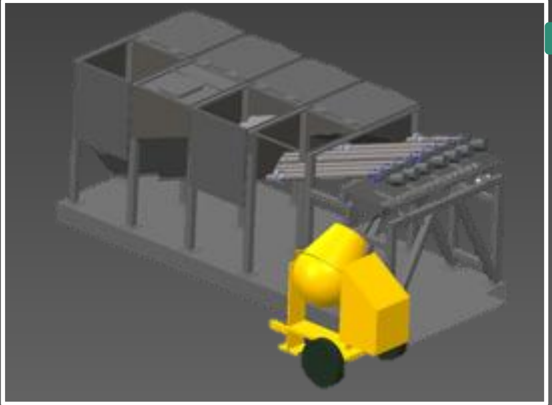
- Reduce construction time from 4-5 days to 1 day per structure
- Reduce construction personnel requirements from 8 to 3 per structure
- Reduced logistics impacts associated with materials shipped, personnel, and resources to sustain the structures and personnel
- Decrease material shipped from out of 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

Additive Construction with Mobile Emplacement (ACME)

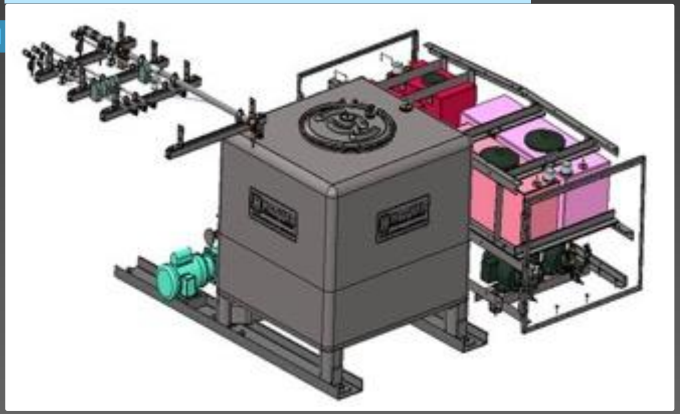
Key Performance Parameters			
Performance Parameter	**State of the Art**	**Threshold Value**	**Project Goal**
KPP-1 Construction Material	Contour crafting with water-based concrete	Use in-situ regolith materials for manufacturing feedstock using imported binders	Use in-situ regolith materials for manufacturing 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

ACES 3 System

Dry Good Storage Subsystem

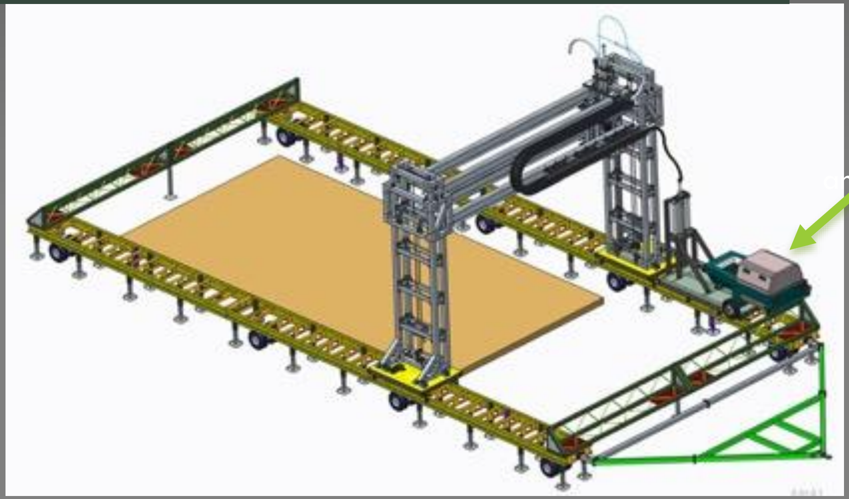


Liquid Storage Subsystem



Continuous Feedstock Mixing Delivery Subsystem (CFDMS)

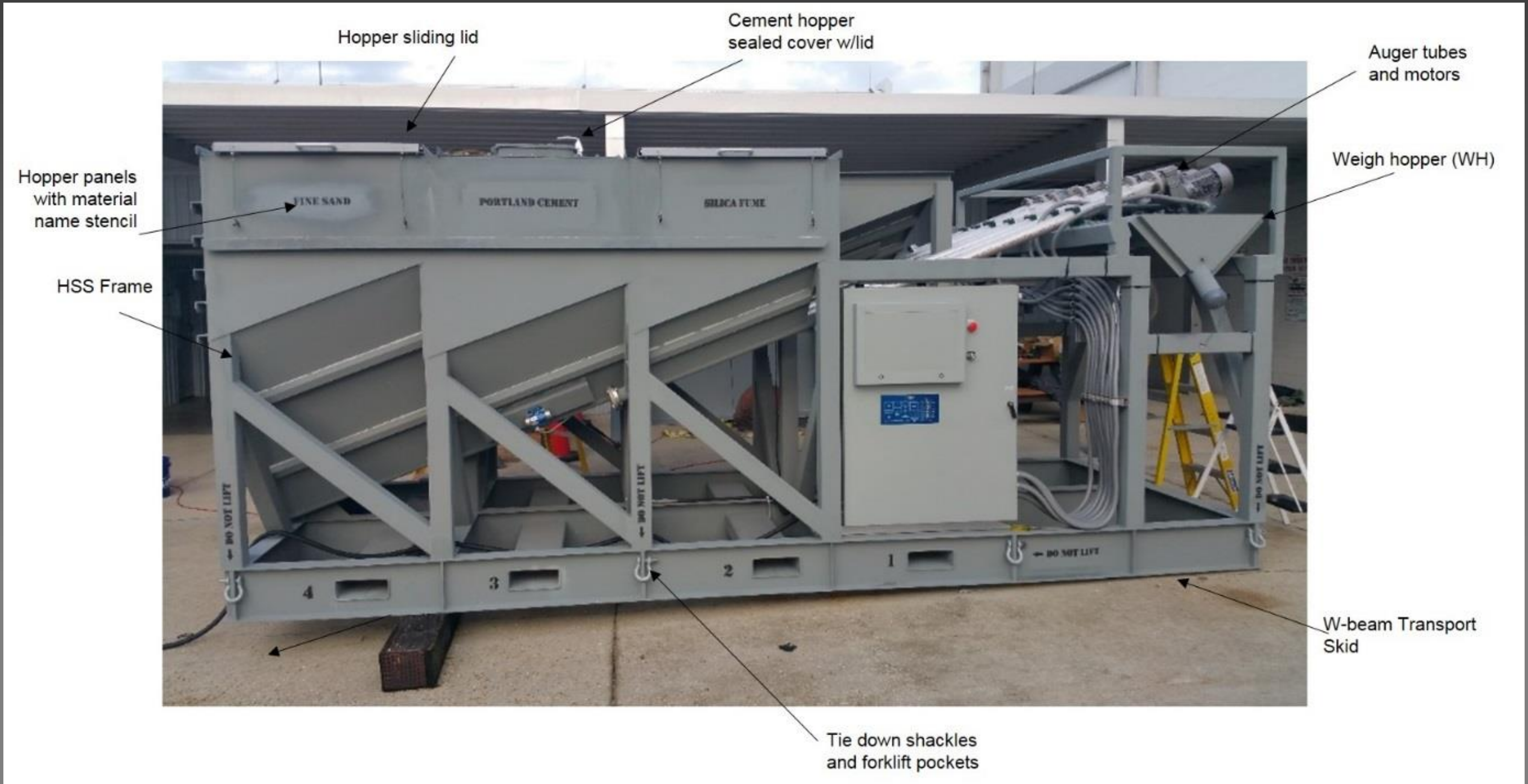
- Accumulator
- Pump Trolley
- Gantry
- Hose Management
- Nozzle
- Electrical & Software



