TOWARD A 3D PRINTED LUNAR VILLAGE

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Image: F+P, ESA

OVERVIEW

- **Results of the past experience (the 2010 lunar 3D printing ESA project)**
- **Our goals, in the frame of the 2020 - 2030 Moon program: using in-situ resources as much as possible, and minimizing the amount of materials to be delivered from Earth**
- **Trade-off, and possibly choose, among possible alternative technologies**
- **Experimenting a few technological concepts**
- **Inflatable structure, internal to the habitat**

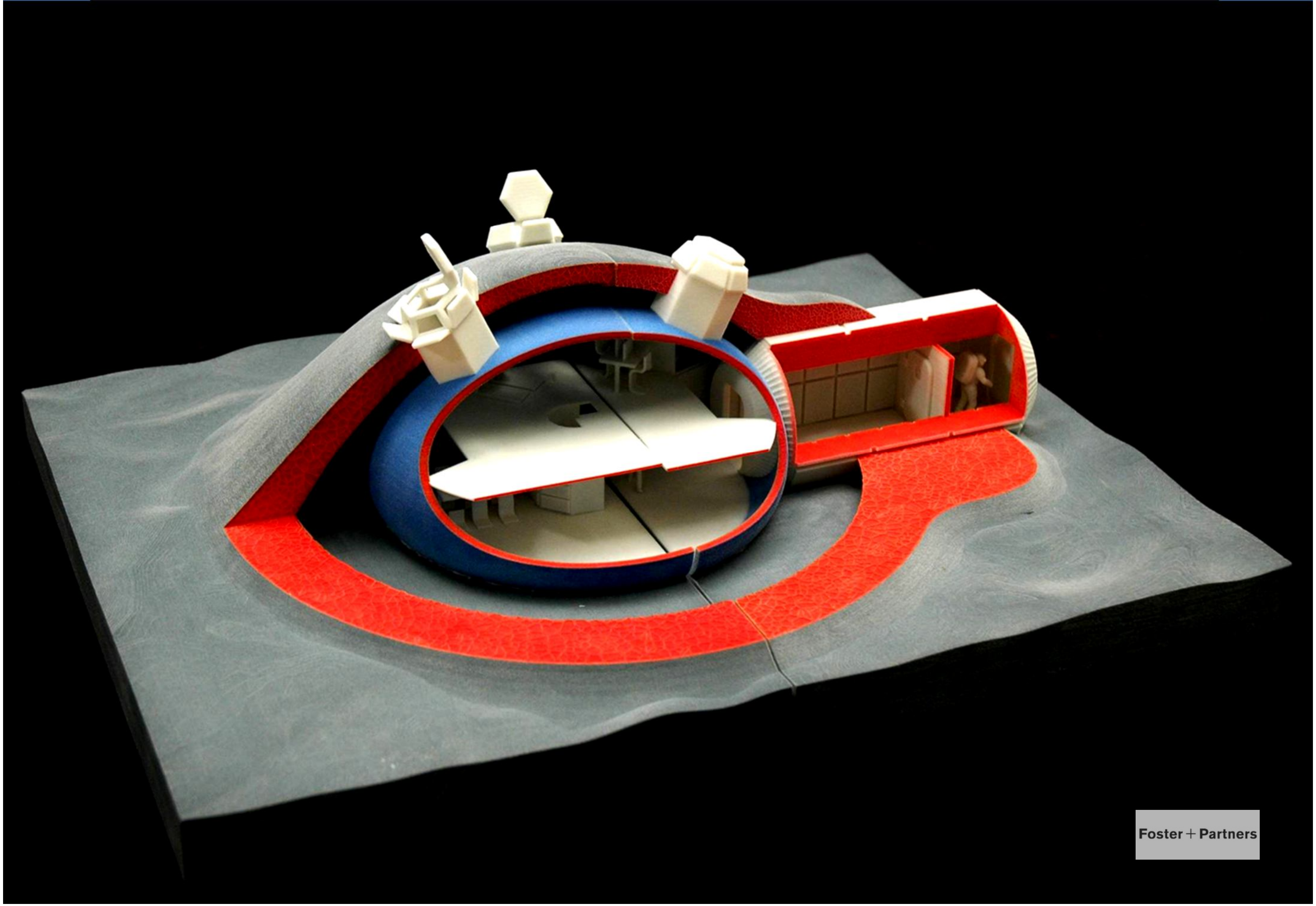
THE PAST EXPERIENCE (2010)

- 2009 ESA awarded a General Study contract to assess the 3D printing concept as a potential way to build habitats on the Moon using lunar regolith.
- The industrial consortium, formed by Alta SpA (now SITAEL SpA), Monolite UK Ltd., Foster+Partners and Scuola Superiore Sant'Anna, merged knowledge in space technology development, 3-D printing at building scale, complex architectural design, and robotics.
- Tests in air and under vacuum demonstrated the reticulation process using the regolith simulant.
- The prevention of the binder evaporation or freezing in vacuum was proofed, by adopting a proper injection method and a newly formulated chemical binder.
- Tests of mechanical properties were made on pieces of the reticulated "concrete".
- The test results were entry data for a preliminary design of a lunar habitat, that was made at Foster+Partners.
- A section of the outpost wall was manufactured at full scale using the D_SHAPE printer and the regolith simulant.
- Within the outputs of the study, guidelines have been developed for future spatialization and automation of the printer and for design and 3D printing of the outpost.

