National Aeronautics and
Space Administration

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NASA's Centennial Challenge for 3D Printed Habitat

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Phase II Outcomes and Phase III Competition Overview

MARSHALL
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Competition Vision

- Advance the automated manufacturing 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 will increase from 6.6 billion to 12.9 billion by 2100
  - Requires aggressive construction practices to satisfy increased demand for 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 printing for construction:**
  - 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

3D printed concrete castle. Image from *Popular Science*.

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
   - Process used by many desktop printers

Additive Construction for Mobile Emplacement (ACME)

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

Image from Lockheed Martin

Potential of 3D Printing Technologies for Space and Earth

- Autonomous systems can fabricate infrastructure (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
  - Disaster response
  - Military field operations

Artist’s rendering of a manufacturing operation on a planetary surface.
Image credit: Contour Crafting.

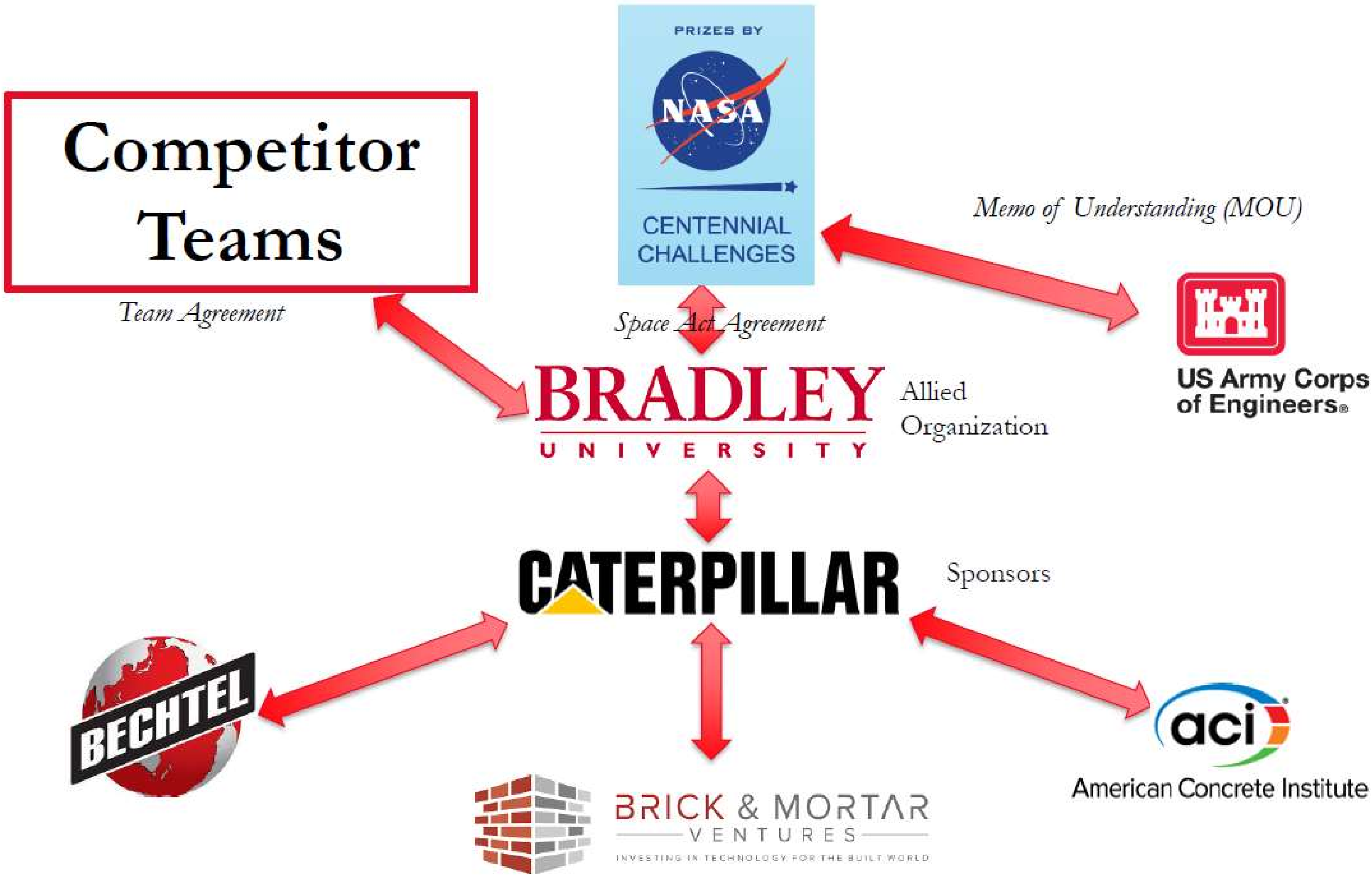
Overview of the 3D Printed Habitat Competition

