INTRODUCTION

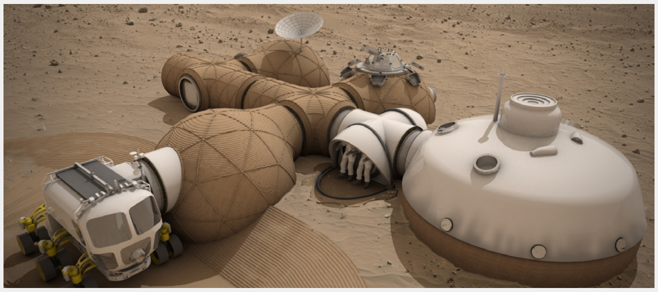


Figure 1 – *Render of the LavaHive concept*

LAVAHIVE is a modular additive-manufactured Martian habitat concept using a proposed novel 'lava-casting' construction technique and utilizing recycled space-craft materials and structures. Our approach represents a realistic response to the design challenge of the competition, and introduces a number of innovative ideas, leveraging the unique experience of our consortia members who are active in application research for these technologies.

Our proposed habitat concept has a number of novel innovations:

- Re-use of commonly discarded Entry, Descent and Landing (EDL) systems, the re-entry back-shell, as part of the central habitat section, providing the housing for mission critical mission elements and personnel and reducing the mission mass requirements.

- 3D printed satellite structures feeding off from the main central habitat, with configurable orientations to suit the mission requirements and terrain.

- Unique use of regolith sintering combined with the novel 'LavaCast' technique, a 3D print methodology, to produce solid basalt structures.

An interpretation of our concept can be seen in the render (fig. 1). A primary central dome, housing critical crew areas and mission critical systems, is connected to a number of smaller ancillary dome structures. This central element will be brought from Earth and will form the core of the habitat. The smaller domes are connected via 3D printed passageways to the central dome and house laboratories, a greenhouse, garage, airlock and other required working areas.

Our understanding and examination of state of the art technologies led us to develop a concept and fabrication approach that would erect free standing 3D printed structures using direct energy input to Martian regolith material. We purposely avoid the use of any binders or additive materials, as we consider the down mass requirement to Mars prohibitive and many aspects, such as thermal cycling, unproven for these approaches. A combination of sintering and melting of regolith emerged as our process of choice.

Our architectural inspiration was driven by beehive huts (Clochán) of the Irish monastic sites and by the traditional South Italian "Trulli". These are ancient domed houses with prehistoric origins, built using the abundant stone materials from the surrounding land, a true example of in-situ resource utilisation (ISRU) on Earth. In order to render the interiors of these houses hygienic and clean, a plaster made of reddish clay soil and pieces of straw mixed with slaked lime was used, similar to our proposed use of epoxy for sealing the inside of our 3D printed structures. The result is an earthquake-proof construction that, thanks to the thermal inertia of the thick walls, provides a cool environment in hot weather and keeps warm in winter.

In this proposal, we will outline our architectural concept and detail our fabrication process. Throughout, we aim to address aspects of the competition, detailing our novel 3D print approach, mission implementation and site selection. Our team highly values a realistic and achievable implementation, which we hope to impress throughout this proposal.

MISSION CONCEPT

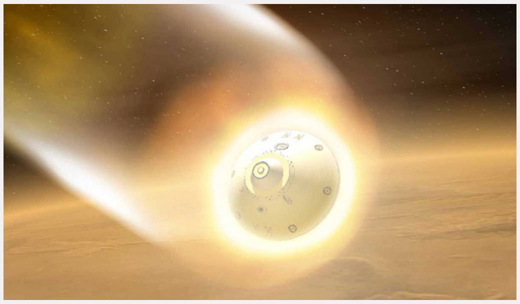


Figure 2 – *Mars Exploration Rover Aeroshell (artists rendition) [6]*

On arrival in the Mars vicinity, the delivery vehicle will detach the EDL system containing the two surface rovers and the central habitat section. The payload will descend and land within range of the preferred site via standard parachute. Two construction rovers will also be included in this payload, which will be used for the 3D construction process. When the entry capsule comes to rest on site, the underside inflatable habitat will deploy. This forms the nexus for the development of the other desired 3D printed structures.