http://www.fosterandpartners.com/practice-data/videos/#&vid=100091043

TOWARD A 3D PRINTED LUNAR VILLAGE

→ MOON 2020-2030



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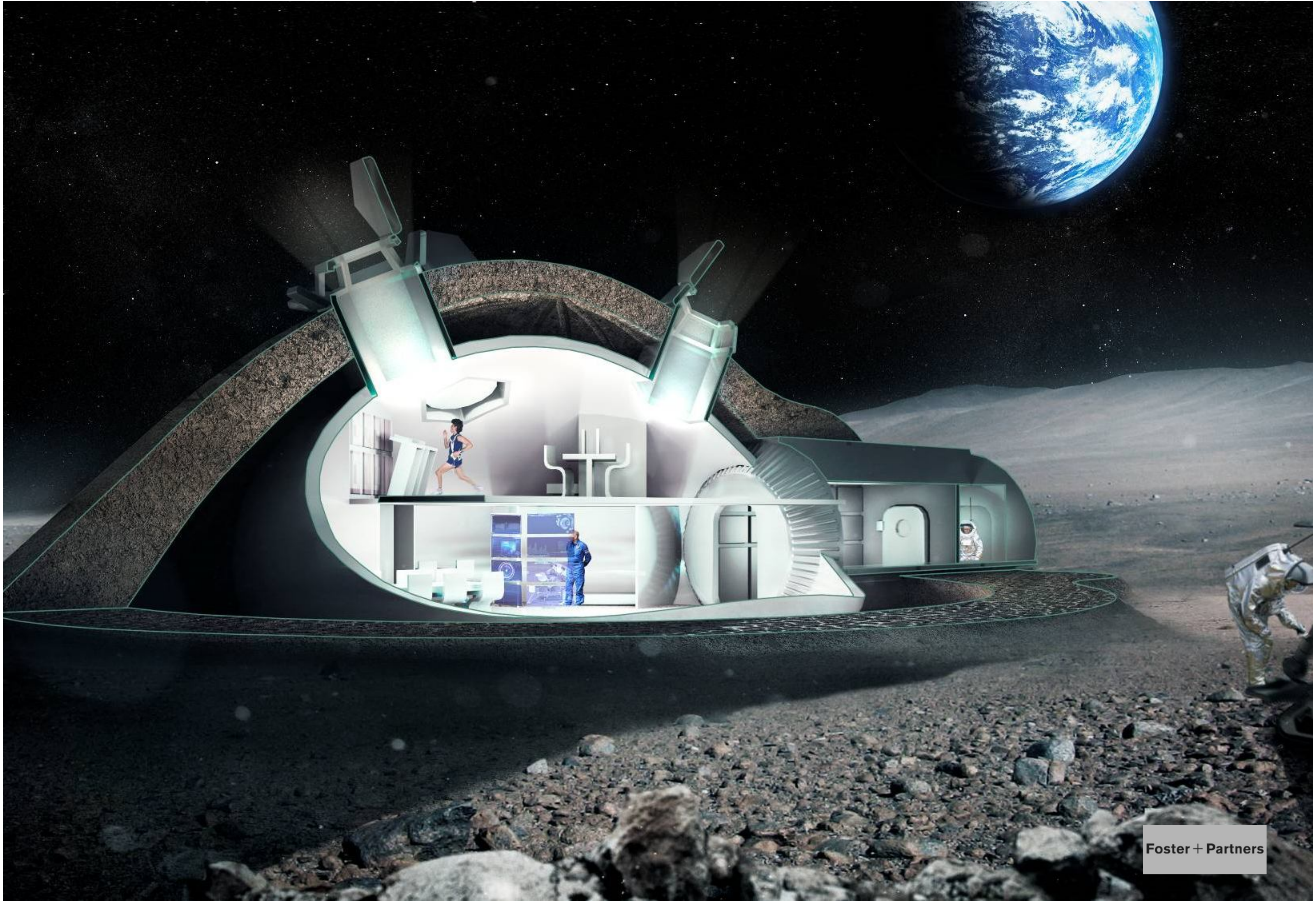
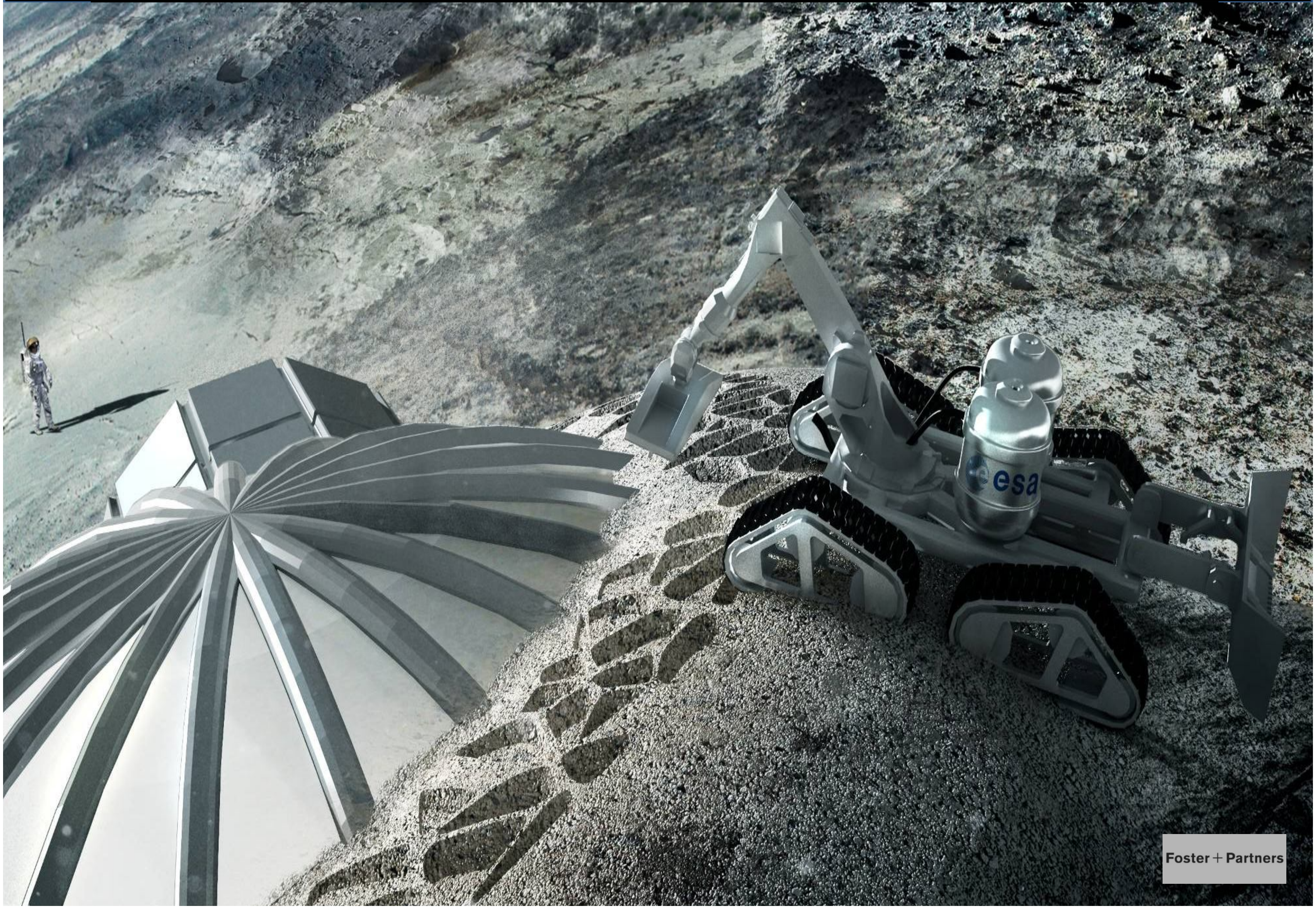
TOWARD A 3D PRINTED LUNAR VILLAGE

