National Aeronautics and
Space Administration

NASA Centennial Challenge: 3D-Printed Habitat

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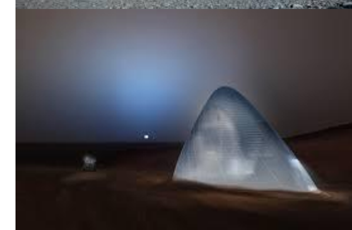
Competition Vision

- 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






What is 3D Printing?

- Process of constructing a 3D object by depositing material layer by layer based on a digital part file

Why use 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 construction applications)

3D printed concrete castle

Overview of current approaches

- In general, processes may be:
  - Contour Crafting process (USC)
    - Cement based materials extruded through a nozzle
    - Process used for NASA/Army Corps of Engineers project Additive Construction for Mobile Emplacement (ACME)
  - Fused Deposition Modeling
    - Material extruded in wire form
    - Same process used by many desktop printers
- In general, printing systems may be:
  - Gantry style systems
    - Extruder is attached to frame that translates in the x-y plane
  - 6 degree of freedom robotic systems
    - Extruder is the end effector of an industrial robot

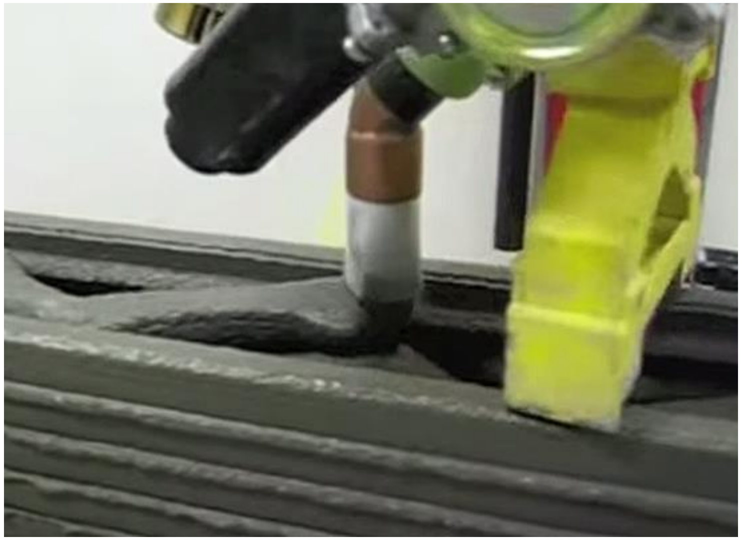
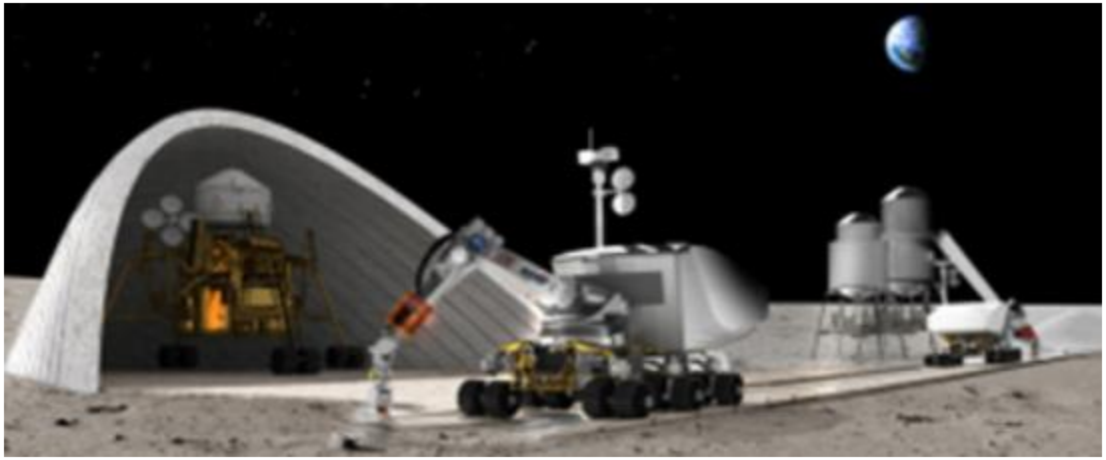


Image of concrete extrusion process from Contour Crafting

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 manufacturing operations on a planetary surface centennialchallenges

Centennial Challenge: 3D Printed Habitat

Objective: Advance additive construction technology needed 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. **Prize Purse Awarded:** $0.04M	**Structural Member:** Demonstrate an additive manufacturing **material** system to create structural components using terrestrial/space based materials and recyclables. **Prize Purse:** $1.1M	**On-Site Habitat:** Building on material technology progress from Phase 2, demonstrate an automated 3D Print System to **build a full-scale habitat**.