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

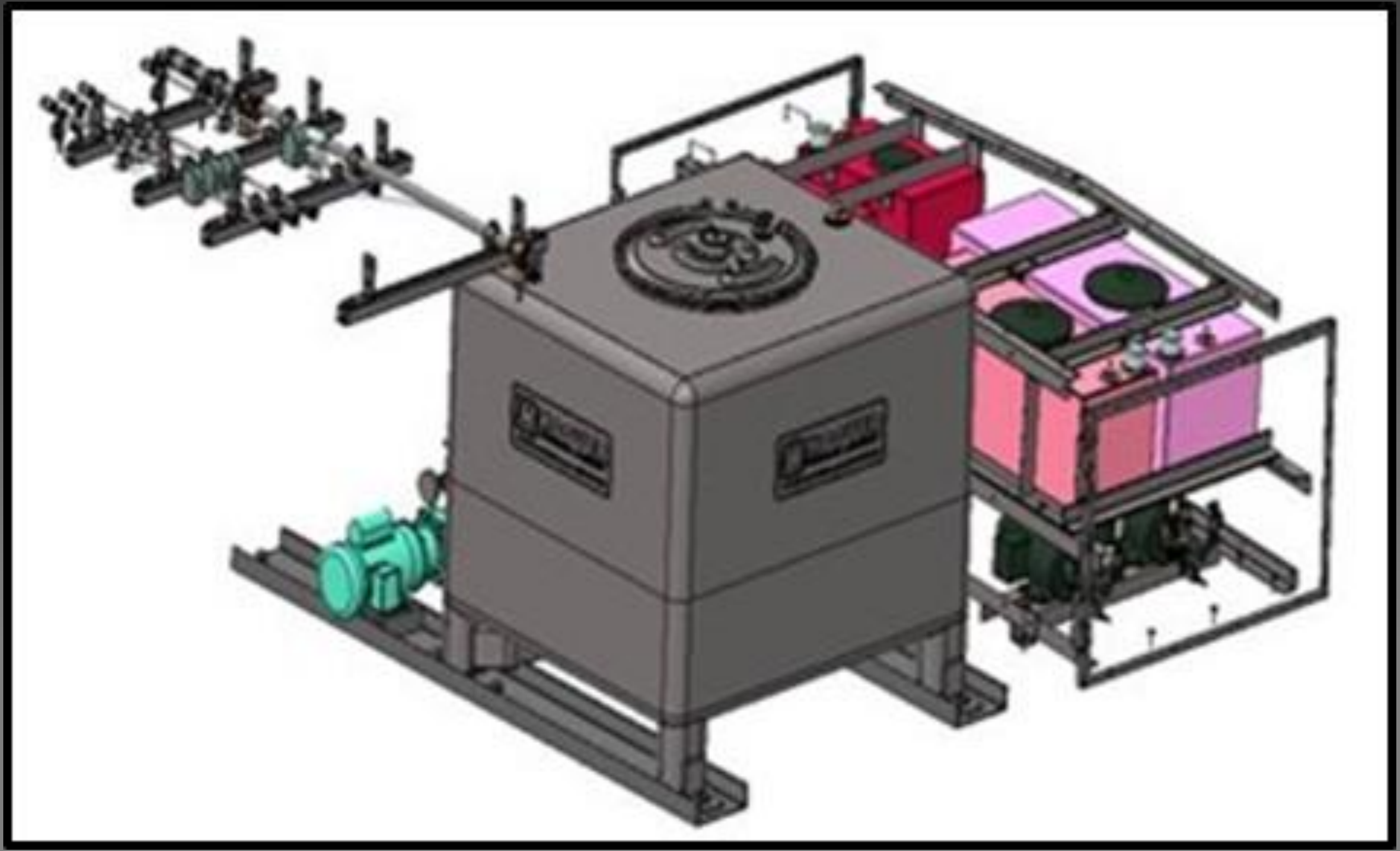
Dry Goods Delivery System

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



Liquid Goods Delivery System

Automated Dispensing of Water & Additives



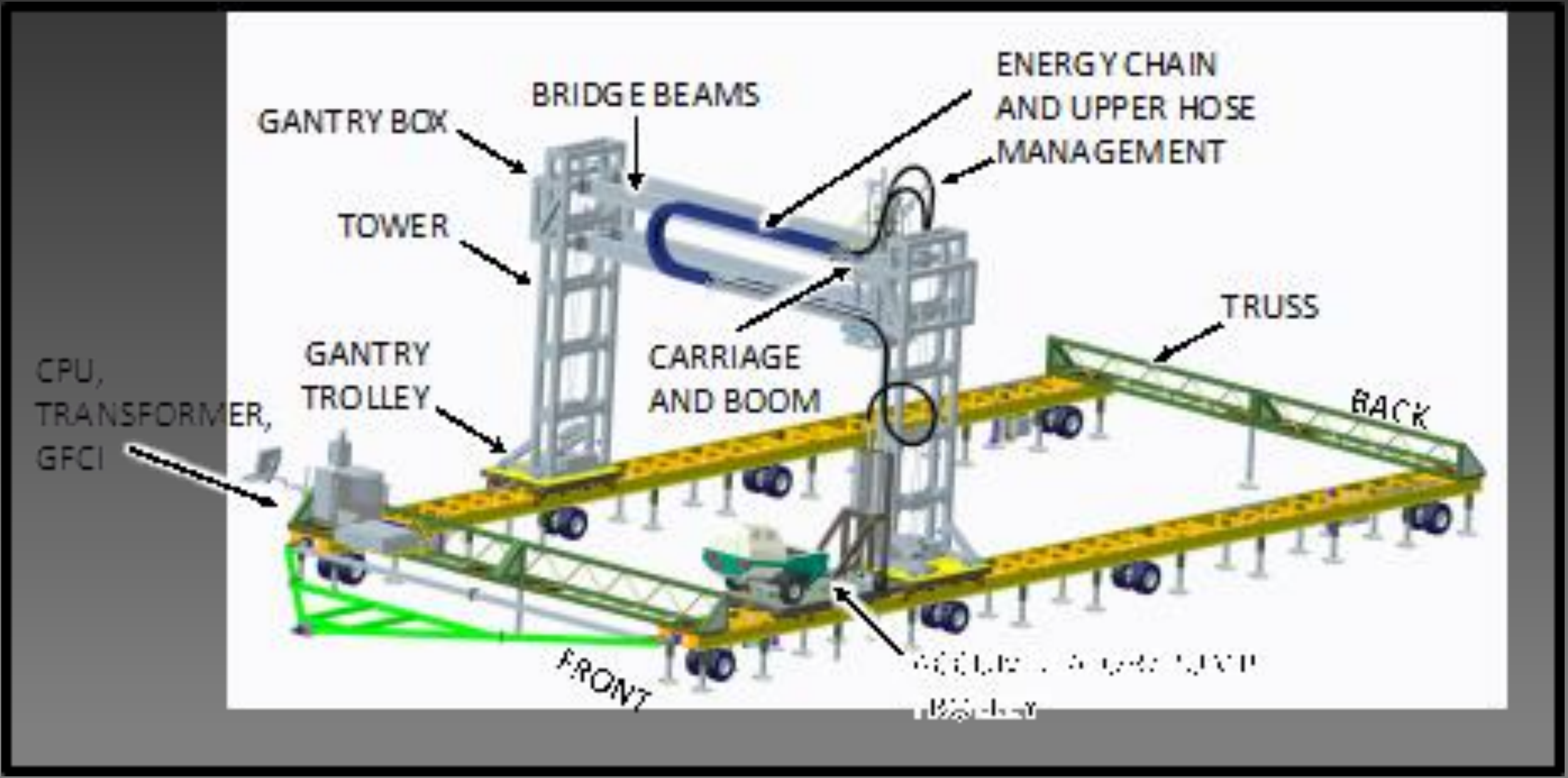
Dry & Liquid Goods Automated Dispensing

Dry Goods in Weigh Hopper

5 Liquid
Discharge Pipes

Dry Materials Discharge

Robotic Gantry Positioning Mechanism
Gantry 3D Printer Concept



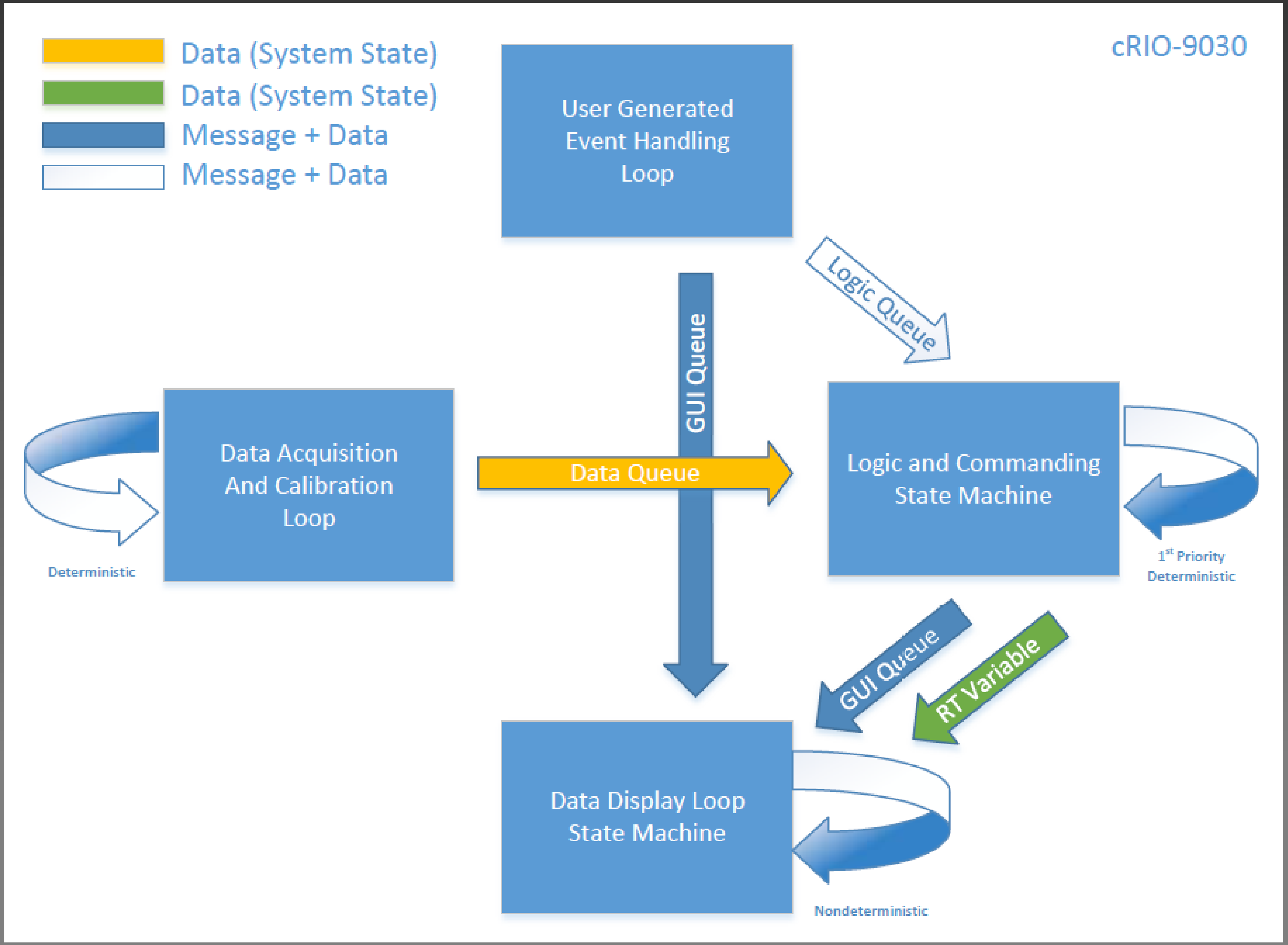
SWAMP WORKS
NASA KENNEDY SPACE CENTER

Marshall Space Flight Center

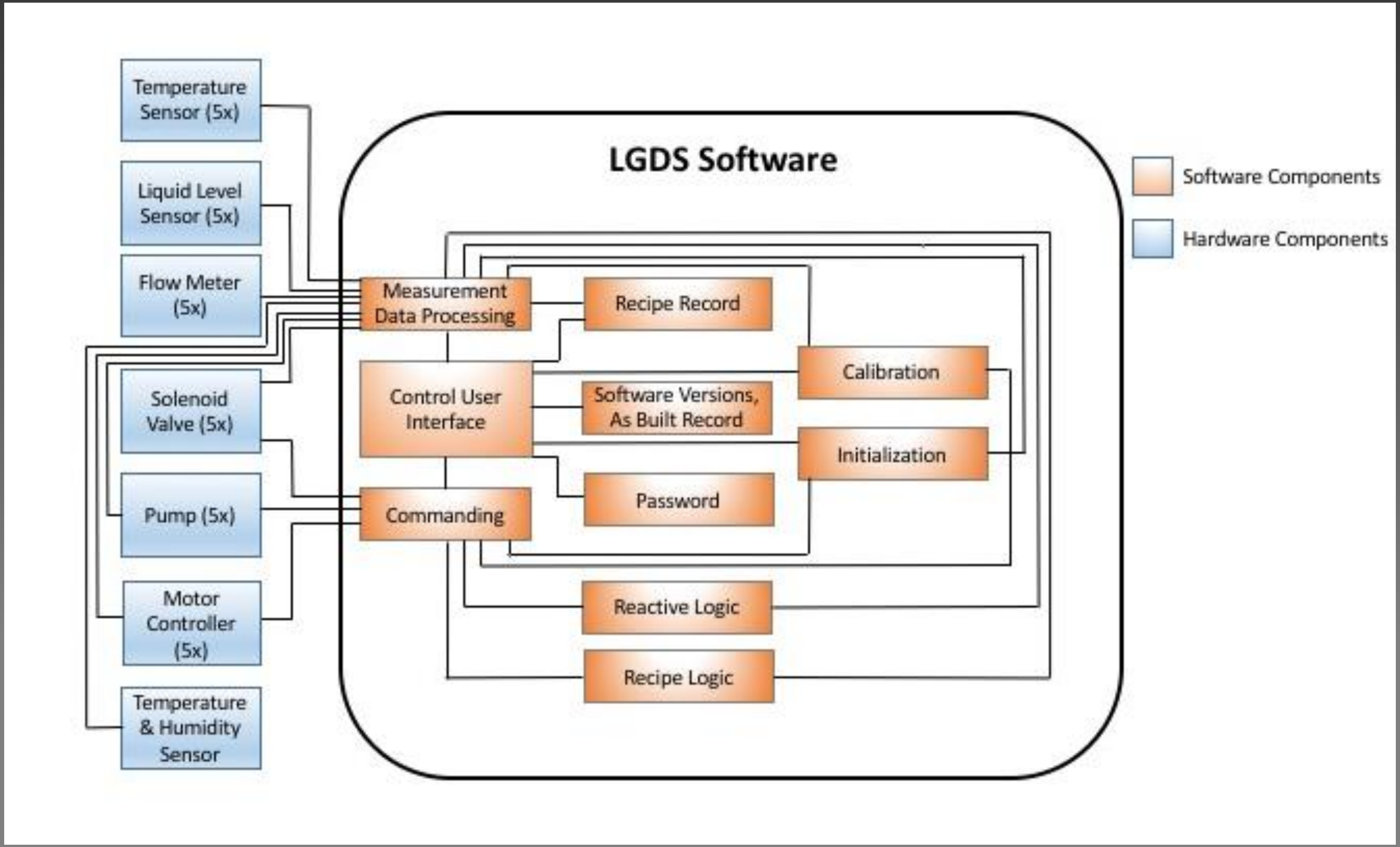
U.S. ARMY ENGINEER RESEARCH AND DEVELOPMENT CENTER ERDC

CONTOUR CRAFTING CORPORATION

Data Acquisition Loop



Block diagram of the LGDS software components, with the associated LabVIEW



Robotic Gantry Positioning Mechanism

Robotic Gantry 3D Printer: As Built

Robotic Gantry 3D Printer: As Built

NASA/Army Photo

Current U.S. Army Corps of Engineers: Barracks "B-Hut"

Future Concept Demonstration: Completed 3D Printed Barracks "B-Hut"

US Army Photo

32' x 18' x 8.5'

[Video of Automated Construction]

3D PRINTING WITH CONCRETE

The Additive Construction with Mobile Emplacement Project explored the use of concrete as a material for 3D printing large scale structures. Partners included the Army Corps of Engineers, Marshall Space Flight Center, Contour Crafting, and Kennedy Space Center – Swamp Works.

Concrete has good potential for use in additive manufacturing but has significant challenges, especially in space applications.