While it is tempting to construct the main habitat in a similar way as the satellite domes, we feel that a terrestrially provided solution has a lower risk overall and offers a number of advantages, such as assured structural integrity as well as housing essential functionality such as Environmental Control and Life Support System (ECLSS) and enviromental sealing of the habitat. The back-shell from the EDL system will be recycled as the roof of this central habitat. This will be used to reinforce and protect the inflatable structure that deploys underneath from hazards such as micrometeorites and radiation. Landing within range of our targeted site, two autonomous rovers will be utilized to begin the preparation of the area for the expansion of the base. The rovers will identify the local fine regolith sources available from aeolian deposits such as craters and beds. Transporting these to the base site, the sintering capable rover will begin the production of the foundations for the smaller habitat sections. The second lava casting robot will then prepare the foundation for the structure. These rovers will then work in tandem to begin the fabrication of the habitat sections and connecting corridors using in-situ resources. Once arrived, astronauts will perform final construction operations either autonomously/tele-robotically from Mars Orbit or from the surface, installing mission elements brought from orbit (such as airlocks, safety doors, etc). Once structurally complete, the sub-habitats will then be hermetically sealed by spraying a sealing epoxy coating on the inside surfaces of the 3D printed sections and forming a sealed environment with the main habitat.

Our approach offers a number of advantages:

- Novel re-use of mission elements is foreseen, as illustrated in the case of using the back-shell for the main habitat roof

- Significant reduction in mass requirements for mission planners by utilizing available local regolith resources for the construction of the satellite structure

- Division of the base into a hybrid structure with some terrestrially delivered elements and 3D printed elements ensures that an element of mission reliability and safety is available. Should problems occur within the 3D printed section, astronauts can safely retreat to the main habitat and effect a repair

- Utilization of a sealing epoxy, as opposed to further inflatables, increases the available area within the 3D printed sections and can allow for better sealing

- Realistic implementation, with processes that can be developed and tested here on Earth at a number of Mars analog sites

- Flexible and expandable layout able to be modified for current and future mission needs

FABRICATION TECHNIQUES

The lava-casting manufacturing process is inspired by naturally occurring terrestrial processes and its feasibility has been confirmed by small scale demonstration projects on Earth [1].

In action, we envision that two autonomous rovers will collect Martian regolith from dunes present in craters or in natural beds. These aeolian dunes and beds are well understood in terms of their particle size distributions (500 ± 100 µm [2]), which is an important consideration for understanding the dynamics of any sintering process. The regolith will be melted inside a furnace on the rover, and then cast in channels made from sintered regolith. Sintering involves using heat and/or pressure to fuse particles and its feasibility has been demonstrated on Earth via numerous projects. When one cast layer has cooled, the rover begins the layering of more regolith sand and a new channel is sintered on top. This process is repeated until the dome is complete. The sintering of a channel for the lava to flow into also provides an element of control to the overall process, as it is well known that the underlying layer onto which lava flows influences the flow properties and final morphology. The pre-sintering of the channel would also likely reduce outgassing events during the lava pour, which could affect the porosity of the basaltic lava. A full schematic of the fabrication process can be seen in the subsequent design document section of this submission.

A number of advantages are realized by utilizing this LavaCast approach. Firstly, as a building material in terms of structural strength, it is superior to thermally induced sintered material. Since the four-man astronaut team would be expected to work safely within these 3D printed structures, confidence in the structural elements supporting the rooms is crucial. Secondly, relative to any sintered material, we can expect basaltic lava, once cooled, to have a much higher density (g/cm^3). This would have considerable benefits in terms of providing radiation shielding in the surface environment. The permeability of basalt stone is also superior to that of a sintered process, which is an important consideration for forming a hermetic seal.