Mars Ice House, winner of the Phase I competition from Space Exploration Architecture and Clouds AO

3D Printed Habitat: 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 is run by Bradley University with Caterpillar as the primary sponsor. Additional sponsors include Bechtel Construction Company and Brick & Mortar Ventures.

Challenge Roles

Centennial Challenges (CC): Program Office

Challenge Role: Oversee the execution of the Challenge and ensure that the outcomes meet the overall goals of NASA and the Centennial Challenges program office

Bradley University (BU): Allied Organization

501(c)(3) nonprofit University with comprehensive array of undergraduate and graduate academic programs in business, communications, education, engineering, fine arts, health sciences, liberal arts and sciences, and technology.

- *Challenge Role: Conduct 3D Printed Habitat Challenge in partnership with Caterpillar by control and maintain the rules, organize the judging process, coordinate with judges' schedules, direct incremental levels, logistics, and receive data submittals. AO will also coordinate the registration process.*

Caterpillar (CAT): Challenge Main Sponsor

Technical Challenge Facilitator

- *Private company specializing heavy construction vehicles and machinery*
- *Providing facilities, logistics, and capability to host head-to-head competition*
- *Challenge Role: Assist Bradley in designing the Technical Details of the Challenge. Engage the Technical Communities that can participate as Challenge Competitors, and amplify the Challenge message to the broader Open Innovation Community*
- *Connects organizations with external innovation resources to accelerate innovation in private, public and social sectors*

Challenge Roles

Marshall Space Flight Center (MSFC): Technology Lead

Challenge Role: Subject Matter Experts; Design the Challenge; define desired technology and transition path

Kennedy Space Center (KSC): Technology support

Challenge Role: Subject Matter Experts; Design the Challenge; define desired technology and transition path

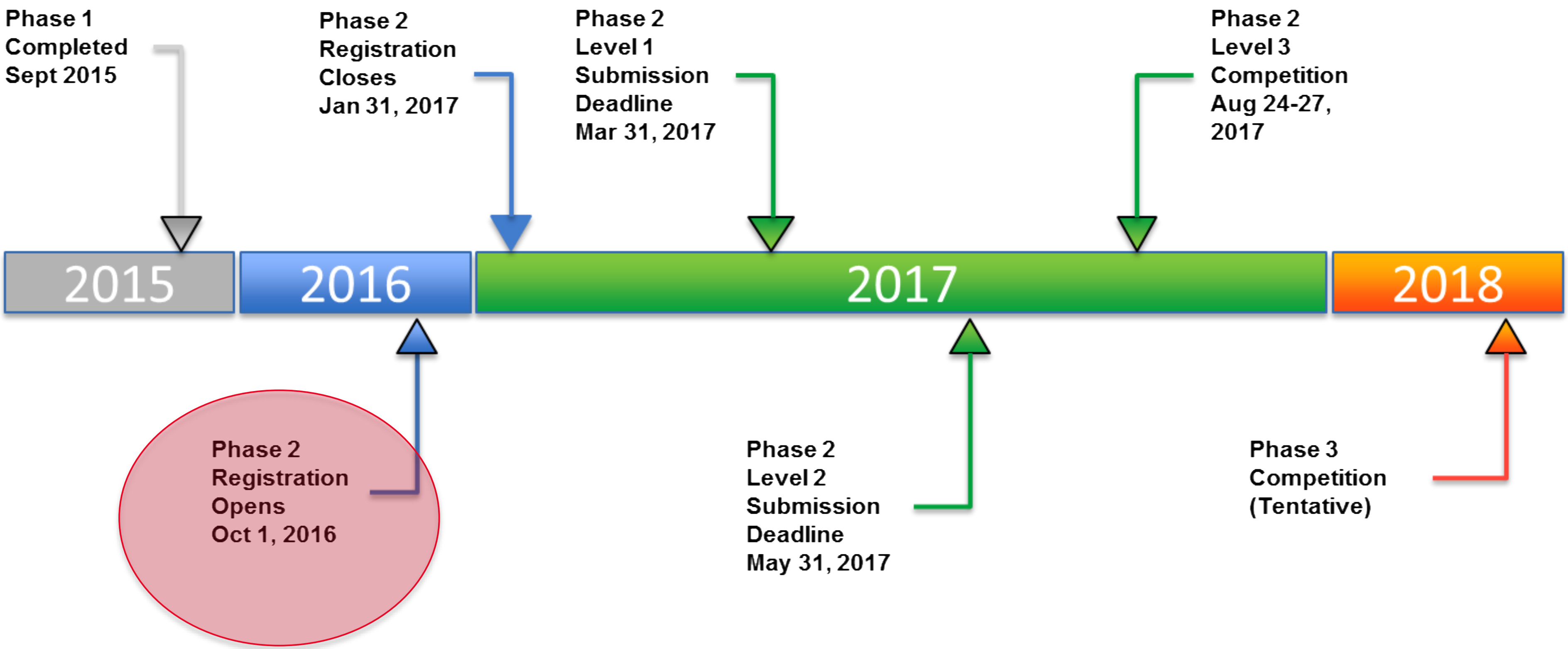
Bechtel:

