NASA Centennial Challenge: 3D Printed Habitat, Phase 3 Final Results

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Successful Historical Leveraged Competitions

Historical Prize Successes:

•Longitude Prize : 1714-1765 (51)
  Solved navigation on the oceans

•Napoleon III, Margarine Prize; 1869
  Developed a butter substitute

•Orteig Prize: 1919-1927 (8)
  First transatlantic flight by a human

•Ansari X Prize: 1996-2004 (8)
  First commercial reusable spacecraft to cross the von Karman line (100 km altitude)

NASA Centennial Challenge Successes (Since 2005):

Some Completed Challenges

1. Green flight challenge
2. Strong tether challenge
3. Power beam challenge
4. Moon regolith Oxygen (MoonROx) challenge
5. Astronaut glove challenge
6. Vertical and lunar lander challenges
7. Regolith excavation challenge
8. Night rover challenge
9. Unmanned aircraft systems airspace operations challenge
10. 3D Printed Habitat challenge

Current Challenges

1. Space robotics challenge
2. Vascular Tissue challenge
3. Cube Quest challenge
4. CO_2 Conversion challenge

3D Printed Habitat Competition Vision

- Advance the **automated construction** and **materials** technologies needed for fabrication of **habitats on a planetary surface** using indigenous materials and mission recyclables

- Terrestrially, these technologies stand to **revolutionize the construction industry** by automating labor intensive processes and enabling **rapid fabrication of large scale structures**

  - World's population predicted to increase from **7.6 billion** to **11.2 billion** by 2100 (47 % increase)

  https://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf

  - Requires **aggressive construction practices** to satisfy increased demand for **affordable housing**

3D Printing 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

General overview of processes and printing systems

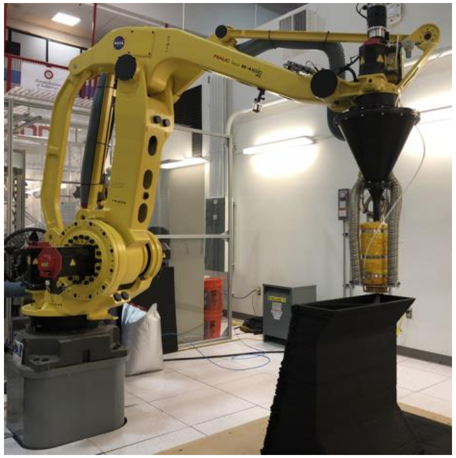
Examples of common printing processes for construction:

1. Cement-based materials extruded through a nozzle
   - Process used by NASA/Army Corps of Engineers/Contour Crafting in the Additive Construction for Mobile Emplacement project
2. Forced extrusion of wire, filament or pellets
   - Process used by many desktop printers

NASA Additive Construction for Mobile Emplacement (ACME) / ACES US Army Corps of Engineers

In general, printing systems take the form of:

1. Gantry style systems
   - Extruder is attached to frame that translates in three dimensions
2. 6 degree of freedom robotic systems
   - Extruder is the end effector of an industrial robot arm