→ MOON 2020-2030



TOWARD A 3D PRINTED LUNAR VILLAGE

→ MOON 2020-2030



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d-shape

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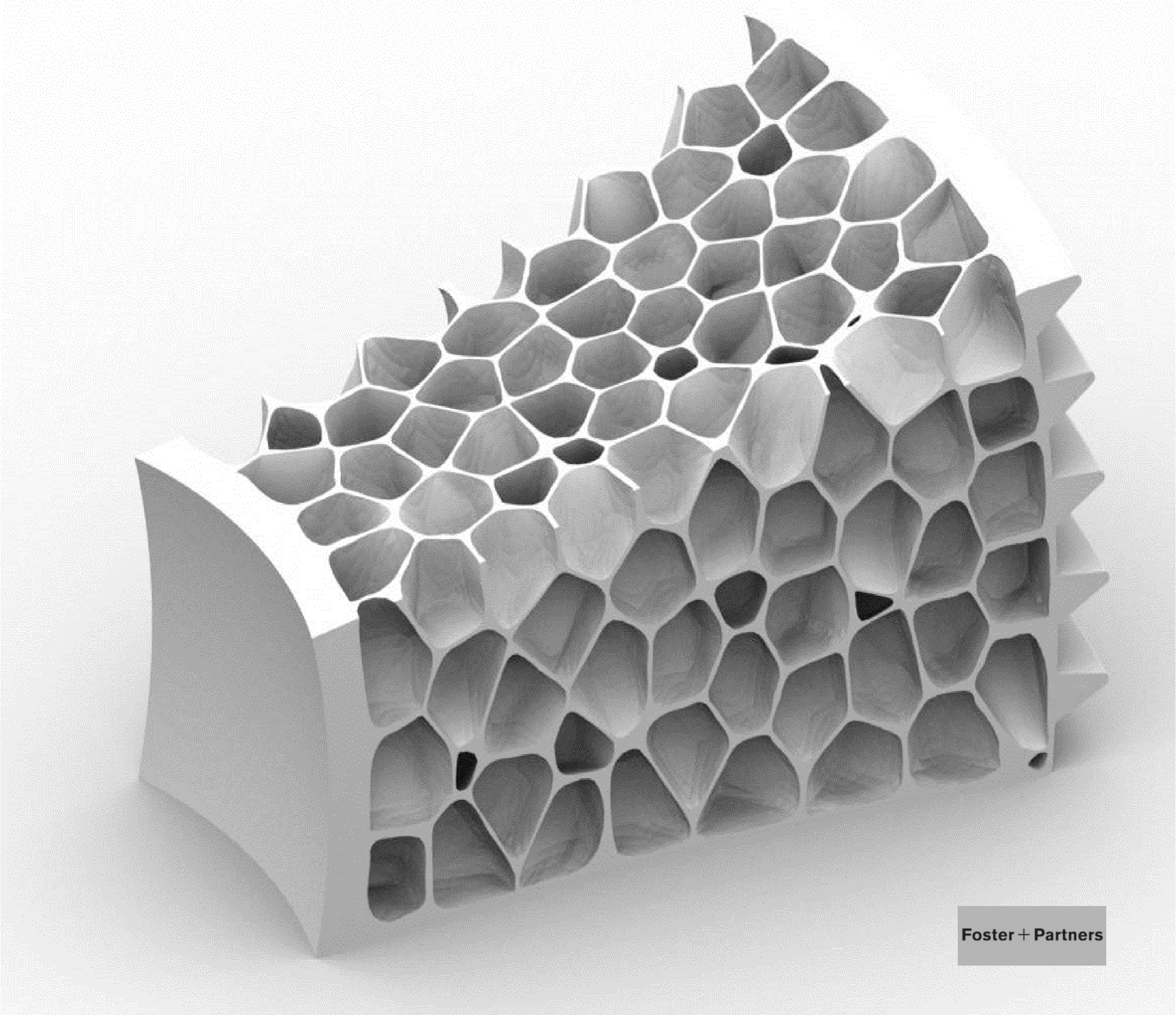
TOWARD A 3D PRINTED LUNAR VILLAGE