NASA Photos

ADDITIVE CONSTRUCTION WITH SINTERED REGOLITH

One method of 3-D printing involves sintering – heating the regolith to just-below-melting temperatures (1200-1500 °C), making the dirt stick together and form a brick-like material. Robotic 3D printers can then build walls of a habitat or landing pads.

http://basalt.today/2017/11/13571/

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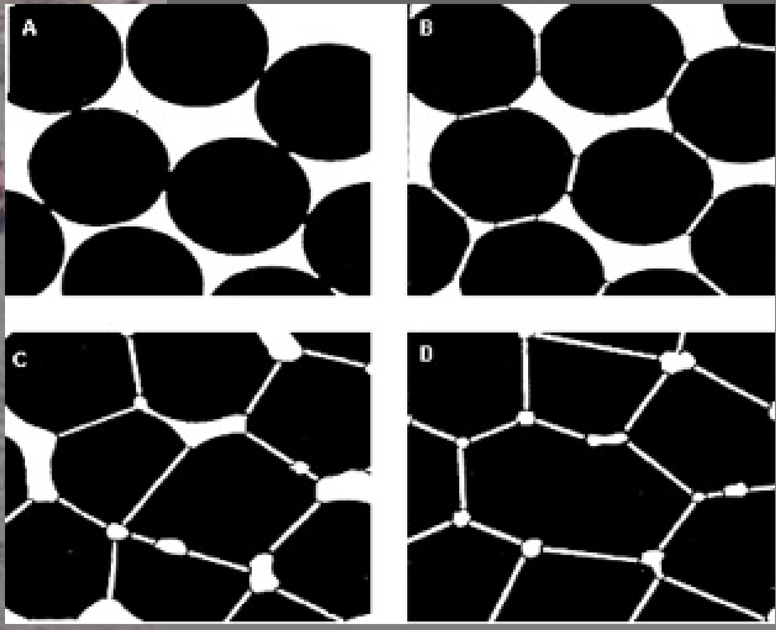
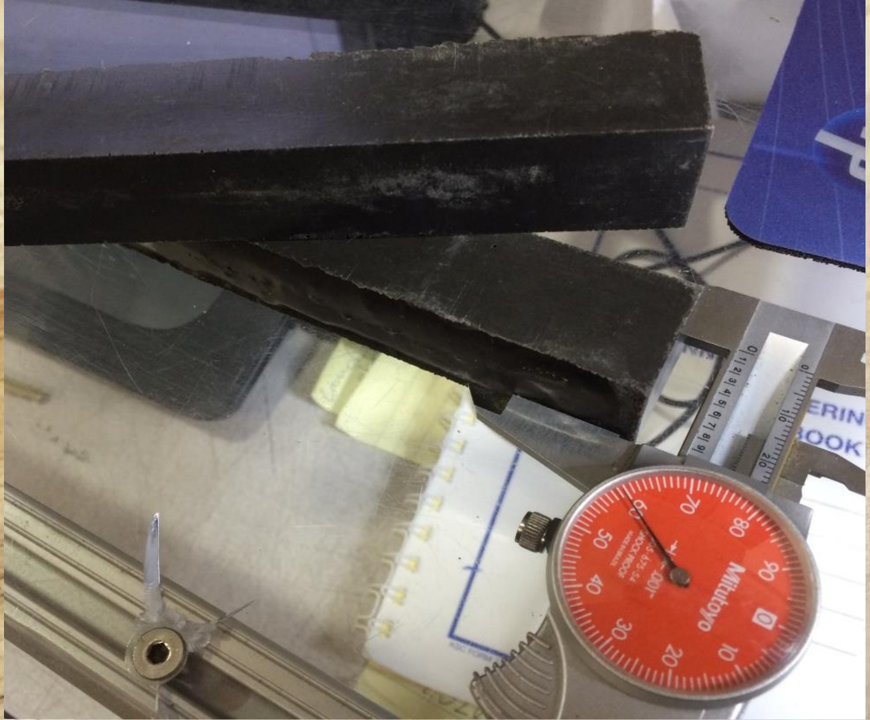
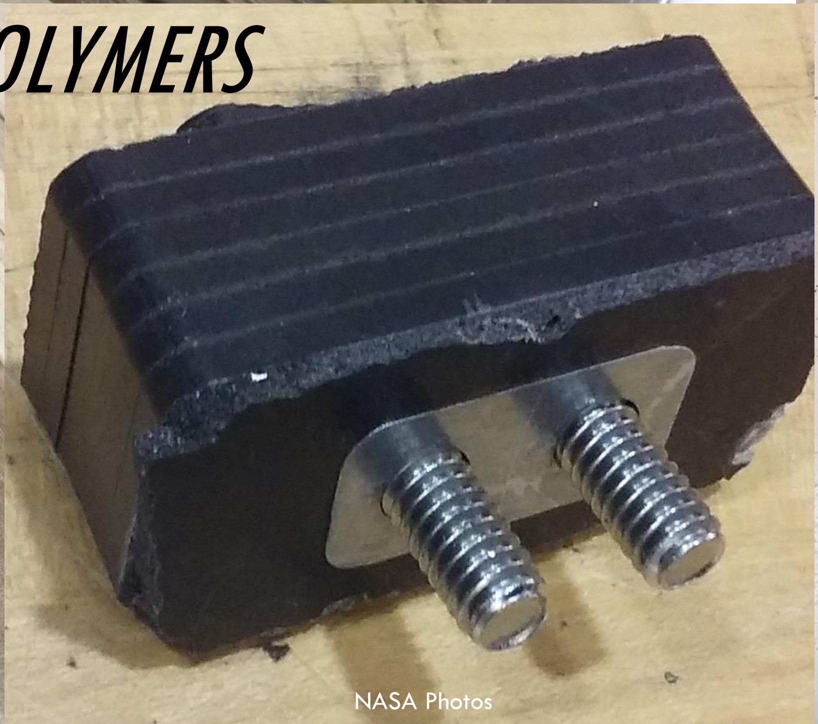