NASA KSC Swamp Works

Basalt Granular Material = Construction Aggregate

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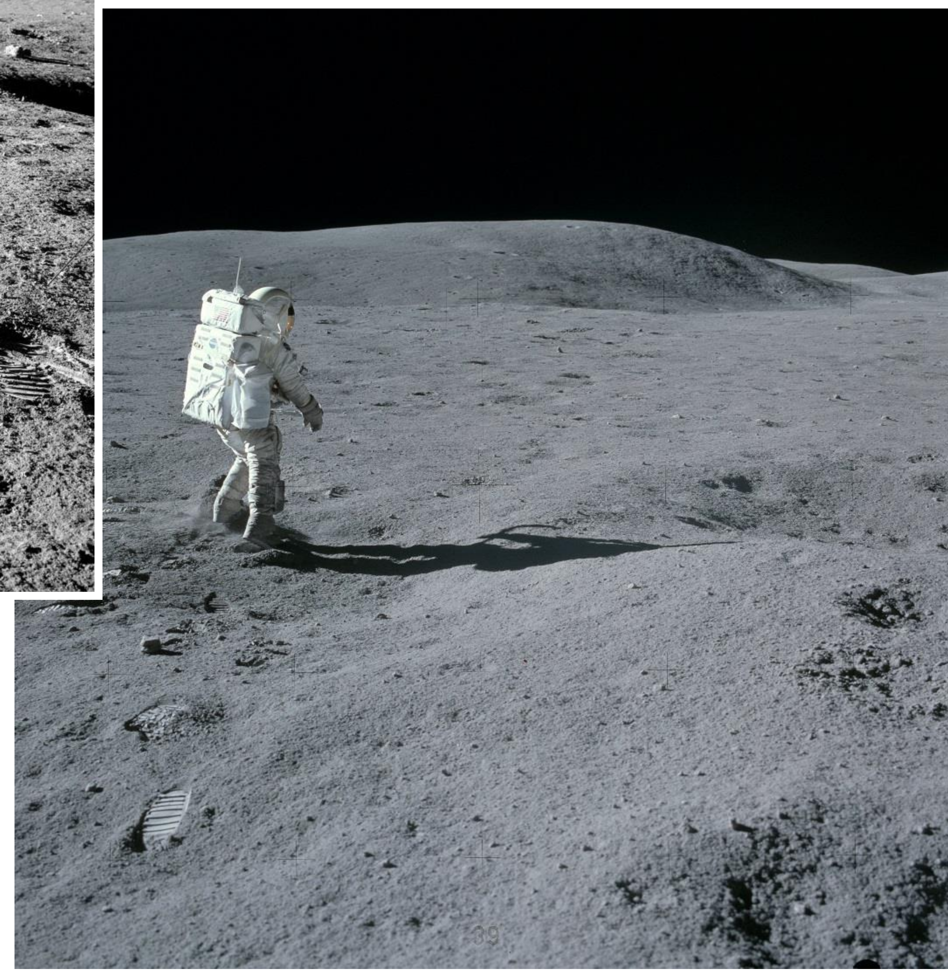