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

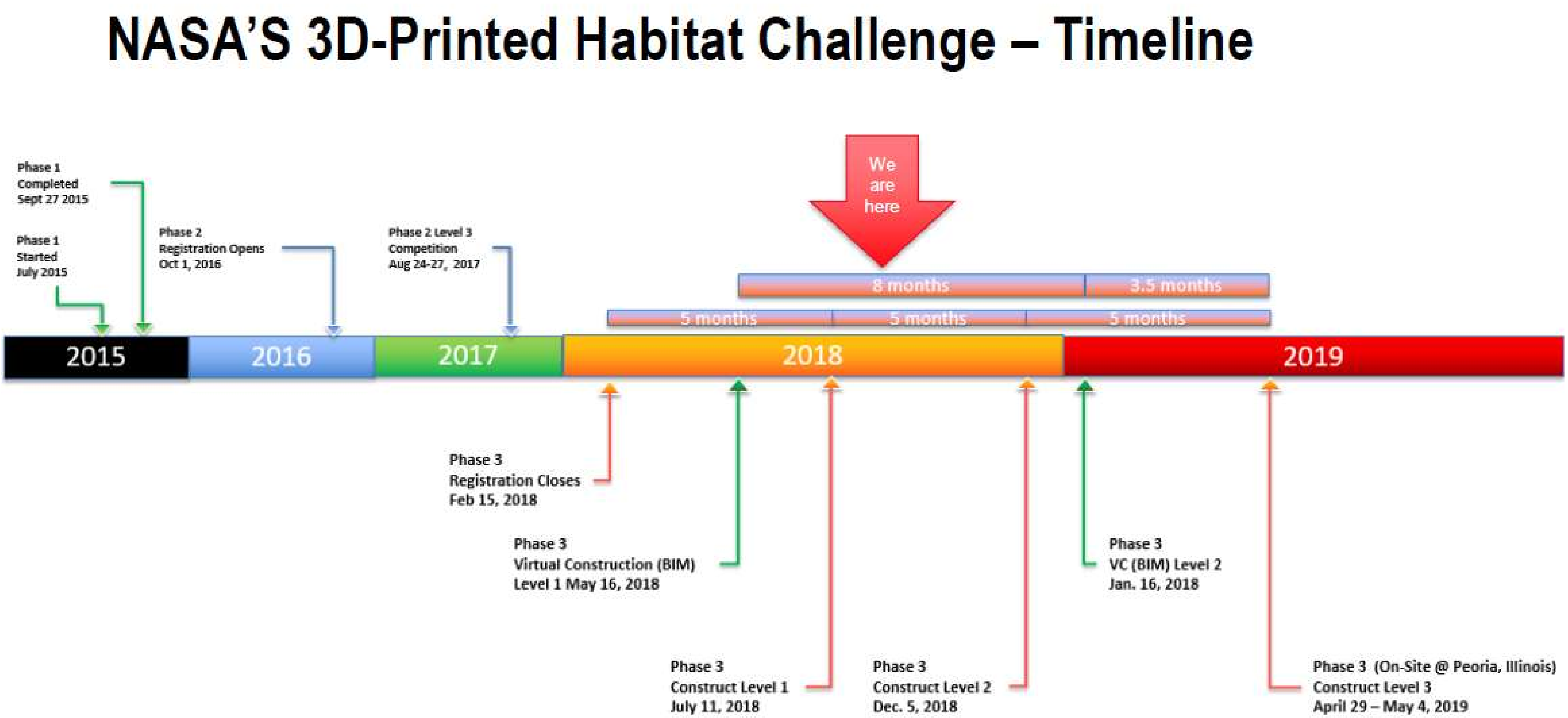
Autonomous, Sustainable Additive Manufacturing of Habitats		
Phase 1	**Phase 2**	**Phase 3**
Design: Develop state-of-the-art architectural concepts that take advantage of the unique capabilities offered by 3D printing.	**Structural Member:** Demonstrate an additive manufacturing **material** system 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 as 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 AO.