→ MOON 2020-2030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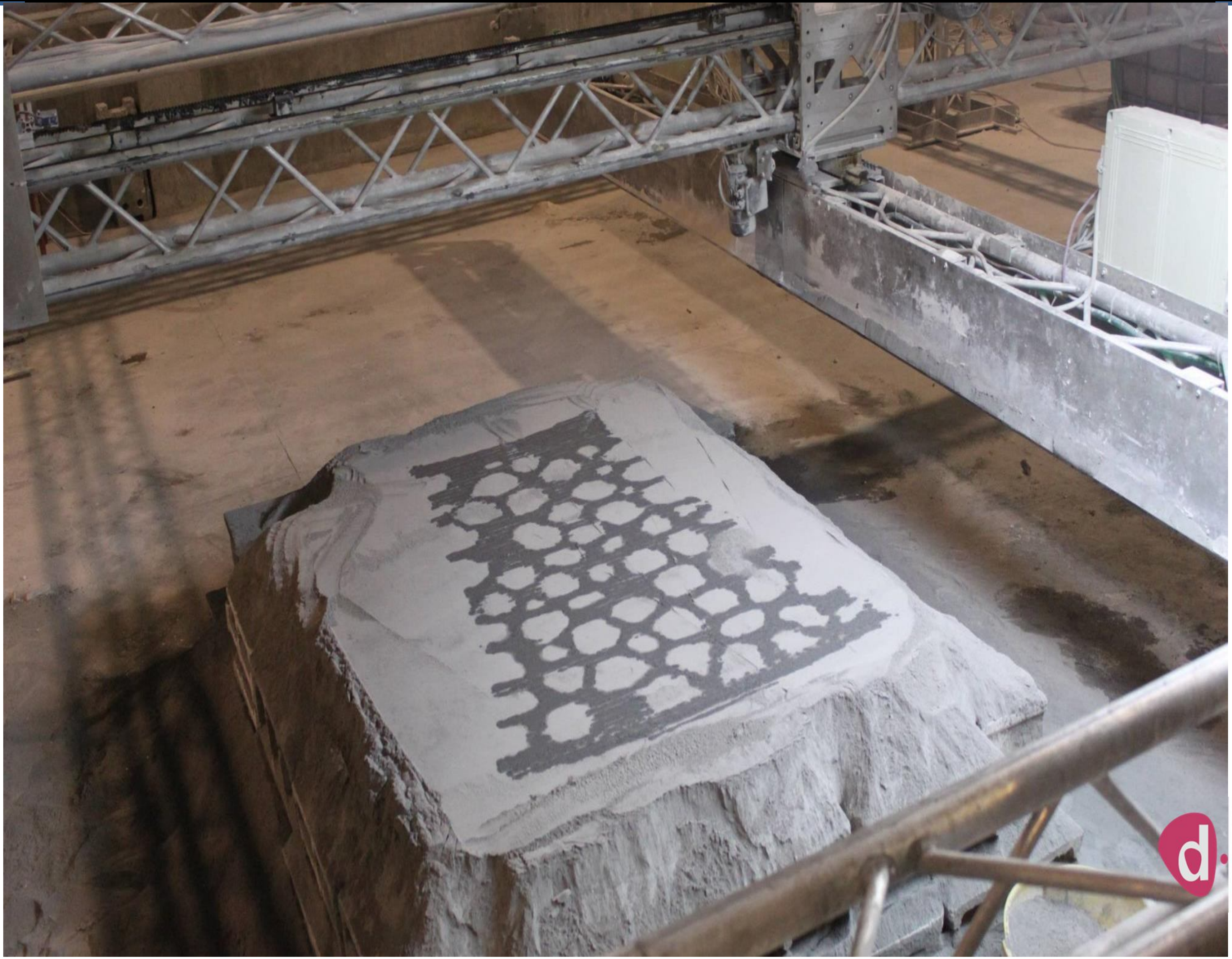
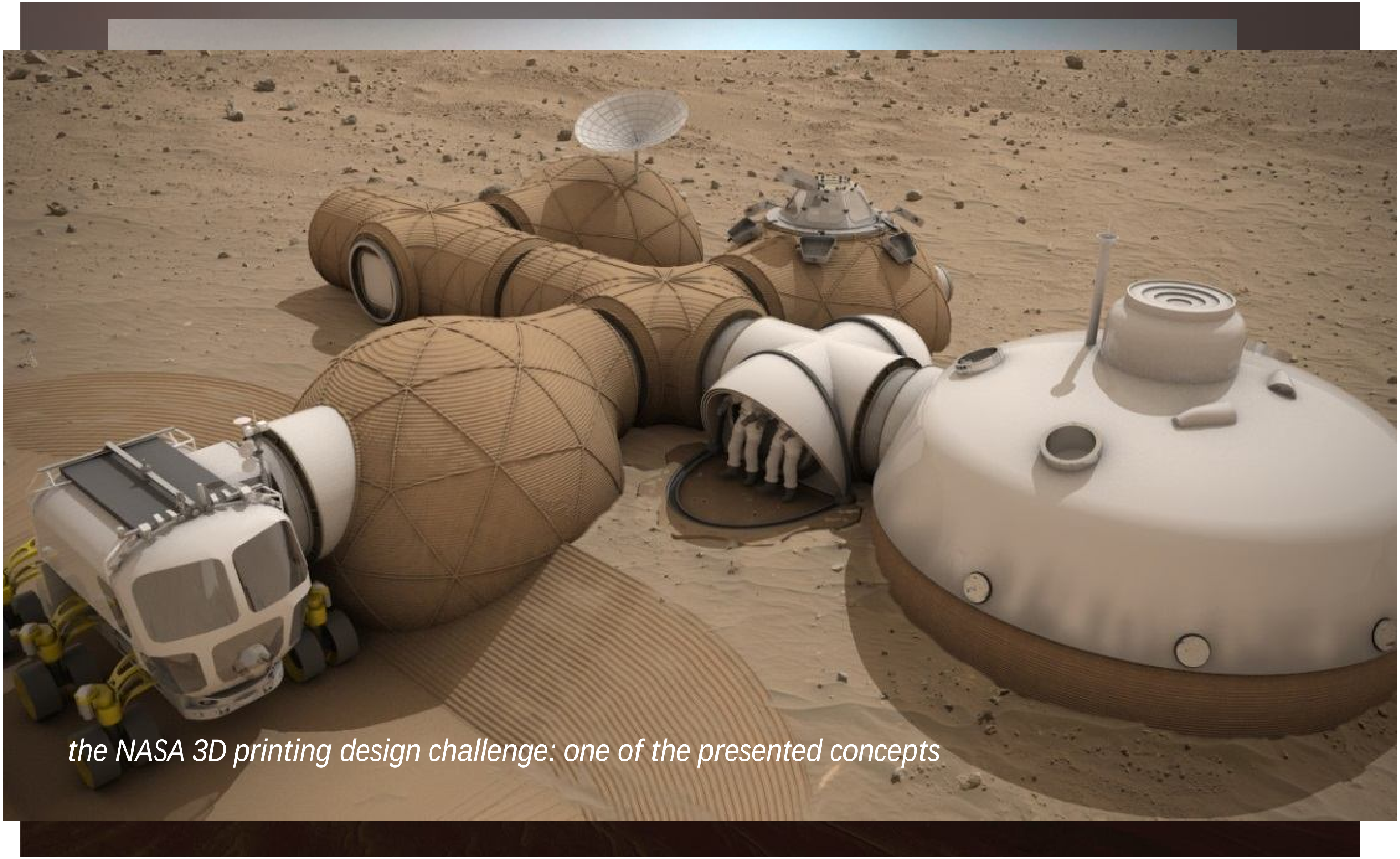


A CONCEPTUAL BIG BANG



the NASA 3D printing design challenge: one of the presented concepts

OUR GOALS, FOR 2020 - 2030 MOON PROGRAM

- In space missions the weight of materials is of big relevance
- Specifically the cost per kg sent from Earth to the Moon will be around $400-600,000/kg.
- Therefore every kg optimized represents an economic advantage but also an operational advantage for the space carrier.
- In order to achieve the above goals, two technologies should be quickly but attentively investigated, at least:
  - **SLS technology** (sintering by laser beam)(1)(2)
  - **Agglomerate technology** (polymer mortar, mineral binder)

(1) Marcus Kaiser (https://www.youtube.com/watch?v=Tsk-24UYFs0)

(2) Takashi Nakamura (http://www.psicorp.com/pdf/library/VG09-193.pdf)

CRITICAL POINTS OF THE RESEARCH

- SLS seems the most promising technology, being already used by several years in various fields of production, but the following issues are still open:
  - understanding the solar energy available on the moon, particularly in the sites target of the settlement
  - the energy requirements of an equipment suitable to mold habitat modules of considerable size.
- The agglomerated solution is based on a paste, composed by a reticulable and flushable mineral (lunar regolith), according to the 3d printing procedures,
- using a heterogeneous mixture of two components: mineral filler and polymeric binder, in weight 95-5; 90-10 ; 85-15
- Compared to today's D-shape technology, such solution will not require the use of water and magnesium chloride (MgCl2).