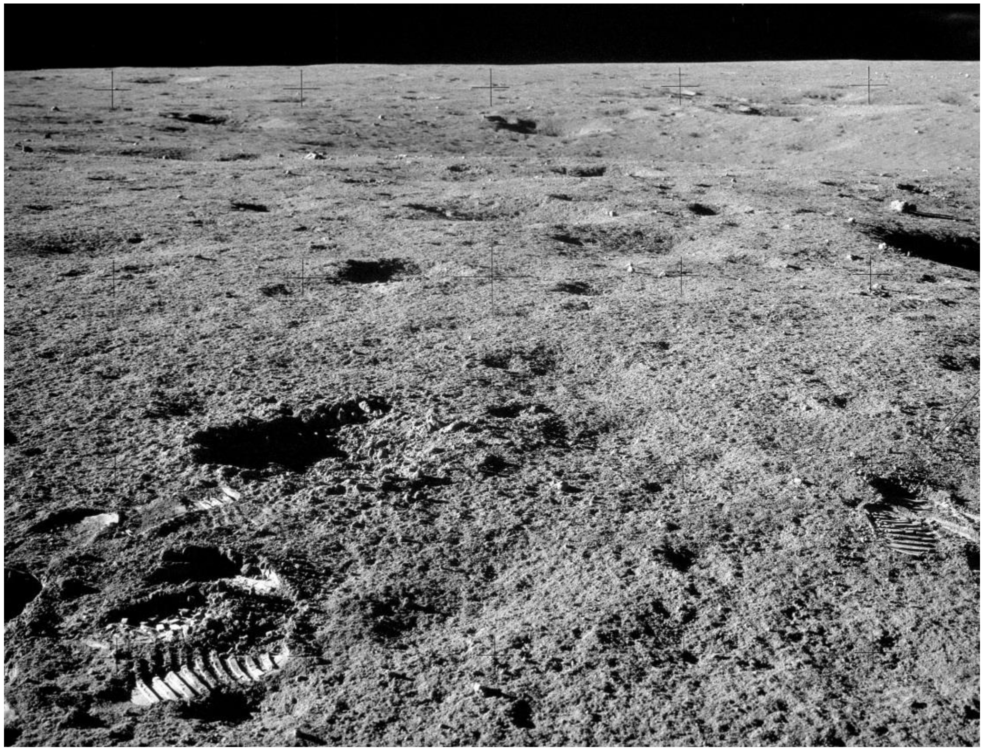

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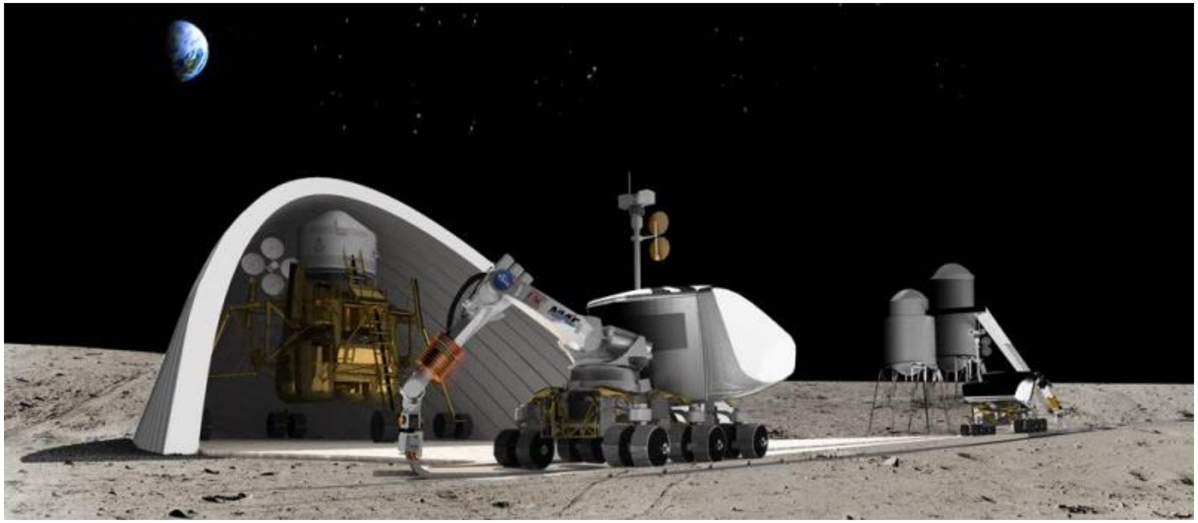
Potential of 3D Printing Technologies for Space and Earth

- Autonomous systems can **fabricate i**nfrastructure (potentially from indigenous materials) on precursor missions
  - Can serve as a **key enabling technology** for exploration by reducing logistics (i.e. launch mass) and eliminating the need for crew tending of manufacturing systems
- Also has potential to **address housing needs** in light of unprecedented population growth
  - Affordable housing globally
  - Military field operations



Artist's rendering of a manufacturing operation on a planetary surface.

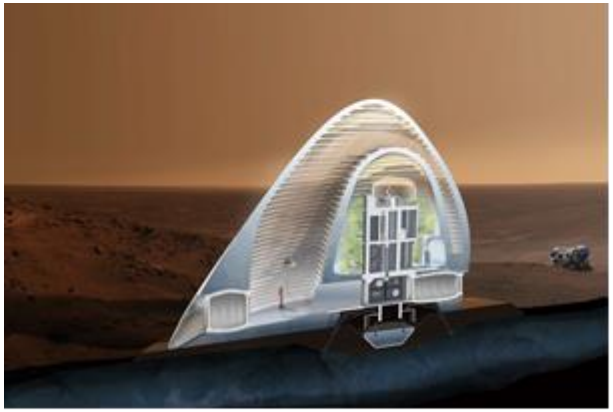
Image credit: Contour Crafting Corp / NASA

https://arch.usc.edu/topics/nasa-research

Overview of the 3D Printed Habitat Competition

Advance additive construction technology to create sustainable housing solutions for Earth and beyond