Competition partners



Competition Timeline



Phase II Competition

Level 1 ($100,000 prize purse)

- Print a truncated cone (material slump test)
- Compression specimen (minimum load at failure of 450 kg)
- At least 70% indigenous materials in mix

Level 2 ($500,000 prize purse)

- Print a beam (flexure) specimen (minimum load at failure of 750 kg)
- At least 70% indigenous materials in mix

Level 3 ($500,000 prize purse)

- Head to head at Caterpillar Edwards
- Teams must produce three compression specimens, three flexure specimens, and a dome structure for testing onsite
- At least 70% indigenous materials in mix

Phase II Competition, Level 1

Specimen 1

- Truncated cone with a tolerance of + 7 mm
- Extruded material must maintain the printed height to within 15% for a minimum of 5 minutes

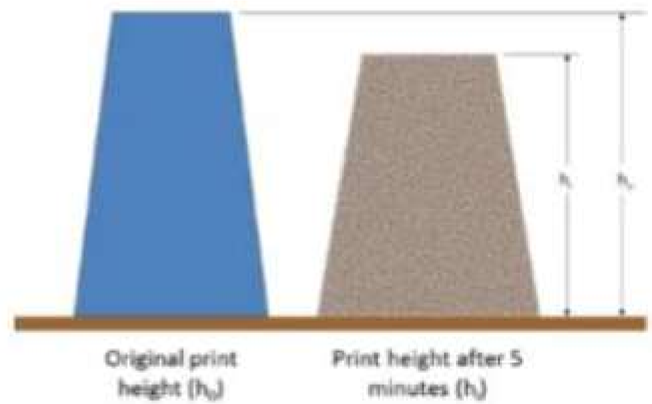
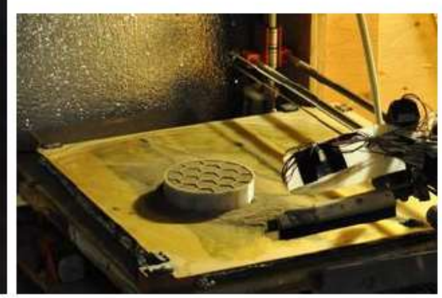


Diagram of slump test

Specimen 2

- Compression specimen (300 mm height and 150 mm diameter) tested per ASTM C39
- Minimum compressive load 450 kg

Winning level 1 entry from Foster + Partners and Branch Technology



Second place: University of Alaska Fairbanks

Phase II Competition, Level 2

Specimen

- Beam 60 cm length x 200 mm height x 100 mm wide cross-section
- Tested per ASTM C78
- Tolerance for specimen width and height was + 7mm
- Tolerance for length was +/-7 mm
- 1st place: MoonX(Seoul, South Korea)
- 2nd place: Oregon State University
- 3rd place: Foster+Partnersand Branch Technology
- 4th place: University of Alaska, Fairbanks
- 5th place: CTL Group
- 6th place: ROBOCON (Singapore)

Second-place team Form Forge of Oregon State University, Corvallis, printed this beam for the phase II, level 2 challenge. Image courtesy Form Forge.

3D printed beam entry (post flexural testing) from Foster + Partners and Branch Technology

Phase II Competition, Level 3

- Head to head competition at Caterpillar's Edwards Demonstration Facility in Peoria, Illinois
    - 5 teams invited to Level 3 competition based on successful completion of Level 1 and Level 2
- 3 teams competed from August 23-August 26, 2017
    - MoonX (South Korea)
    - Foster+Partners and Branch Technology
    - Penn State