THE “POLY-U-REGOLITHE”

- The Poly-U-Regolithe approach to lunar habitat constructions includes the following items:
  - **lunar regolith**
  - **polyurethane chemistry**
  - **inflatable containment structures**
  - **3d printing**

AGGLOMERATE TECHNOLOGY

PLUS	MINUS
does not require water	it requires temperature calibration timing of reticolation
low steam pressure	high viscosity at low temperatures
low agglomeration Tg (-50 : -70 ° C)	mixing and fluxing polymer paste
it reticulates even in the absence of oxygen	Fluxing catalyst mixture in the polymer paste
it reticulates even in the absence of water (both liquid and vapor)	
good mechanical properties at low temperature	
excellent properties of adhesion on the surfaces	

OVERVIEW METHODOLOGY AND FORMULATIONS

INSTITUTE
OF COMMUNICATION,
INFORMATION
AND PERCEPTION
TECHNOLOGIES

Scuola Superiore
Sant'Anna

Liquid polyurethane precursors has been a viable method to tackle some problems in lunar regolith handling. The formulations and methods are two fundamentally:

- Liquid Polyurethane blending with regolith to produce building blocks by mold
- Polyurethane foam by expansion of polymer inside inflatable mold

Polyurethane-regolith blocks
by *Adherent Technologies Inc.*

Inflatable mold by Adherent Technologies Inc.

THESE ITEMS CAN BE USED AS RETAINING WALLS OR IN THE BUILDING OF COVERED RADIATION SHELTERS FOR LUNAR HABITAT

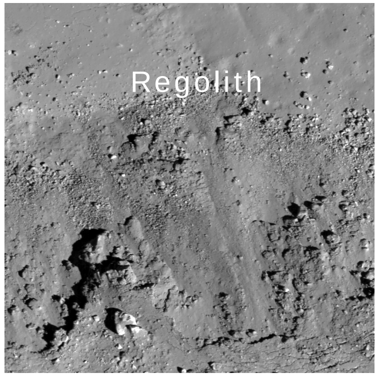
The methodology for the production of foam stabilized inflatables in a vacuum environment was a major technological breakthrough

Drums bicomponent polyurethane

It allows the production of very large lightweight structures in space environment carrying from Earth the minimal amount in mass of building materials in fact typical drums (A and B) can allow to fill around 90 m^{3}of volume

Foam expansion

AGGLOMERATE POLYURETHANE FOAM



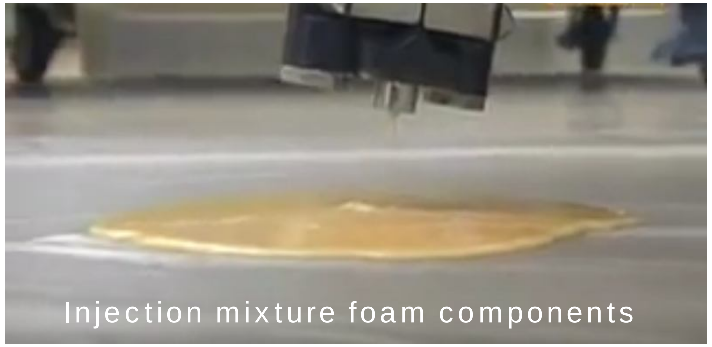
Bicomponent polyurethane foam

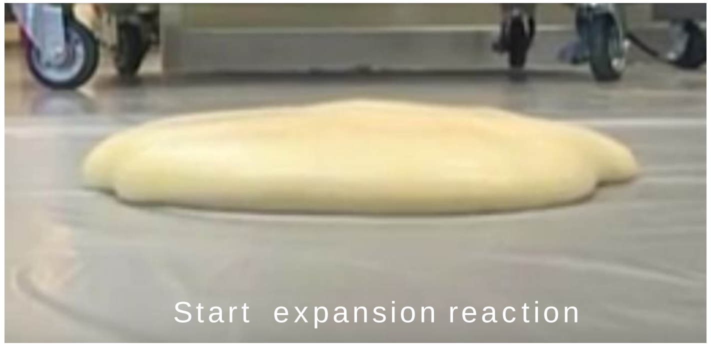
Before curing reaction

Regular shape by mold

Expansion inflatable structure

POLYURETHANE FOAM EXPANSION

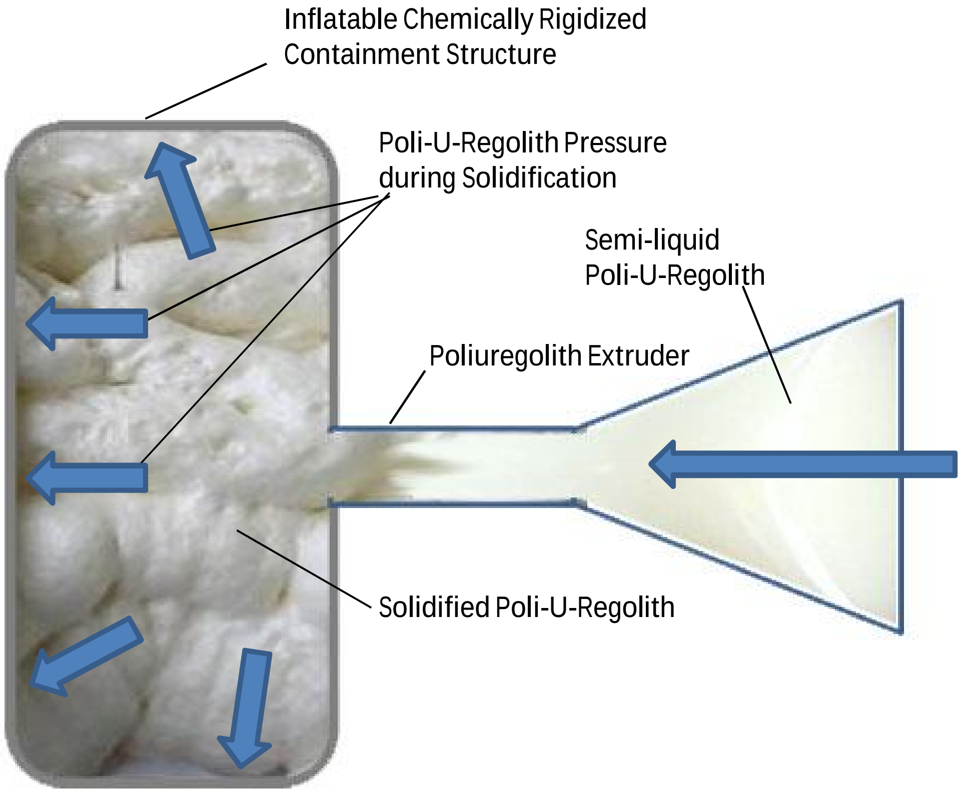

Injection mixture foam components


Start expansion reaction

Typical expansion rate
1:100 times of liquid
1:200 times of liquid
1:300 times of liquid