Challenge Role: Private Company supporting the rules development and potential benefactor for successful competitors. "This type of construction challenge that has been essence of the Bechtel Corporation's more than one hundred years of history. Participating in meeting and overcoming the challenges of inter-planetary construction will help to ensure that our organization will remain an industry leader for the next one hundred years."

Brick & Mortar:

Challenge Role: Private Company supporting the rules development and potential benefactor for successful competitors.

Timeline for All Phases



Phase II Competition: Materials

- One objective of competition is creation of construction materials from indigenous materials and mission waste (polymer recyclables which would otherwise be "nuisance" materials)
- Sliding materials scale rates material based on relevance to planetary missions
  - Teams are penalized for use of imported materials (those that would be transported to earth specifically for construction purposes)
  - 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 for phase II

Phase II Competition: Materials

Material Applicability	Options
Aggregate/ Indigenous	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) GSS - Gypsum sand and siliceous sedimentary rocks (e.g., sand box sand, mudstone) CSR - Carbonaceous sedimentary rocks (e.g., limestone, dolomite) IRS - Igneous rocks with SiO_2 weight percent greater than 57 (e.g., granite) MR - Metamorphic rocks (e.g., slate)
Recyclables	LP - Low Density Polyethylene (#4 recycle code) HP - High Density Polyethylene (#2 recycle code) PT - Polyethylene Terephthalate (#1 recycle code) NY - Nylon (#7 recycle code) PP - Polypropylene (#5 recycle code) AF - Aluminum Foil or ground up aluminum parts PS - Polystyrene (#6 recycle code) VY - Vinyl (#3 recycle code)

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Phase II Competition: Materials

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

- 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)
- GSS - Gypsum sand and siliceous sedimentary rocks (e.g., sand box sand, mudstone)
- CSR - Carbonaceous sedimentary rocks (e.g., limestone, dolomite)
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- MR - Metamorphic rocks (e.g., slate)

- LP - LDPE polyethylene (#4 recycle code)
- HP - HDPE polyethylene (#2 recycle code)
- PT - Polyethylene Terephthalate (#1 recycle code)
- NY - Nylon (#7 recycle code)
- PP - Polypropylene (#5 recycle code)
- AF - Aluminum foil or ground up aluminum parts
- PS - Polystyrene (#6 recycle code)
- VY - Vinyl (#3 recycle code)