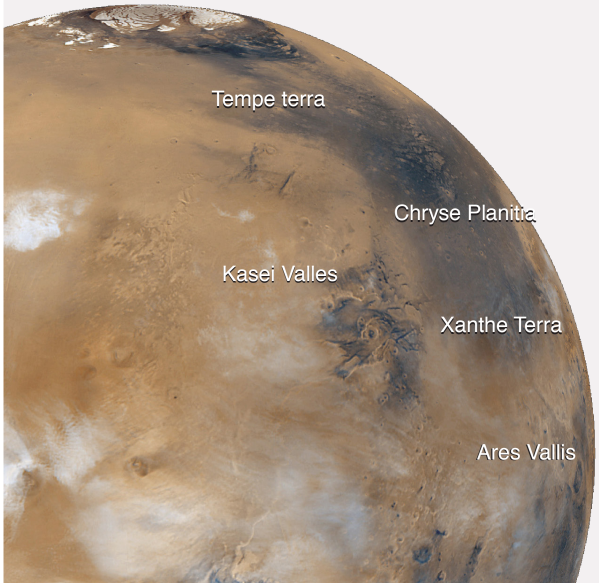
Heating and control of the lava itself, while it may seem difficult, is relatively easy to achieve – lava is highly viscous yet can readily flow long distances before cooling owing to its thixotropic and shear thinning characteristics. In terms of realizing a representative test habitat here on Earth, we believe it is eminently achievable and lessons learned are transferable to the Martian environment.

Sintering of the flow channel for the LavaCast technique would likely best be achieved via a thermal sintering approach, with a strong candidate being a laser sinter system [3]. In addition to creating the flow channels, this multi-functional sinter rover would also provide a basic leveling and preparation of the foundation via sintering. Upon this foundation, the 3D printed structure would be built layer by layer. Once the fabrication process is complete, elements such as experimental load locks and external rover airlock doors would be put in place.

SITE SELECTION

The site of the Martian habitat will be an area in the south of Chryse Planitia. It is one of the lowest altitude regions of Mars, providing a higher density atmosphere, more protection against cosmic radiation and better temperature stability. It is close to the equator, providing higher temperatures for the habitat and more direct sunlight to produce energy from solar arrays. The selected region contains large flat plains dotted with craters, providing a perfect landing spot. The area contains deposits of loose regolith that can be harvested for the construction of the habitat.

Hawaii is proposed as the location for an analog site. The presence of natural basaltic rock from lava flows, as well as a remote location and an existing analog infrastructure, make it an ideal training location.



INTERNAL LAYOUT

The main habitat, as the most secure zone, will house crew quarters and living spaces such as lounge, dining and hygiene areas. Working areas are separated by an airlock and are accessible through a central corridor. Three sub-habitats are proposed for the initial habitat, with the ability to add more sub-habitats at later stages. The initial three sub-habitats will contain laboratory space, a maintenance workshop, and a greenhouse. The sub-habitat working space will have a range of equipment suitable for geological, engineering, biological and other scientific work. It is important to take into account human factors for the crew to reduce workload and stress. Features such as a cupola, greenhouse, separated living and working areas and individual bedrooms will help to keep the crew happy and productive. The ECLSS systems and main plumbing and electrical systems will be located under the main habitat roof, accessible for repairs by the crew.