Penn State

MoonX

Branch Technology and Foster + Partners

Phase II Competition, Level 3 Results

1st place, $250,000:
Branch Technology and Foster + Partners

2nd place, $150,000:
Penn State

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

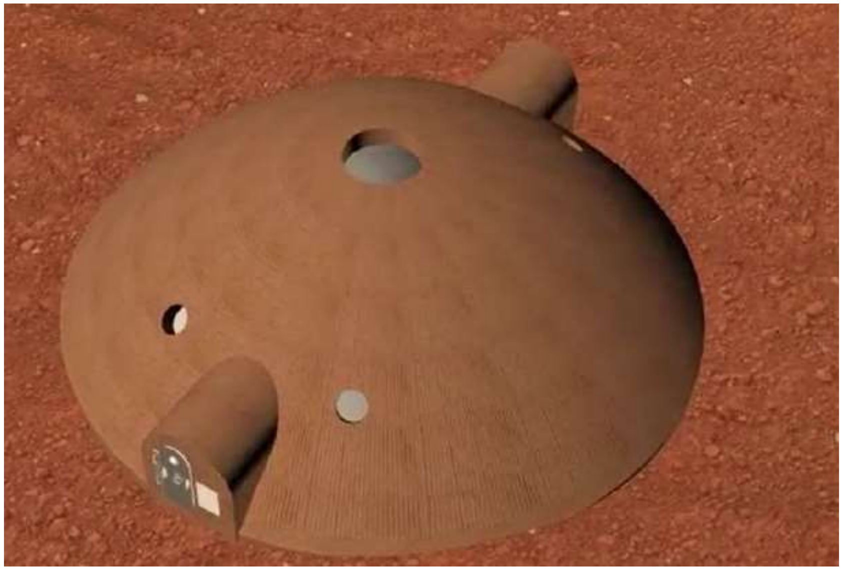
3rd place, Kahn-Yates

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 Competition

$1.8M 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
  - **Teams are no longer penalized for use of imported materials (those that would be transported from earth specifically for construction purposes) as they were in phase II, but indigenous materials are scored higher than nonindigenous materials on the sliding scale**
  - **No penalty for water**
  - **Material feedstock must be a blend suitable for the competition (see FAQ 3.12)**
- 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.

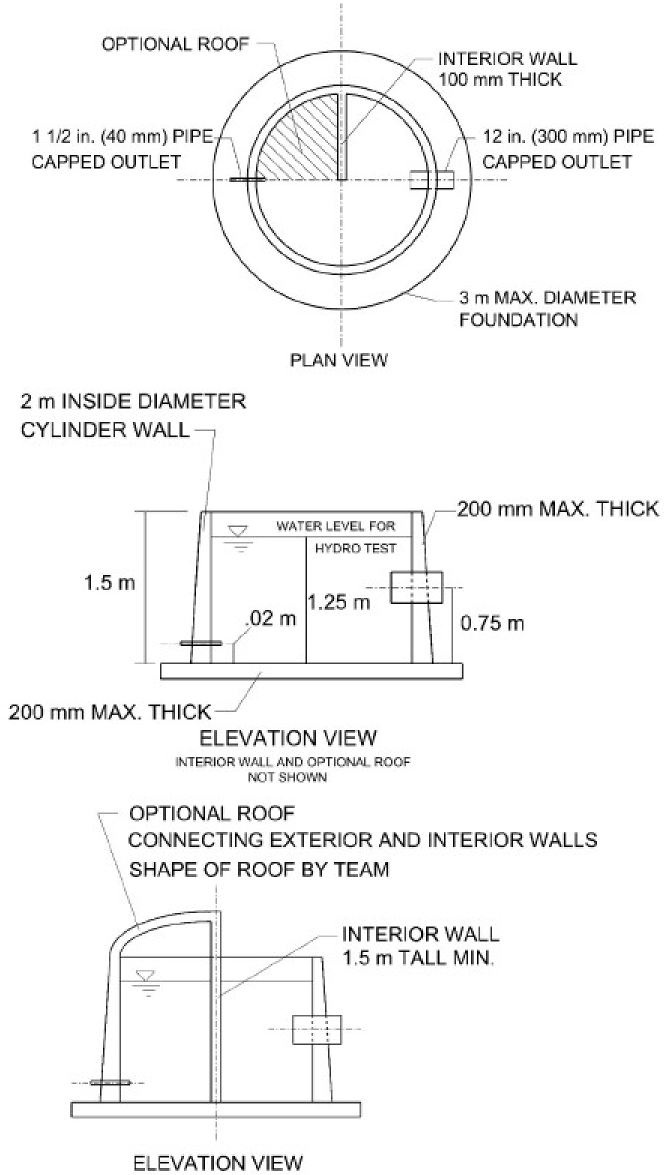
Penn State won second place in this level of NASA's 3D-Printed Habitat Challenge. Pictured above is a shotput drop on the foundation to assess its impact resistance.

Phase III, Construction Level 1 Results

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

Phase III, Construction Level 2: Hydrostatic Test

3D-printed habitat element for hydrostatic test



Phase III Construction, Level 3

- Head to head competition from April 29-May 4, 2019 at Caterpillar's Edward Demonstration Facility in Peoria, Illinois
- 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


NASA'S
3D-PRINTED
HABITAT
CHALLENGE
A NASA CENTENNIAL CHALLENGE