3DP Factor calculated based on weighted average

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

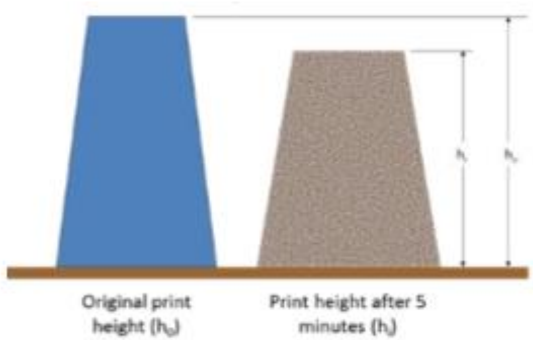
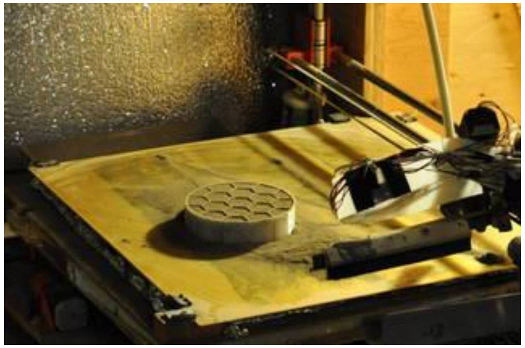


Diagram of slump test

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 at Fairbanks

Phase II Competition: Level 1

Composite Scoring Equation for Level 1 C39 Cylinder Compression Test

$$\{\%mass \times 3DP_{indigenous} + \%mass \times 3Dpfactor_{imported} + \%mass \times 3DP_{recyclable}\}/1000 \times Compressive\ Cylinder\ Load + slump\ test$$

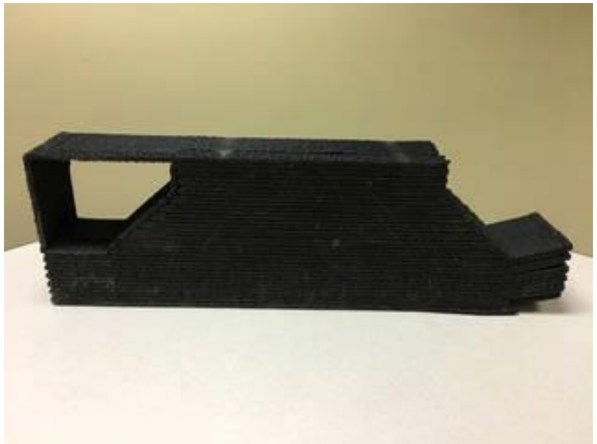
Level 1 Example Score Calculation	Actual Rating	Units	3DP Factor	Weight Multipliers	Level 1 Challenge Points
Use of indigenous materials	80	% mass	5	400	
Use of imported materials	15	% mass	-20	-300	
Use of recyclable materials	0	% mass	7	0	
Use of water	5	% mass	-10	-50	
Measured maximum supported mass from the ASTM C39 compression specimen	454	kg		0.05	23
Truncated cone score (0 or 100)	100	points			100
Total Points					123

Phase II Competition: Level 2

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

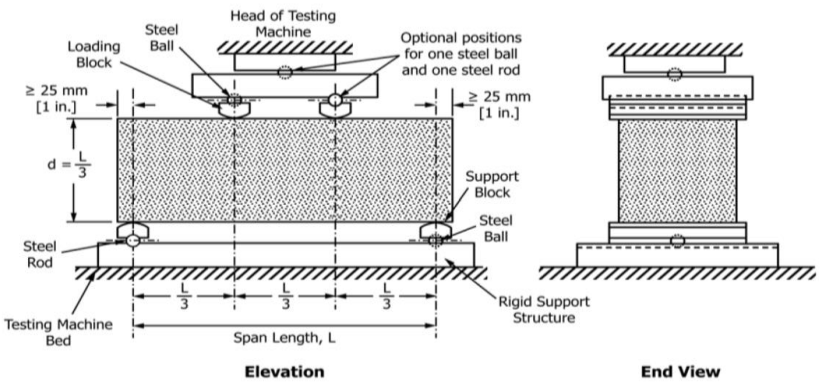
Specimen

- 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+Partners and Branch Technology
    - 4th place: University of Alaska, Fairbanks
    - 5th place: CTL Group
    - 6th place: ROBOCON (Singapore)



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

Phase II Competition: Level 2



$$\frac{\%mass \times 3DP_{indig} + \%mass \times 3DP_{imp} + \%mass \times 3DP_{recyc} + \%mass \times 3DP_{water}}{1000} = DP_{factor}$$

$$Level\ 2\ Score = DP_{factor} \times C78$$

Level 2 Example Score Calculation	Actual Rating	Units	3DP Factor	Weight Multipliers	Level 2 Challenge Points
Use of indigenous materials	80	% mass	5	400	
Use of imported materials	15	% mass	-20	-300	
Use of recyclable materials	0	% mass	7	0	
Use of water	5	% mass	-10	-50	
Measured maximum supported mass from the ASTM C78 flexural specimen	750	kg		0.05	38
Total Points					38