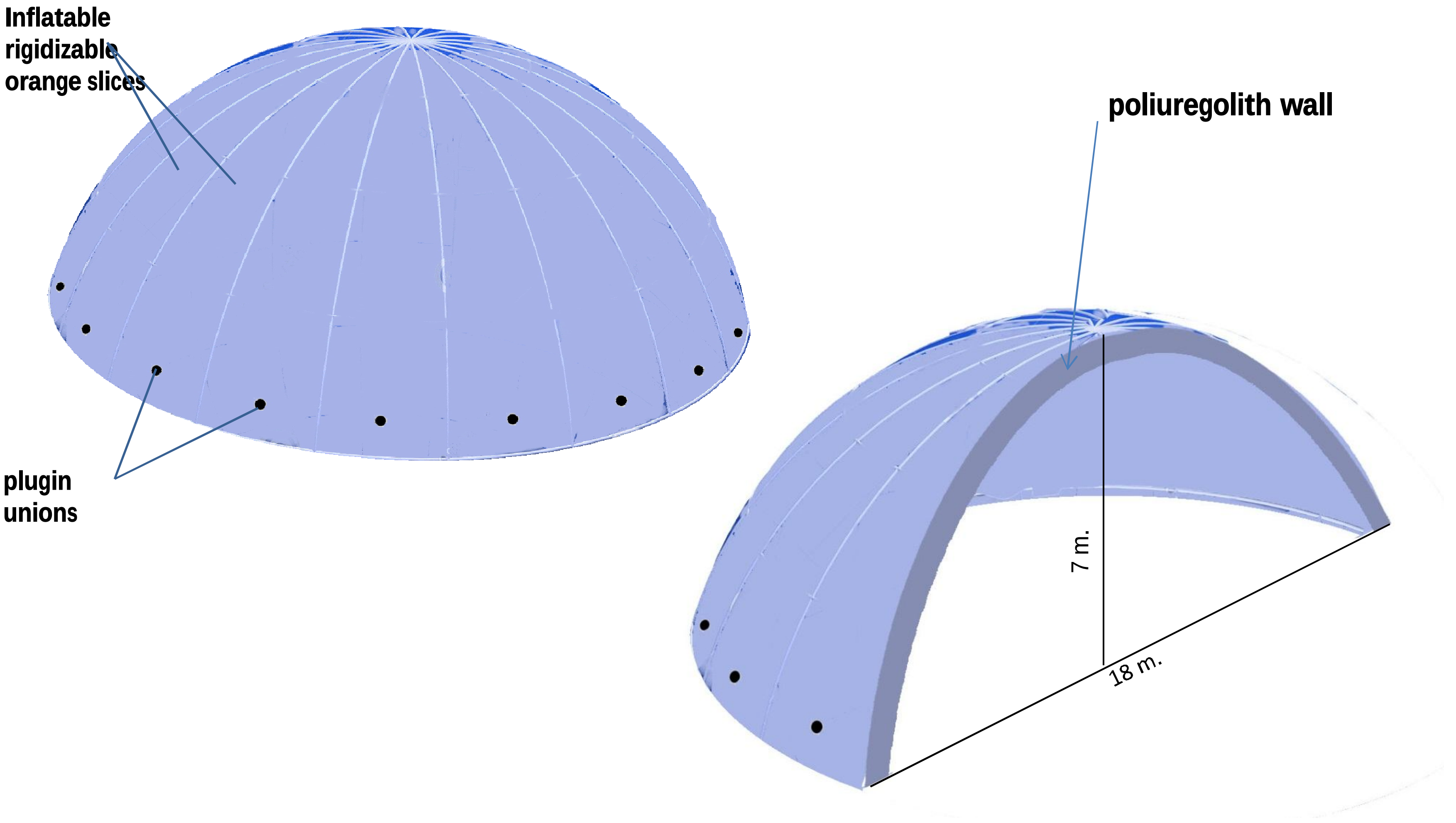

Finished expansion reaction

INFLATABLE CONTAINMENT STRUCTURES



The Poli-U-Regolith expansion process inside ICRS

LUNAR “ORANGE SLICES DOME”