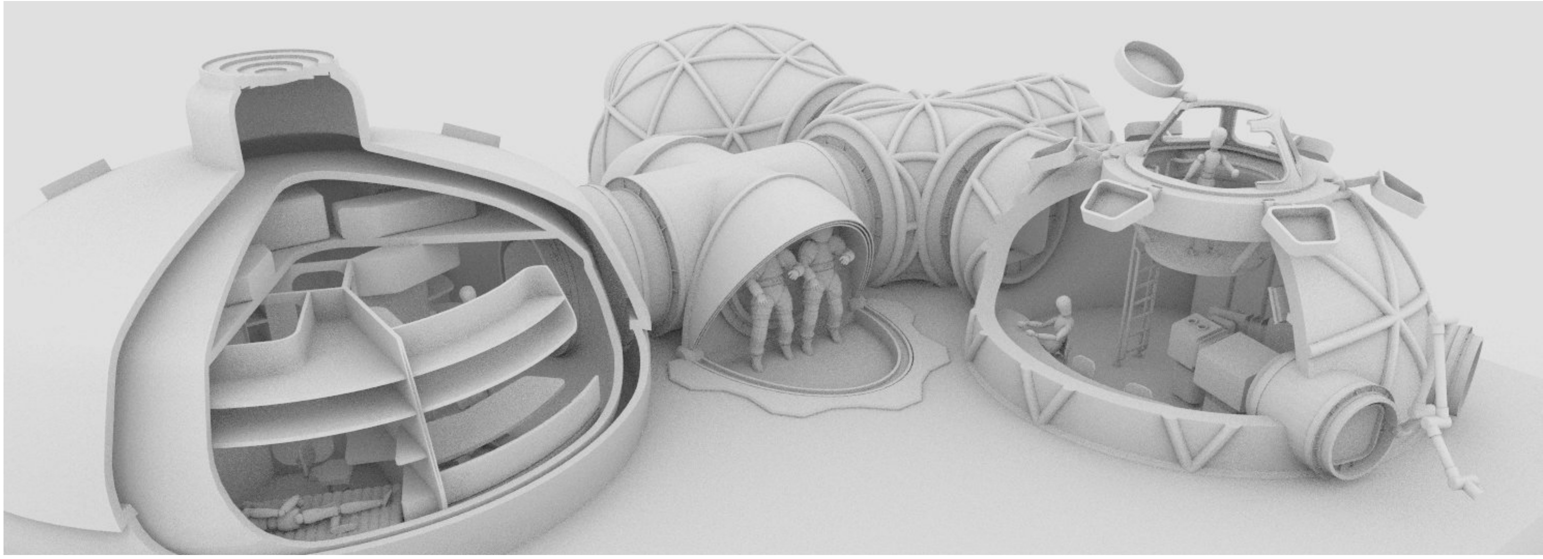
RECYCLING CONCEPT

The LavaHive concept incorporates usually-discarded components as a key element of the habitat concept. One of the features of this recycling approach is the reuse of the entry back-shell. The usually discarded back-shell forms an encapsulating element over the inflatable habiat section underneath. The back-shell is also used to house volatiles in repurposed fuel tanks.

Additionally, materials like nylon, polyester, kevlar, low density polyethylene, titanium, carbon fiber composites, polyimide and PTFE, and parts such as fuel tanks and wiring will be taken from the unused EDL vehicles post-landing and reused inside the habitat, for example as ECLSS water or gas storage. Recycling of polymers opens up novel reuse applications within the interior of the habitat. Using the waste polymers as feedstock for existing plastic additive manufacturing techniques we can produce a variety of mission specific tools and fittings. This recycling approach increases mission flexibilty and is paramount for a logistically self-sustaining mission to Mars.

SUMMARY

LavaHive is a novel 3D LavaCast habitat made from sintered and molten Martian regolith as well as recycled spacecraft parts. It is a modular design for an initial mission of four crew, with the ability to expand or adapt to changing mission requirements. In its initial state, a main habitat is connected via a central corridor to three sub-habitats made entirely from in-situ resources. The main habitat houses crew living areas with the sub-habitats used for experiments, Martian surface exploration preparation and maintenance. The construction approach, mixing early building techniques from Earth with a novel regolith 'LavaCast' technique has obvious public appeal and alongside the wider mission can help inspire the next generation of scientists and engineers.



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[1] Syracuse University Lava Project: http://lavaproject.syr.edu/

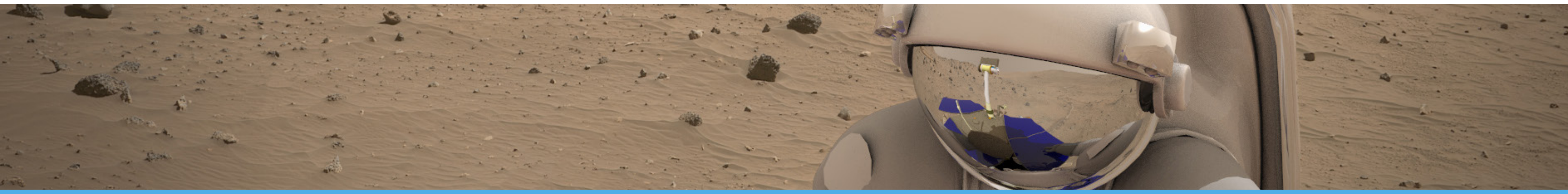
[2] Edgett K.S., and Christensen P.R.,The Particle size of Martian Aeolian Dunes. Journal of Geophysical Research. Vol. 96 No. E5, pp. 22765-22776, December 25, 1991

[3] Additive Construction using Basalt Regolith Fines – NASA

[4] Paton, M. D. et al. (2013). "High-fidelity subsurface thermal model as part of a Martian atmospheric column model". Instrum. Method. Data Syst. Discuss. Vol 2, 17-23