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 (Chattanooga)
    - Penn State

Penn State

MoonX

Branch Technology and Foster + Partners

Phase II Competition: Level 3

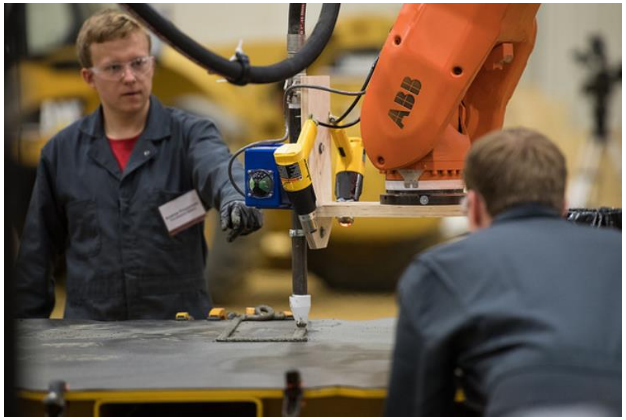
- Specimens for Level 3
  - Three compression cylinders (300 mm in height x 150 mm in diameter) printed onsite and tested per ASTM C39
  - Three flexure specimens (60 cm length x 200 mm height x 100 mm wide cross-section)
  - Dome specimen
- Process flow for competition
  - Day 1: print cylinders and beams (8 hour printing window)
  - Day 2: test cylinders and beams, print dome (12 hour printing window)
  - Day 3: test dome

CAD model of dome

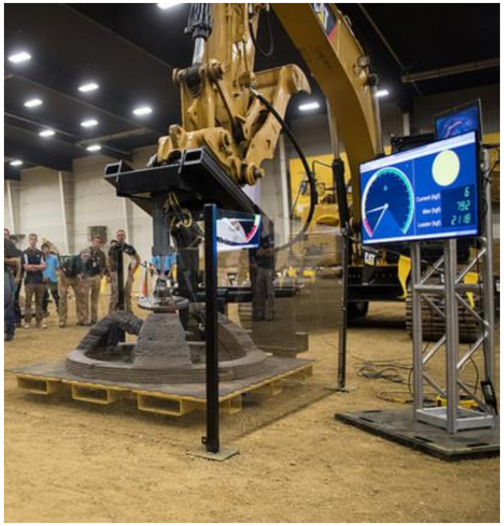
$$\frac{\%mass \times 3DP_{indig} + \%mass \times 3DP_{imp} + \%mass \times 3DP_{recyc} + \%mass \times 3DP_{water}}{1000} = DP_{factor}$$

$$Level\ 3\ Score = DP_{factor} \times \left\{ \frac{C39_{avg}}{10} + C78_{avg} + (Dome \times 10) \right\}$$

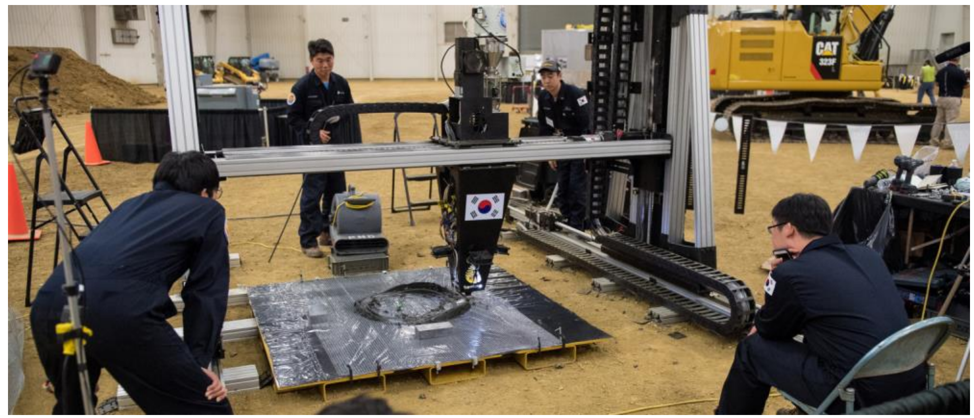
Phase II Competition: Level 3
Penn State