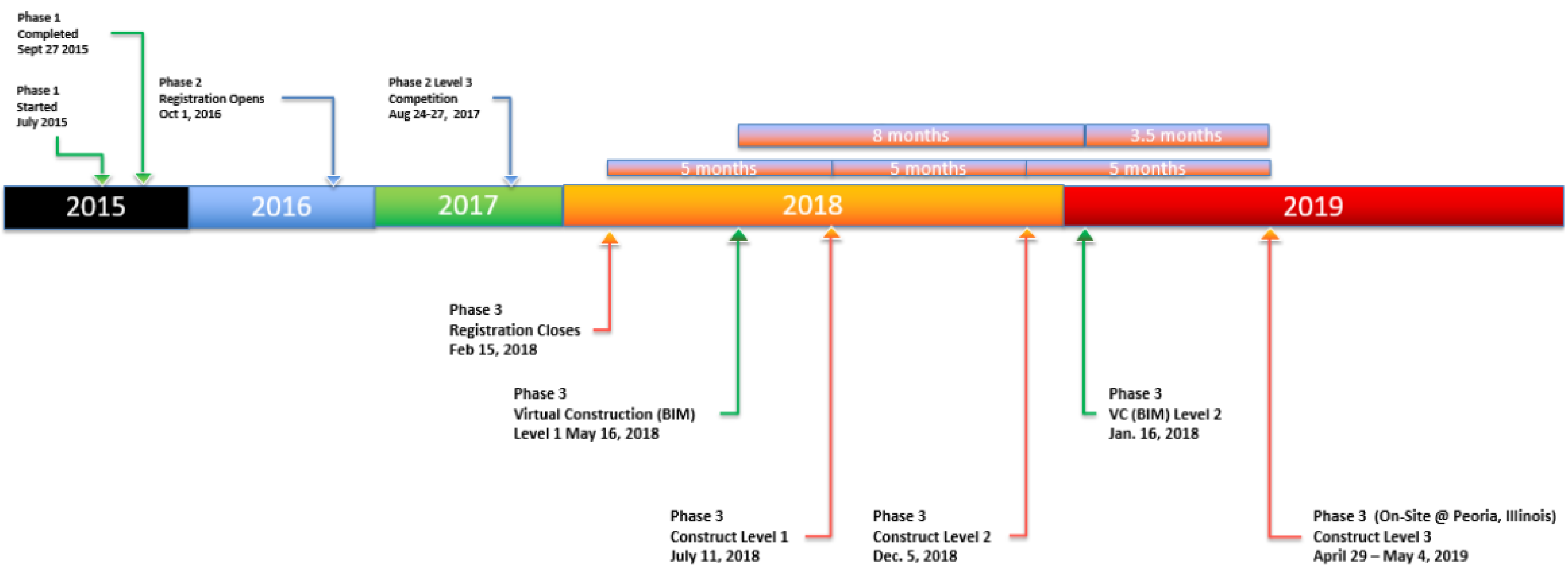
Autonomous, Sustainable Additive Manufacturing of Habitats		
Phase 1	**Phase 2**	**Phase 3**
Design: Develop state-of-the-art architectural concepts that take advantage of the unique capabilities offered by 3D printing.	**Structural Member:** Demonstrate an additive manufacturing **material** system to create structural components using terrestrial/space based materials and recyclables.	**On-Site Habitat:** Building on material technology progress from Phase 2, demonstrate an automated 3D Print System to **build a full-scale habitat**.
Prize Purse Awarded: $0.04M	**Prize Purse:** $1.1M	**Prize Purse:** $2.0M



Phase I was an **architectural concept competition**. Picture on the left is the **Mars Ice House**, winner of the Phase I competition from Space Exploration Architecture and Clouds Architecture Office. http://www.marsicehouse.com/

Competition Timeline

NASA'S 3D-Printed Habitat Challenge – Timeline



Phase III, Virtual Construction Competition

Teams had to use Building Information Modeling (BIM) software.
Overall Winners:

1st Place: SEArch+/Apis Cor - New York - $33,954.11
2nd Place: Zopherus – Rogers, Arkansas - $33,422.01
3rd Place: Mars Incubator – New Haven, Connecticut - $32,623.8

- **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 2 Results

1st place, SEArch+/Apis Cor

The habitat is an inward facing arch design (a hyperboloid) with two layers. High density polyethylene (a polymeric material with good properties for radiation shielding) functions as the inner layer, while the exterior is regolith. Radiation shielding is accomplished via overhangs.

Phase III, Virtual Construction Level 2 Results

2nd 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.

3rd place, Mars Incubator

A series of habitats arranged in a hub and spoke design, with the largest, primary volume at the center. Panels in the design consist of polyethylene and basalt fiber. The habitat in this design is not fabricated via continuous additive manufacturing; instead, additively manufactured panels are mechanically assembled via robotic manipulation.

Phase III, Virtual Construction Level 2

Hassell + EOC.

Hassell + EOC's concept relies on a swarm of wheeled mining robots to excavate and collect regolith for processing into feedstock. Concurrent printing along the x-y footprint of the structure by the fleet of robots enables rapid and efficient fabrication. The resulting Mars habitat has a contoured structure intended to complement the surrounding environment.

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 2

Kahn-Yates

Kahn-Yates of Jackson, Mississippi proposed a habitat consisting of an inner and outer polymer shell sandwiching a sulfur concrete. The sandwich layer is omitted in certain locations to provide natural light. The habitat contains a central cylinder with panels that unfold horizontally to divide the structure into three floors.