http://slideplayer.com/slide/10453626/

3D PRINTING : REGOLITH &POLYMERS

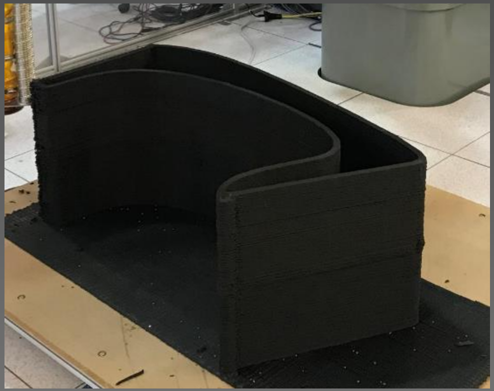




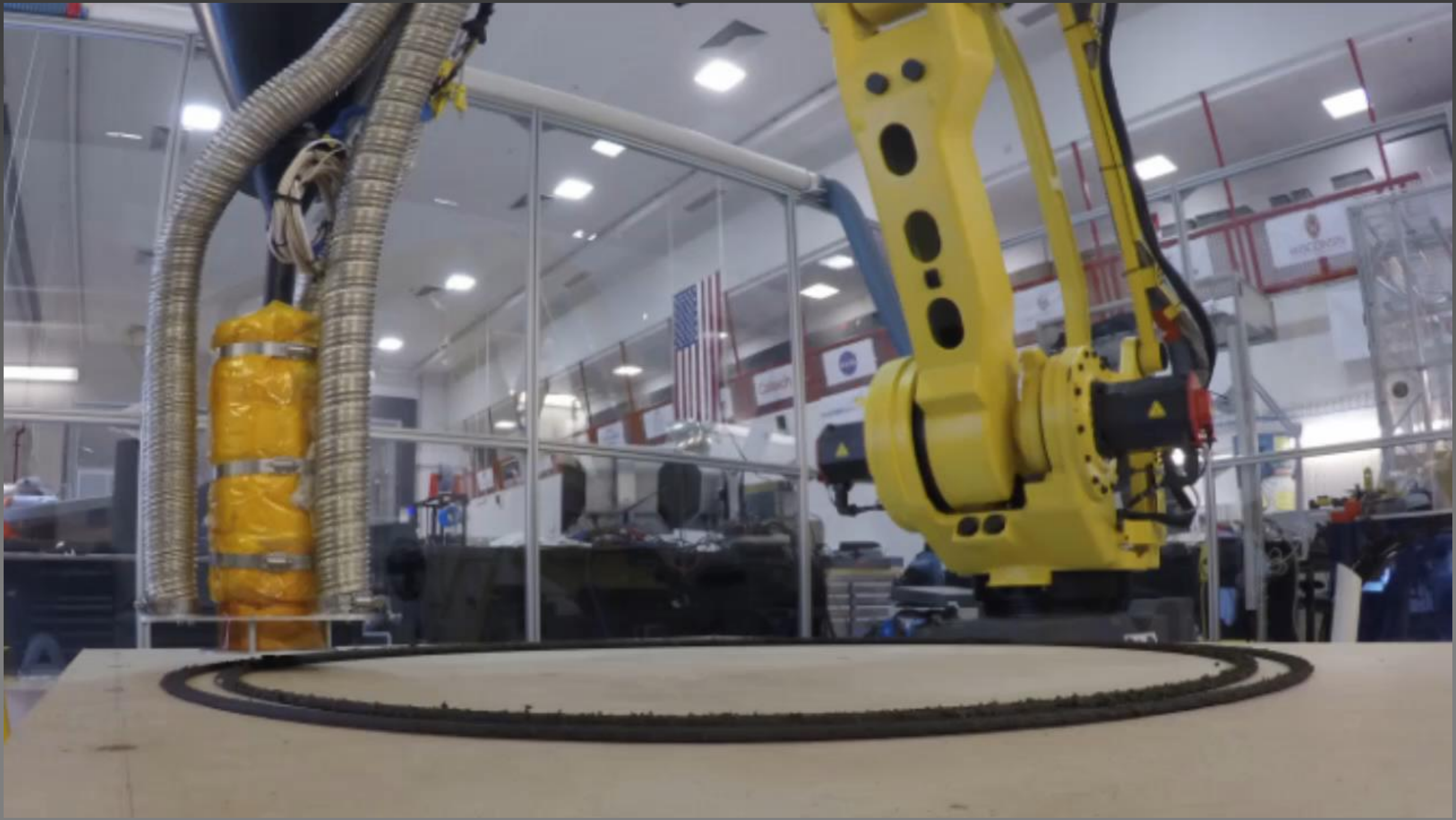
NASA Photos

ZERO LAUNCH MASS 3D PRINTER

NASA Photos



3D PRINTING A HABITAT CONCEPT



NASA Video

PARTNERING WITH THE ARMY CORPS OF ENGINEERS

The Army and NASA have similar challenges: to build long term outpost in remote locations. Both organizations have similar raw materials on hand for use as construction materials.

3D printing B-Huts, barriers, culverts, and other structures using materials available "in theater" simplifies logistical challenges and produces better products in many cases.

NASA Photo

PLASTIC TRASH + LOCAL SOIL = 3D PRINTED INFRASTRUCTURE

Spaceport Infrastructure

Fig 1. KSC Industrial Area Water Tank

NASA Photo

Centennial Challenge: 3D Print a Habitat

$2.5 Million Prize Money

Video

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.

Phase 1: Design Competition

162 Notices

98 Entries

30 Finalists

Design Brief

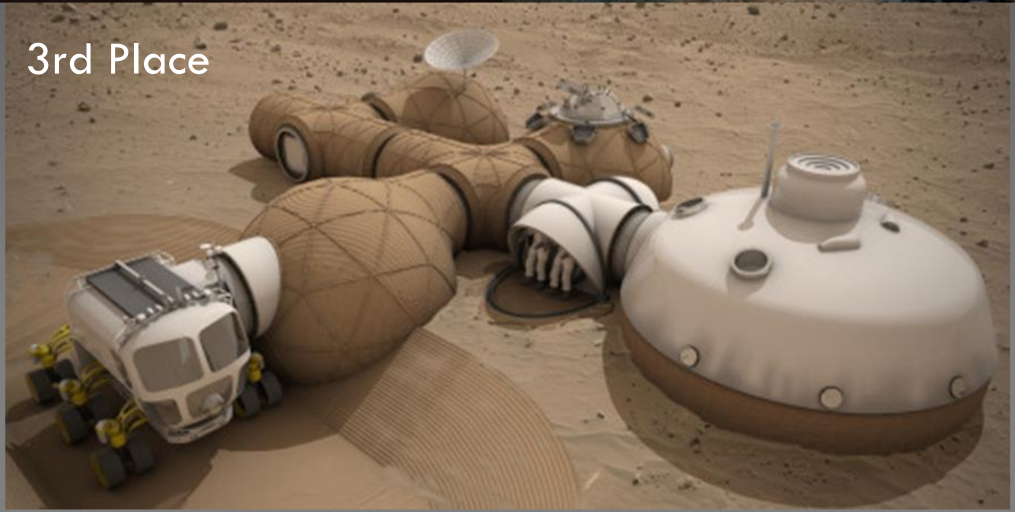
Mission Requirements

- Crew of four on a year long research mission to Mars in the year 2035
- Production of habitat using in-situ resources
- 1000 ft^2 habitable space
- Three 45 ft^3 ECLSS systems

Phase 1: Winners

$25,000 Prize

$15,000 Prize



https://www.youtube.com/watch?v=HfvDIX7Gtvk

Phase 2: Structural Member Competition

Level 1	Level 2	Level 3
Truncated Cone & Cylinder	Beam Member	Head to Head
Cone Slump Test & ASTM C39 compression test cylinder to destruction @ certified test facility 450 kg to qualify for Level 2 by March 31, 2017	ASTM C78 flexural test to destruction @ certified test facility 750 kg to qualify for Level 3 By May 31, 2017	3 x C39 Cylinder (average) 3 x C78 Beam (average) Dome Aug. 24-27, 2017 @ Caterpillar Edwards Facility
10 teams with highest scores awarded prize proportional to score for Total Level 1 amount of $100k	10 teams with highest scores awarded prize proportional to score for Total Level 2 amount of $500k	3 teams with Top 3 Scores win 1st $250k 2nd $150k 3rd $100k
Teams that meet minimum success criteria will advance to Level 2	Teams that meet minimum success criteria will advance to Level 3	Teams that print successful Dome will be invited to participate in Phase 3

Phase 2: Structural Member Competition

78 Entries

7 Qualified

3 Finalists

Phase 2: Structural Member Competition

Material Applicability	Least Relevant								Most Relevant	
Fine Rock Aggregate (< ¼" mean particle diameter)		MR		IRS		CSR		GSS	BSR	CBI
Coarse Rock Aggregate (> ¼" mean particle diameter)	MR		IRS		CSR		GSS	BSR	CBI	
Trash Recyclables	VY	PS	AF		PP	NY		PT	HP	LP
3DP Factor	1	2	3	4	5	6	7	8	9	10

Scoring Rewards Planetary and Mission Recyclable Materials Relevance

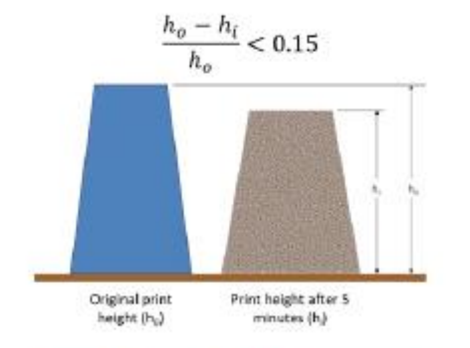


Figure 3: Truncated Cone Slump Measurements

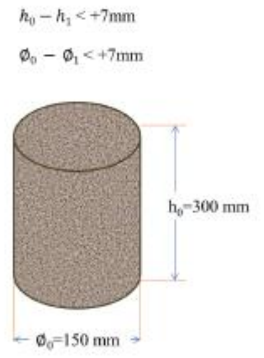


Figure 4: Compression Test Cylinder

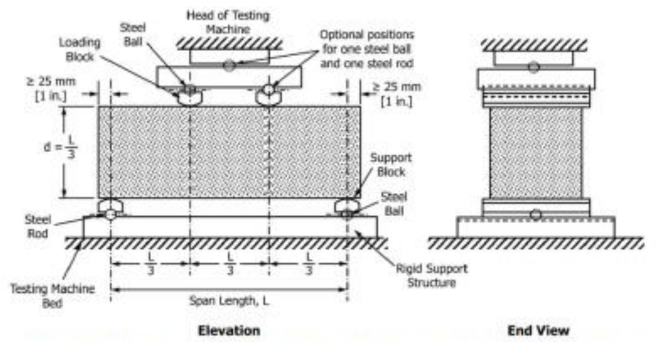
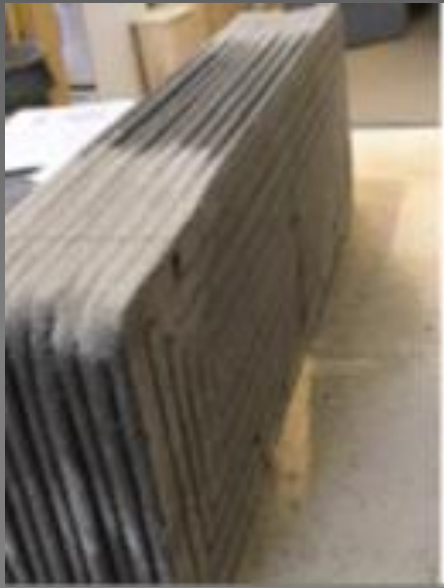