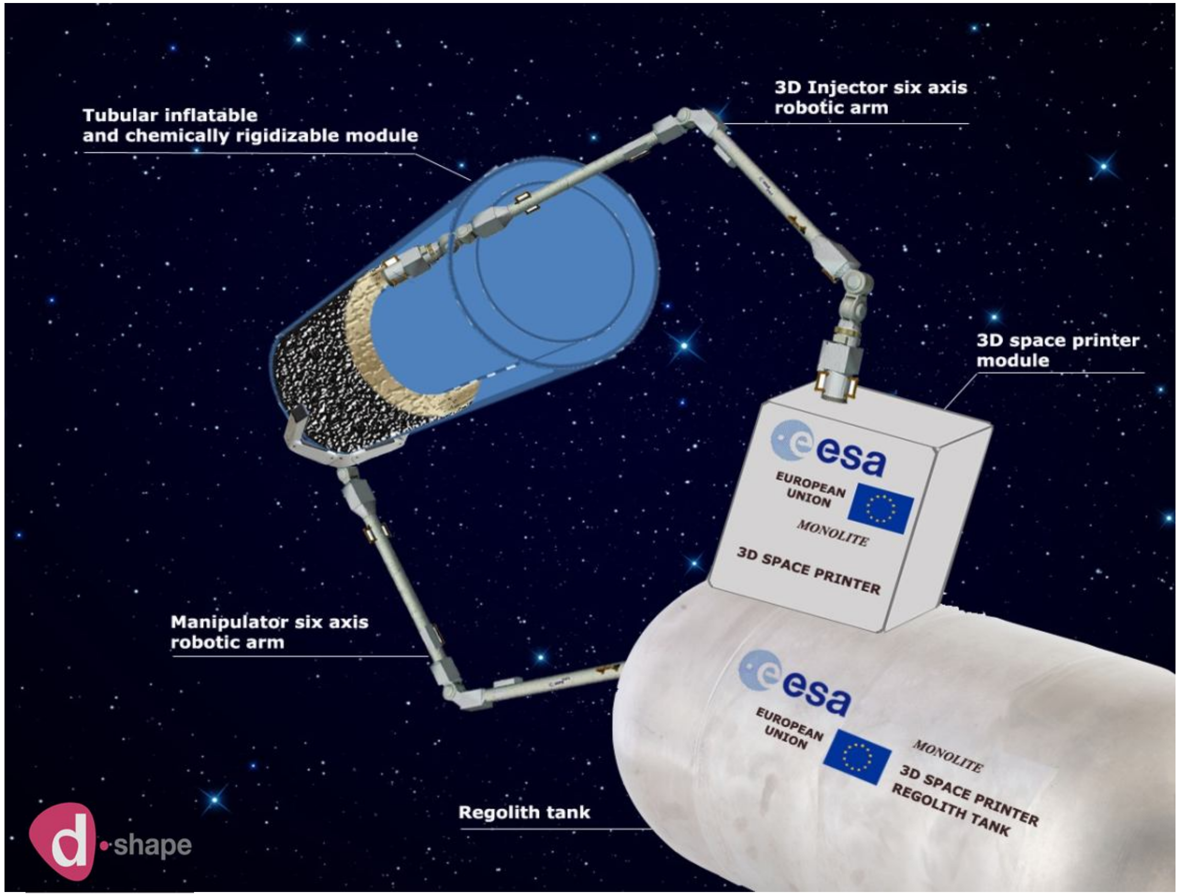


Inflatable rigidizable orange slices

poliuregolith wall

plugin unions

3D PRINTING AT ZERO G, VACUUM CONDITIONS



“Polyuregolith” Building Blocks
Study Contribution

Compliant Containment Structures for Rigidizable Lunar Regolith Building Blocks

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CONTAINMENT STRUCTURES – SOME DESIGN CONSIDERATIONS

- Module types
- Compliant-structures approach
    - materials
    - geometry & design outline
    - deployment aspects
- Preliminary estimates
    - Mass
    - Packaging

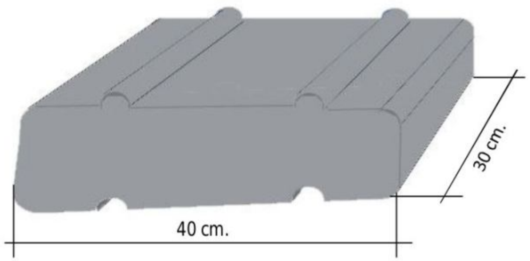
CONTAINMENT STRUCTURES: PURPOSE & TYPES

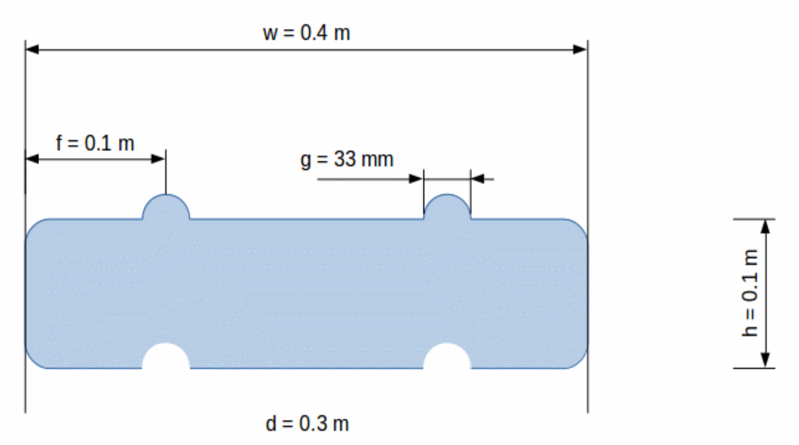
- The containment structures serve to shape the regolith mixture during its setting process
- They receive the activated “fluidized” material, interacting with
    - the dispensing devices (e.g. robot arm support, plus...)
    - regolith mixture during the trasfer, and
    - during the expansion and setting stages
- May have to support thermal control of the ensemble, assist release of reaction gases, ...
- Three types of structures considered
    - basic building block
    - “Orange Slices Dome” lunar habitat module
    - zero-g habitat module

A COMPLIANT-STRUCTURES APPROACH

- The team has suggested a flexible-wall (inflatable) structure approach, possibly to undergo a rigidification step of its own
- The content for the structures and associated inertia loads mark these as heavy-duty expandable structures (HEDES), but with limited pressurization loads
- If compared to an inflatable habitat structure's wall, these items combine the bladder function with the anti-scuff layers; reinforcement serves to limit shape deviations under active loads
- First suggestion for the wall laminate:
    - Hypalon bladder
    - reinforcement by a polyethylene cloth or aramid grid
    - scuff-protection film (internal)
    - thermal-control film (outside)
- Low pressure, low strain inflation deployment, with mitral valves giving access to the dispensing devices while maintaining inside pressure
- Mainly relying of inherent stiffness (and residual pressure) to keep deployed shape in the space environment

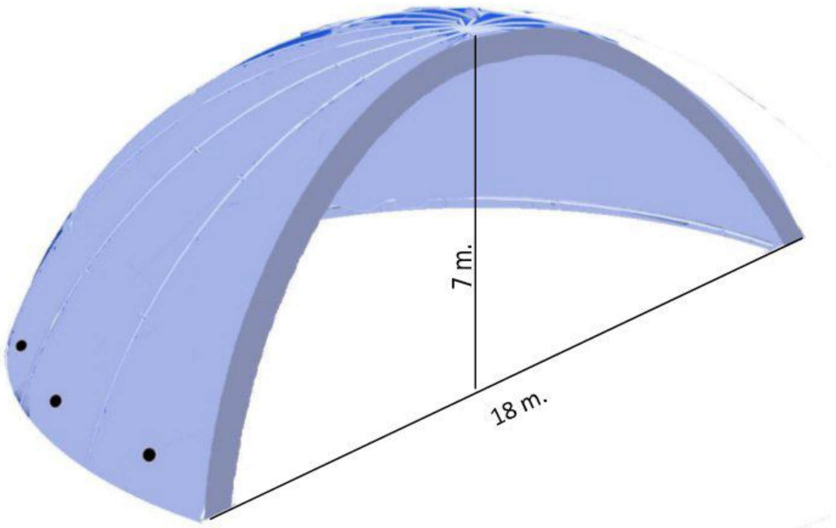
GEOMETRIC OUTLINE: THE BASIC BUILDING BLOCK





- Basically a parallelepiped with roundings on the four shorter edges, assumed having the same radius as that of the nubs and groves on the larger faces
- Geometric parameters:
    - area 0.4134 m^2
    - volume 0.0119 m^3

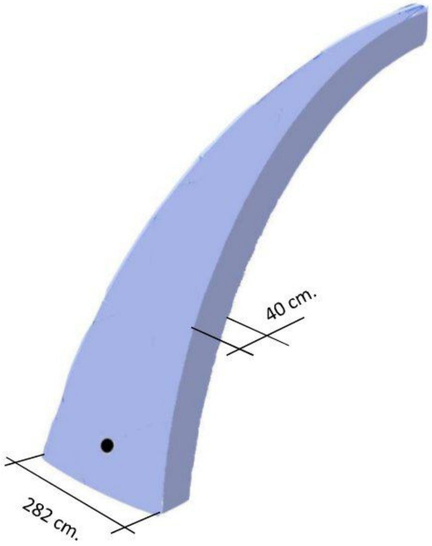
GEOMETRIC OUTLINE: THE “ORANGE SLICES DOME”