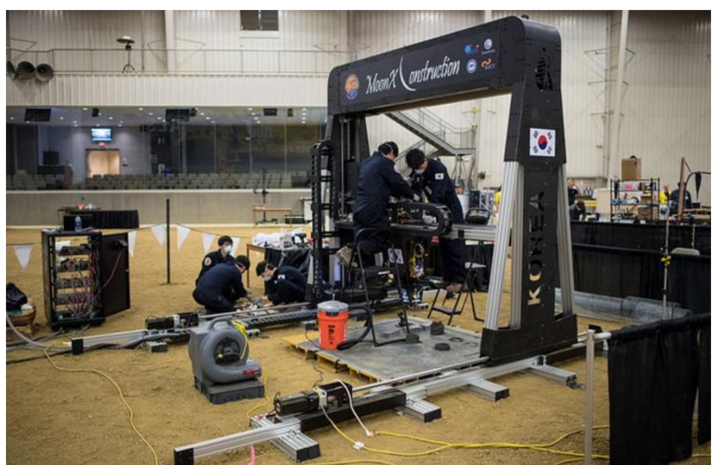





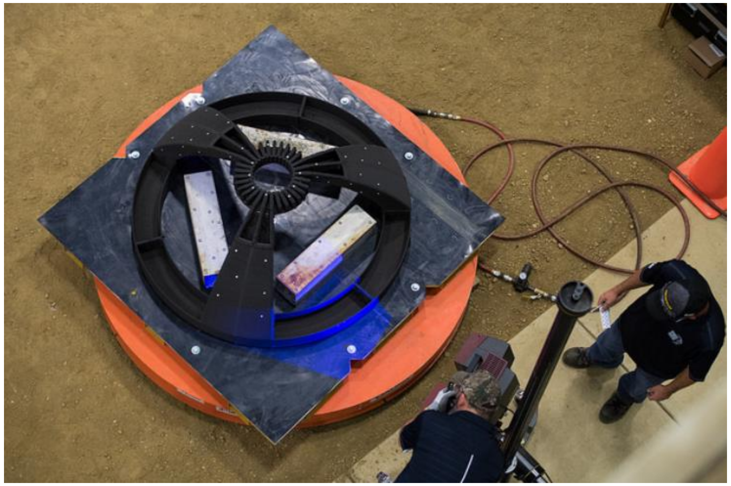



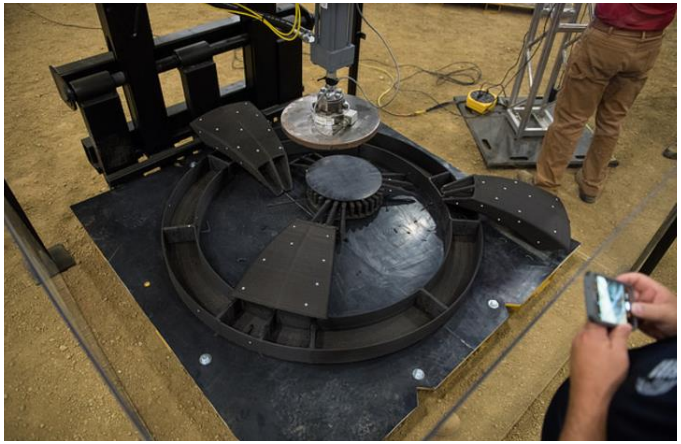
Phase II Competition: Level 3
MoonX





Phase II Competition: Level 3
Foster + Partners and Branch Technology





Phase II Competition: Level 3 Results

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

2nd place, $150,000: Penn State University

Significance of the 3D Printed Habitat Challenge

- Challenge was successful in spurring innovation in the materials, processes, and manufacturing systems needed to manufacture an off-world habitat using mission recycled materials and/or indigenous materials.

- The construction industry is a 3 trillion dollar per year industry and technology advancements made through this challenge may provide beneficial new solutions for revitalizing infrastructure, providing cheaper housing, and enabling improved disaster response.

- Scaleability is the major challenge that will be addressed through the phase III competition.
- 3D-Printed Habitat Challenge Phase 3, Request for Information: www.fbo.gov/index?s=opportunity&mode=form&id=7e5f6badeb0c51cd88a65ea59789495f&tab=core&_cview=0