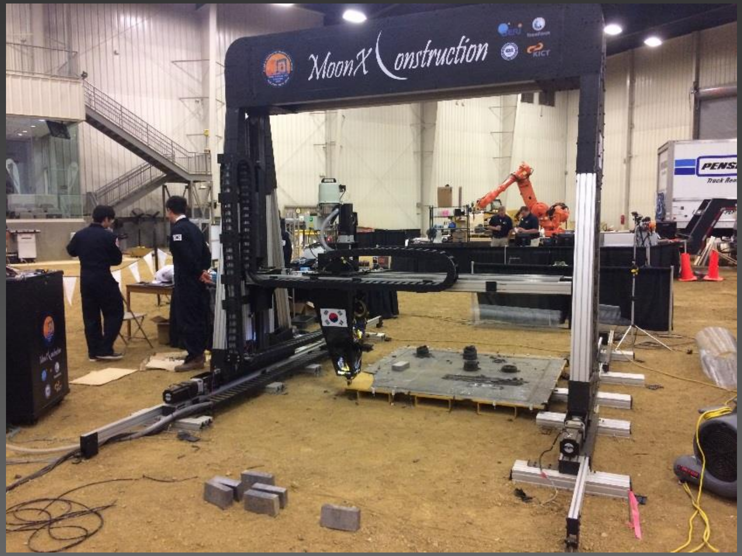
Figure 5: Flexure Test Model Diagram (taken from ASTM C78/C78M)