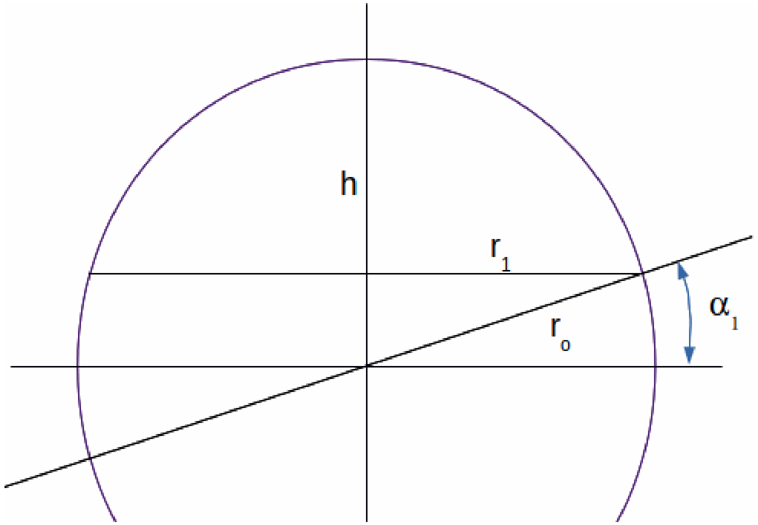


- Follows the geometry of a spherical cap
- From the subdivision of the cap into n slices results the actual modular element
- A pole hole of finite radius appears opportune for assemblying the cap – its radius was not indicated
- The meridian arc, α_o, over the cap can be estimated as:

$$\alpha_o = \frac{\pi}{2} - \alpha_1 = \frac{\pi}{2} - \arctan\left(\frac{r_1^2 - h^2}{2 h r_1}\right)$$

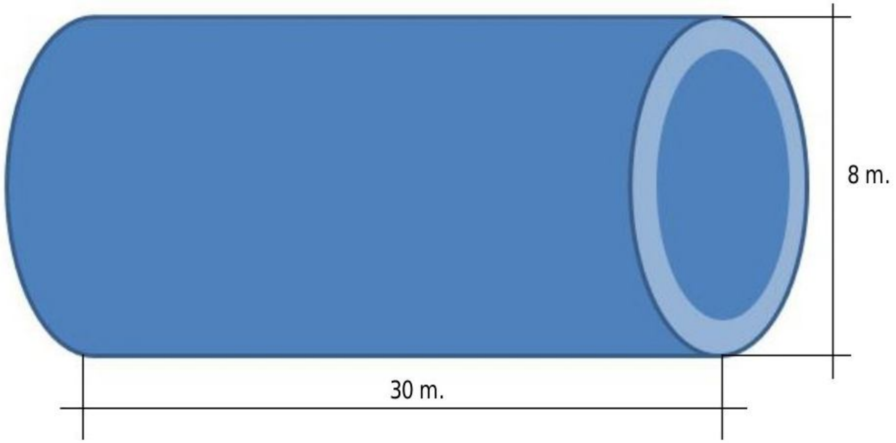
THE SLICE GEOMETRY





- Geometric parameters:
    - sphere radius 9.286 m
    - meridian arc length 1.3221 radians
    - slice area 49.701 m^2
    - slice volume 7.6471 m^3

GEOMETRIC OUTLINE: THE ZERO-G HABITAT MODULE



- A cylindrical shell, with a wall thickness taken (conservatively) at 0.8 m
- To arrive at the required shape, *m* radial webs have to connect the two cylindrical membranes (not gas-tight, e.g. *m* = 36)
- Geometric parameters:
  - area 1393.359 m^2
  - radial webs area 864.0 m^2
  - volume 542.867 m^3

LAMINATE APPROACH

- Reinforcements limit deviations from the prescribed shape under active loads: a 0.1% strain guideline (under deployment pressurization loads) used here
- A sample laminate construction:

	Material	No of layers	Thickness [mm]	Area Mass [kg/m^2]	Membrane Stiffne [MN/m]
Bladder sublaminate "Tunnel"			(0.060)	(0.123)	(0.078)
Gas barrier	Plastic film (e.g. Aclar)	2	0.025	0.105	0.068
Adhesive		1		0.018	0.010
Restraint sublaminate "Tunnel"			(0.11)	(0.130)	(4.010)
Structure	high-strength fibre fabrics plies	1	0.1	0.112	4.000
Adhesive		1			0.010
Meteoroid protection sublaminate (omitted)					
Inner cover sublaminate			(0.060)	(0.104)	(0.220)
Scuff layer	Plastic film (e.g. Torelina)	2	0.025	0.068	0.200
Adhesive		2			0.020
Outer cover sublaminate			(0.035)	(0.058)	(0.085)
Thermal layer	Plastic film (high emissivity/ ssm)	1	0.025	.040	0.075
Adhesive		1	0.01	.018	0.010
	Total		**0.265**	**0.315**	**4.393**

DEPLOYMENT ASPECTS

- Upon release from packaging restraint, elastic energy stored in the structure's wall initiates the deployment, together with the residual gas
- Pressurization then begins to deploy the object fully
- Critical parameter: residual-gas-control ratio, η_r – i.e., the gas mass remaining within the stowed structure relative to the gas mass in the deployed volume, at barometric pressure.
- While residual pressure has a negligible import for a pressurized shelter, the containment elements represent a rather novel combination of parameters
- By the full pressurization, the structure acquires a measure of stiffness: under space conditions this may well suffice (in combination with partial pressure levels) to provide the shaped volume for receiving the regolith mixture.

PRELIMINARY ESTIMATES

- A first estimate of various geometric design properties of the containment structures for realizing the proposed items confirms that they represent quite substantial elements
- The stowage volume estimates are generic ones, based on a 10%-packaging efficiency
- Mass values below do not include any considerations for seams, pressurant marges, gas bottles, packaging ancillaries, interfaces, or control items

Module	**Containment Structure's Mass [kg]**	**Inflation Pressure [kPa]**	**Unit Gas Mass [kg]**	**Stowage Volume [m3]**
Basic Building Block	0.130	33	0.005	0.0011
Dome Slice (single)	15.656	1	0.090	0.132
Orange Slices Dome (full)	313.116	1	1.809	2.634
Zero-G Habitat Module	499.388	1	7.453	4.124