X-Arc

In the X-Arc habitat concept, materials for feedstock are extracted from the planetary surface via excavating robots. Polyethylene can be readily manufactured on the Martian surface, which has an atmosphere of approximately 95% CO_2 and water available. Ground basalt is added to the polyethylene and extruded into feedstock from a gantry-style 3D printer. The habitat concept is a printed shell structure with 3 levels. Prefabricated components are placed inside the habitat and as penetrations via robotic assistance.

Phase III, Virtual Construction Level 2

Northwestern University

In Northwestern University's design, rovers additively manufacture a foundation and deploy an inflatable shell. The rovers print the habitat's outer shell, which overlays the inflatable structure. The layout is a hub and spoke design, with a central multiuse 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 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, Construction Level 1 Results

1st Place: 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.

2nd Place: 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.

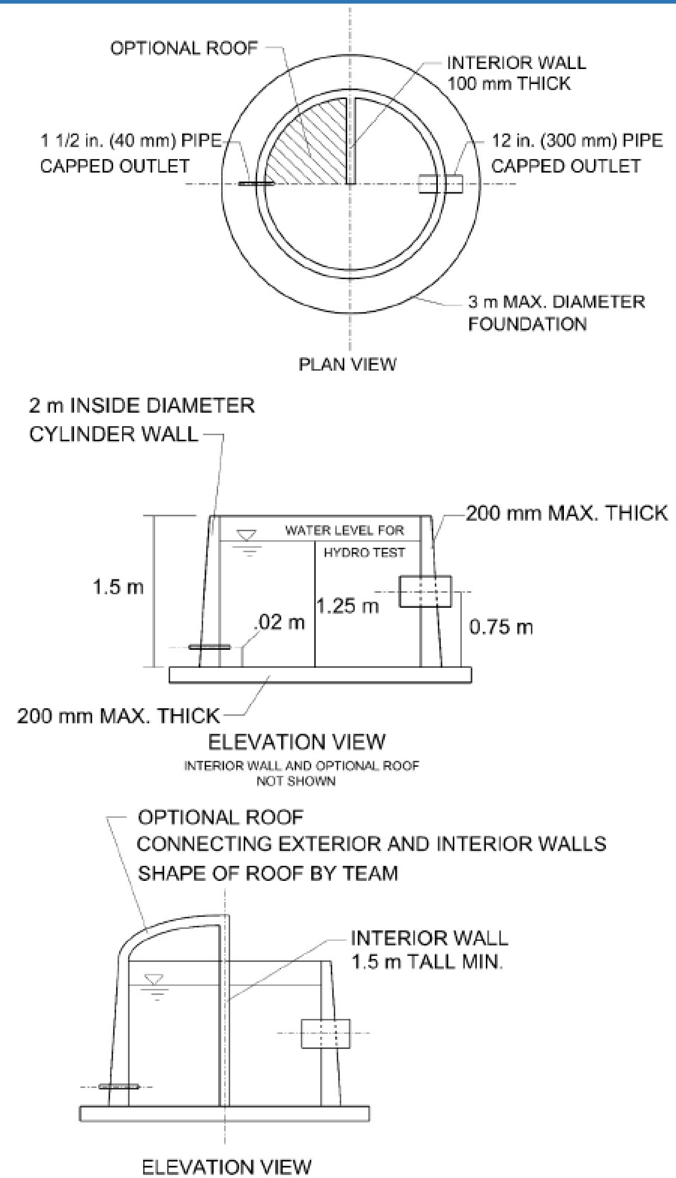
Phase III, Construction Level 1 Results

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

1st Place: 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



Phase III, Construction Level 2: Hydrostatic Test

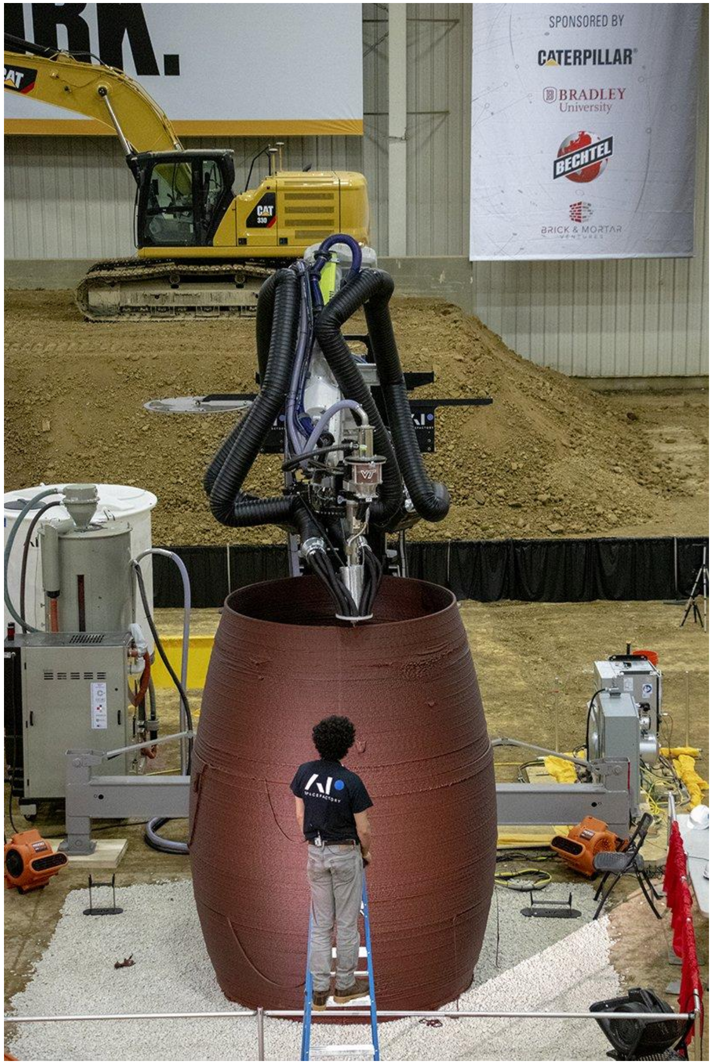
1st Place: Habitat element for hydrostatic testing printed by SEArch+/Apis Cor.

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
- 2 teams were invited to compete: Penn State University & AI Space Factory
- 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 was 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 was required
- Autonomous construction with penalties for human intervention.

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



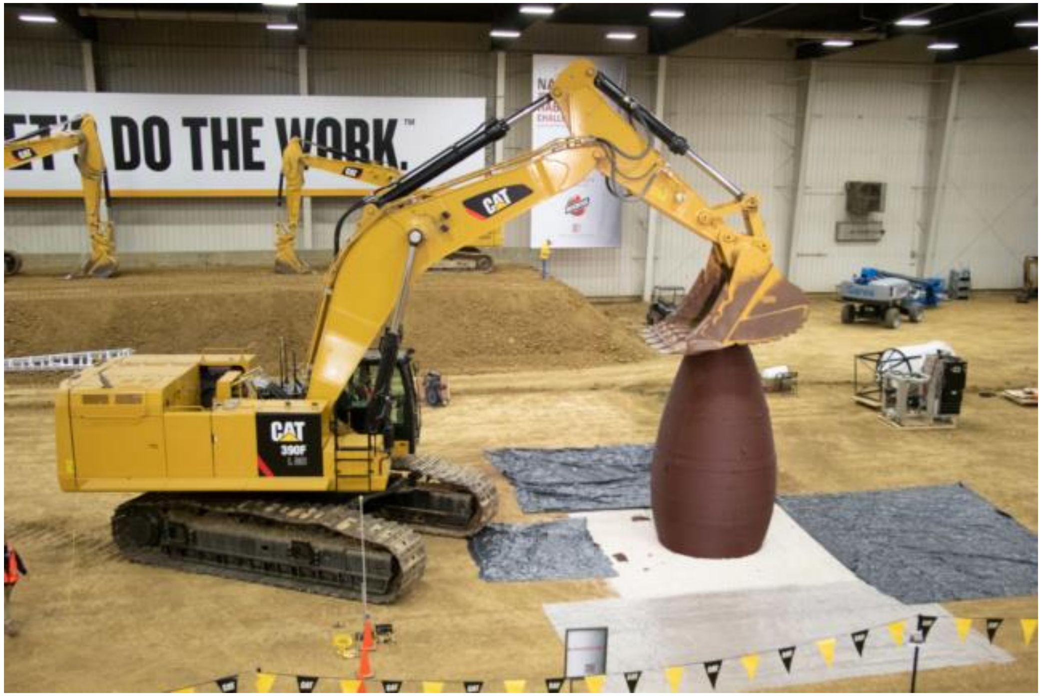
Penn State University

AI Space Factory

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

Penn State University



AI Space Factory

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

Teams that attended the Head to Head Phase III, Level 3 event:

1st Place: $500,000

AI Space Factory

2nd Place: $200,000

Penn State University