Phase 2: Structural Member Competition

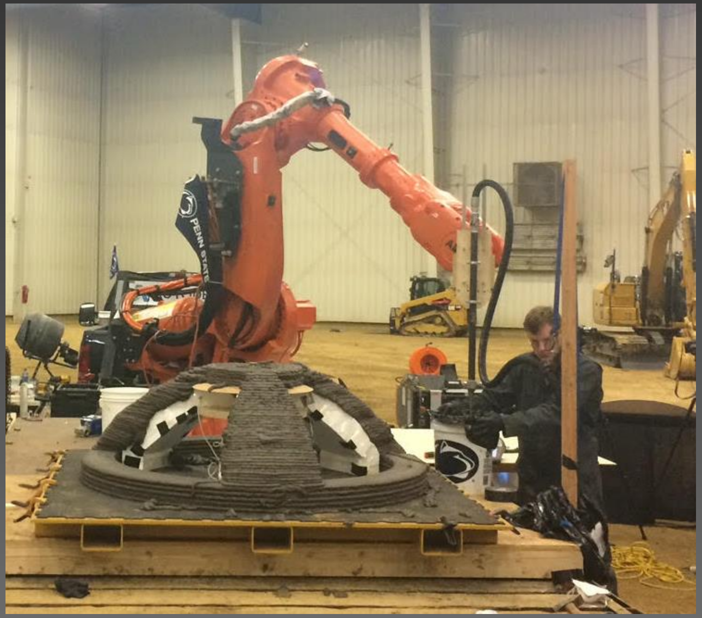


NASA Images

Phase 3 Robots: On-Site Competition



Moon X Construction
South Korea



NASA Images

Penn State University, USA

Foster & Partners | Branch Tech. USA

Crushing Domes – Caterpillar, Peoria, Illinois

NASA Image

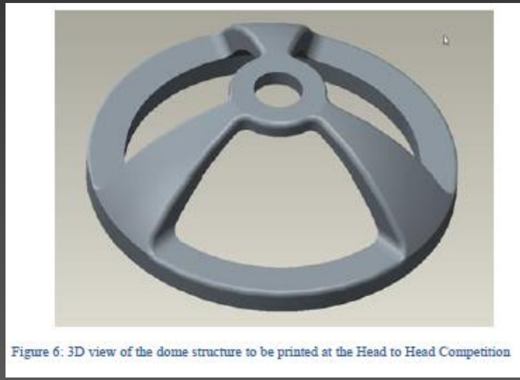
Phase 2: 3D Print a 1.5 m Diameter Dome

Foster & Partners | Branch Tech

1st Place

$250,000 Prize

Polymer | Basalt Concrete

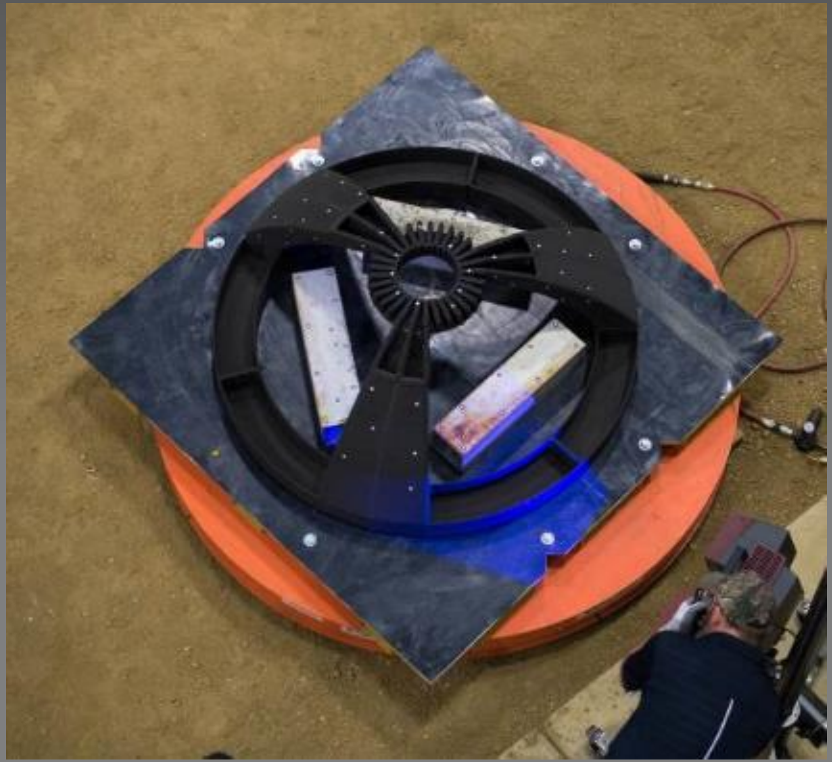


Penn State University

2nd Place

$150,000 Prize

Metakaolin | Basalt Concrete



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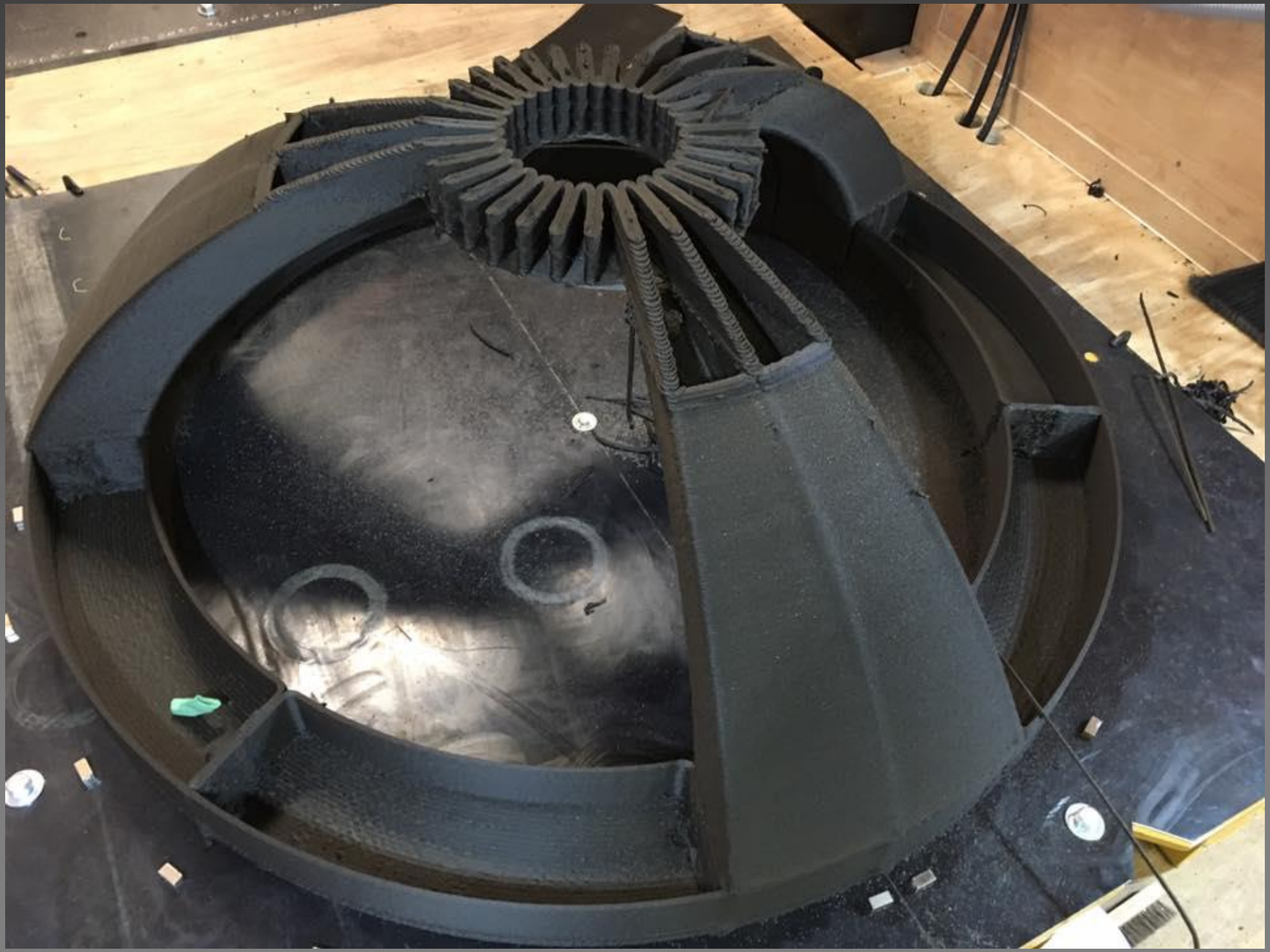
Foster & Partners | Branch Tech
1st Place



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F+P | Branch Technologies

[NASA 3D Printed Habitat Level 2.mp4]

NASA Images

Phase III, Construction Competition

$2 M prize purse, strong emphasis on autonomy (penalties for human and remote interventions during printing process)

- **Construction Level 1 –Foundation**
  - Print a foundation (2m x 3m with 100 mm slab thickness)
    - Evaluate flatness and levelness
  - Evaluate slab durability (impact test), material compressive strength (ASTM C39) and material durability (freeze/thaw test per ASTM C666)

- **Construction Level 2 –Hydrostatic Testing**
  - Print a foundation and a cylindrical habitat element with penetrations. Fill with water and measure rate of leakage at two fill levels.
  - Complete other material tests if formulation is changed from level 1

- **Construction Level 3 –1:3 Scale Habitat Printing**
  - Print a 1:3 scale simplified version of team's habitat design at the head-to-head event
  - Complete other sample prints and evaluations (smoke test for leakage, a projectile drop test, a crush test for ultimate strength and material strength and durability tests)

Phase III, Materials Selection

- Focus is on creation of construction materials from indigenous materials and mission waste (polymer recyclables which would otherwise be “nuisance” materials)

- As in phase II, a sliding materials scale rates construction material selection based on relevance to planetary missions Polymer scale is based on frequency of use of polymeric materials in packaging for the International Space Station (ISS)

- Aggregate scale is based on relative availability of materials on the planetary surface

Basalt, considered an indigenous material, is rated highly on the sliding scale of materials.

Phase III, Materials Selection

Aggregate

CBI	Crushed basaltic igneous rock (SiO_2 weight percent less than or equal to 57)
BSR	Basaltic sedimentary rocks (talus, alluvium with very little alteration/weathering, or mine tailings)
GS	Gypsum (calcium sulfate dihydrate) and other sulfate minerals
SS	Siliceous sedimentary rocks and clays (sand box sand, mudstone)
MG	Marble and other metamorphic rocks (e.g., slate), granite
LD	Limestone and dolomite (carbonaceous sedimentary rocks)

Polymers

PE (HD & LD)	Polyethylene (high density and low density, #2 and #4 recycle codes, respectively)
PP	Polypropylene (#5 recycle code)
BR	Polybutadiene (butadiene rubber)
PVC	Polyvinyl chloride
VY	Vinyl (#3 recycle code)
PMMA	Poly (methyl methacrylate)
PET	Polyethylene terephthalate (#1 recycle code)
PETG	Polyethylene terephthalate glycol
PS	Polystyrene (#6 recycle code)
PC	Polycarbonate
S	Styrene

Phase III, Materials Selection

Material Applicability	Earth Relevant							Mars Relevant		
Aggregate	LD	MG			SS			GS	BSR	CBI
Polymers (including fibers)	MR, EVOH	NY, PU	PT, ABS	S	PS, PC	PMMA, PET, PETG	PVC, VY	BR	PP	PE (HD and LD)
Additives	FP	AM	SC							B
Binders	PG	HA	IW					GST		MBC
3DP Factor	1	2	3	4	5	6	7	8	9	10

Scoring Rewards Planetary Relevance and Use of Mission Recyclable Materials

Materials score = sum of % weight of material in formulation multiplied by corresponding 3DP factor

Phase III, Construction Level 1 Results

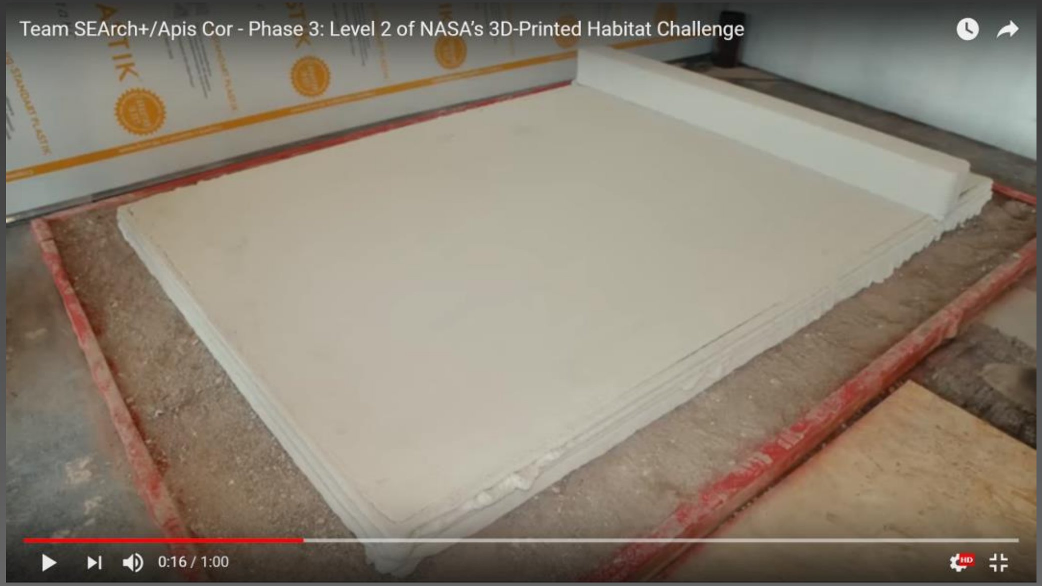
Team SEArch+/Apis Cor of New York won first place in this level of NASA's 3D-Printed Habitat Challenge. The team is pictured above dropping a shotput on their foundation to simulate a meteor strike.

Penn State won second place in this level of NASA's 3D-Printed Habitat Challenge. Pictured above is a shotput drop on the foundation to assess its impact resistance.

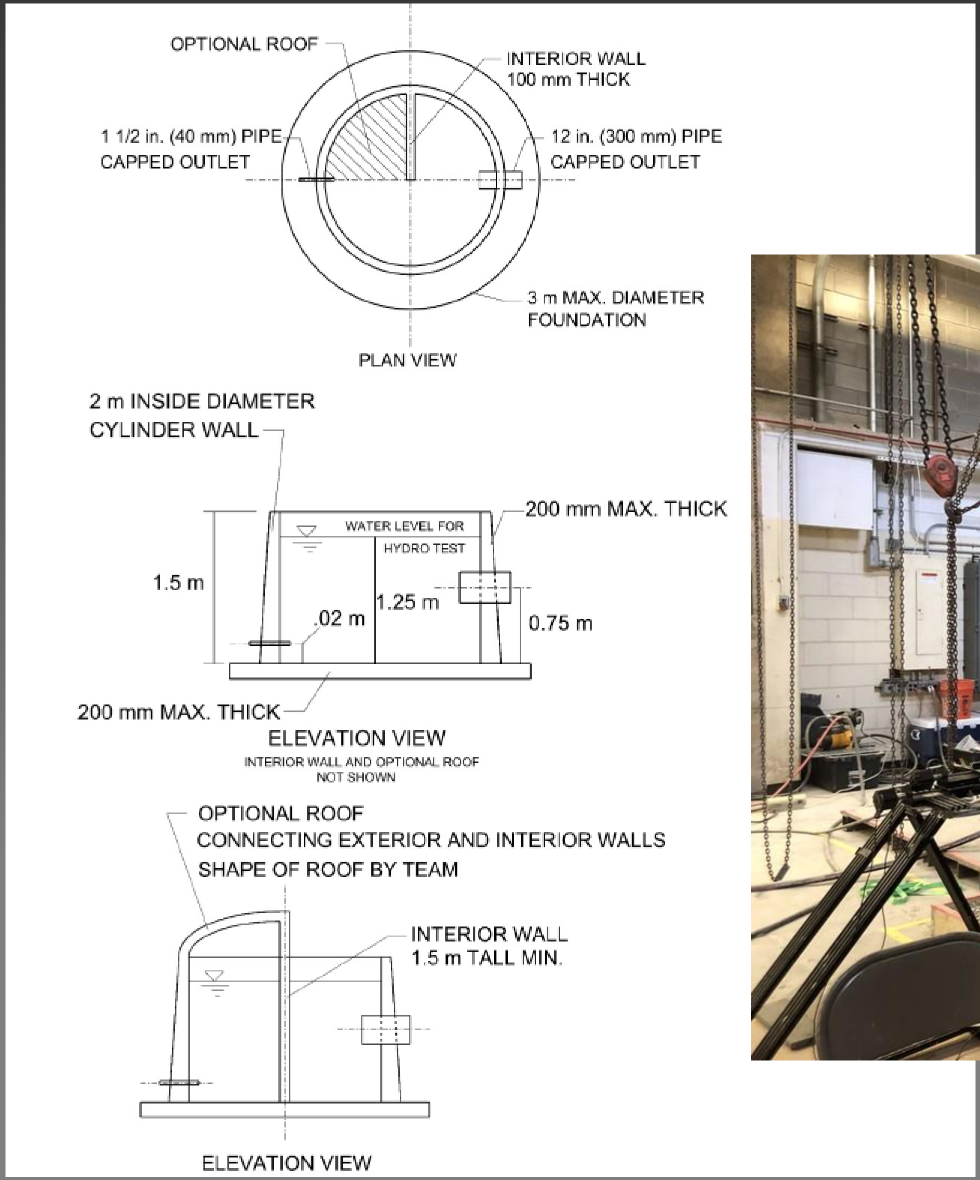
Phase III, Construction Level 1 Results

FormForge | Austin Industries | WPM of Austin, Texas, won third place in this level.

Team SEArch+/Apis Cor of New York won first place in this level of NASA's 3D-Printed Habitat Challenge. The foundation produced was of high quality



Phase III, Construction Level 2: Hydrostatic Test



3D-printed habitat element for hydrostatic test

Penn State University

Phase III, Virtual Construction Competition

$200,000 Prize Purse Overall. Teams must use Building Information Modeling (BIM) software.

- **Virtual Construction, Level 1**
  - minimum of 60% of the information required for construction of the pressure retaining and load bearing portion of the habitat
  - MEP and ECLSS design (LOD 100)
  - Structure and Pressure Retaining Walls/Components (LOD 300)

- **Virtual Construction, Level 2**
  - 100% of information required for construction
  - MEP an ECLSS design (LOD 200)
  - Structure and Pressure Retaining Walls/Components (LOD 400)

MEP: Mechanical/Electrical/Plumbing
ECLSS: Environmental Control and Life Support Systems
LOD: Level of Design

Evaluation criteria: LOD, system information, layout/efficiency, aesthetics, constructability, and BIM use functionality

Phase III, Virtual Construction Level 1 Results

1st place, Team Zopherus

Lander structure encloses the printer, providing a pressurized, thermally controlled print environment for processing of the extracted materials (ice, Calcium Oxide, and Martian aggregate) into feedstock and fabrication of the first habitat module.

2nd place, AI Space Factory

Vertically oriented cylinder made of PLA reinforced with basalt fiber. The cylindrical geometry was chosen to
maximize the ratio of usable living space to surface area and reduce structural stresses. A double shell structure allows for expansion and contraction of material with the thermal swings the structure will experience on the Martian surface.

Phase III, Virtual Construction Level 1 Results

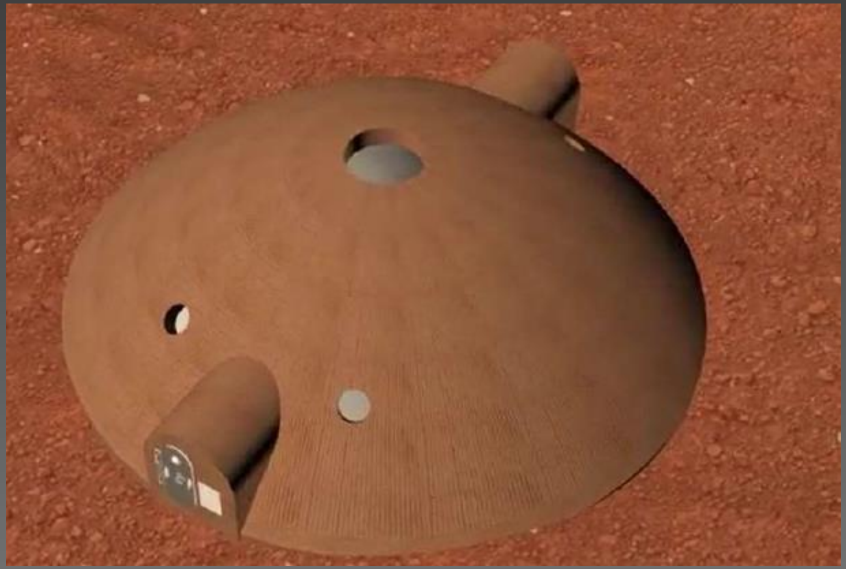
3rd place, Kahn-Yates

The habitat consists of an inner and outer polymer shell which sandwiches a sulfur concrete. The sandwich layer is omitted in certain locations to provide natural light.

4th place, SEArch+/ApisCor

Materials and thicknesses selected specifically to provide radiation shielding. The habitat is flanked by overlapping shells and oriented at 30 degrees above the horizon; these features allow for the entrance of natural light without compromising radiative protection.

Phase III, Virtual Construction Level 1 Results



5th place, Northwestern University

Rovers additively manufacture a foundation and deploy an inflatable shell. The rovers print the habitat's outer shell, which overlays the inflatable. The layout is a hub and spoke design, with a central multi-use space surrounded by sectioned spaces programmed to support various mission functions (crew quarters, lab space, kitchen/dining, etc.) In this concept, a series of modular habitats are connected by a network of tunnels.

Phase III Construction, Level 3

- Head to head competition from April 29-May 4, 2019 at Caterpillar's Edward Demonstration Facility in Peoria, Illinois, USA
- Up to 8 teams will be invited to compete
- The 1:3 scale model of the habitat must be printed in a 4.5 meter by 4.5 meter area at the head to head competition.
- Total time allocated to printing activities is 30 hours
- A BIM model with structural and pressure retaining elements at LOD 400 which corresponds to the structure that will be printed at the event is required

Phase 3: On-Site Habitat Competition

Focused on the 3D-Printing fabrication of a scaled habitat design, using indigenous materials combined with or without recyclables.

Phase 3: On-Site Habitat Competition

A.I. Space Factory

1st Place

PLA Polymer | Basalt Concrete

Penn State University

2nd Place

Metakaolin | Basalt Concrete

NASA Images

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Prize Purse of $700,000

Awarded in May 2019!

1st Place; $500,000
A.I. Space Factory

2nd Place; $200,000
Penn State University

Questions?