[5] Schultz, Richard A. "Brittle strength of basaltic rock masses with applications to Venus." Journal of Geophysical Research: Planets (1991–2012) 98.E6 (1993): 10883-10895

[6] Public domain image taken from http://mars.nasa.gov/mer/gallery/artwork/hires/entry.jpg

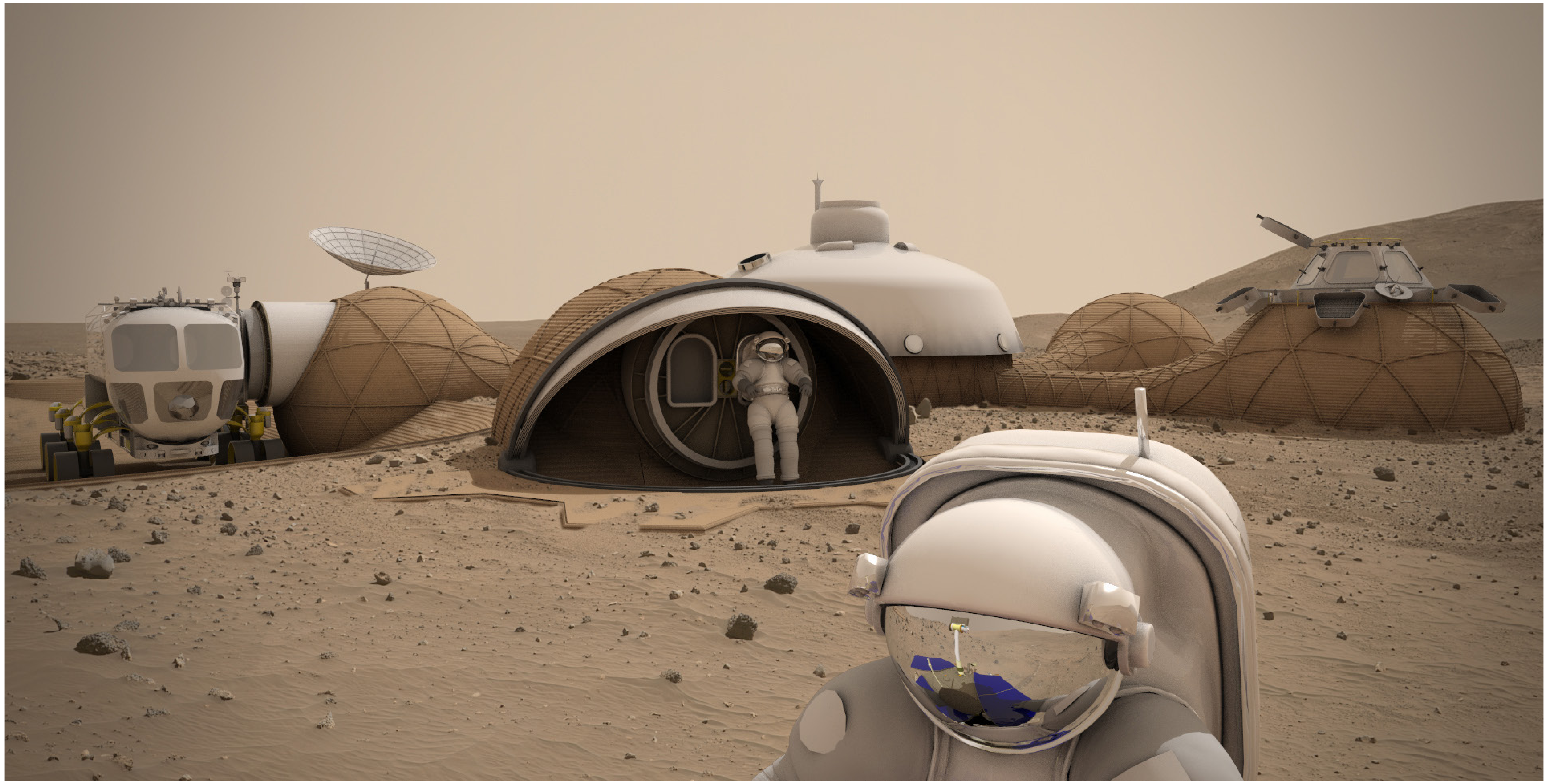


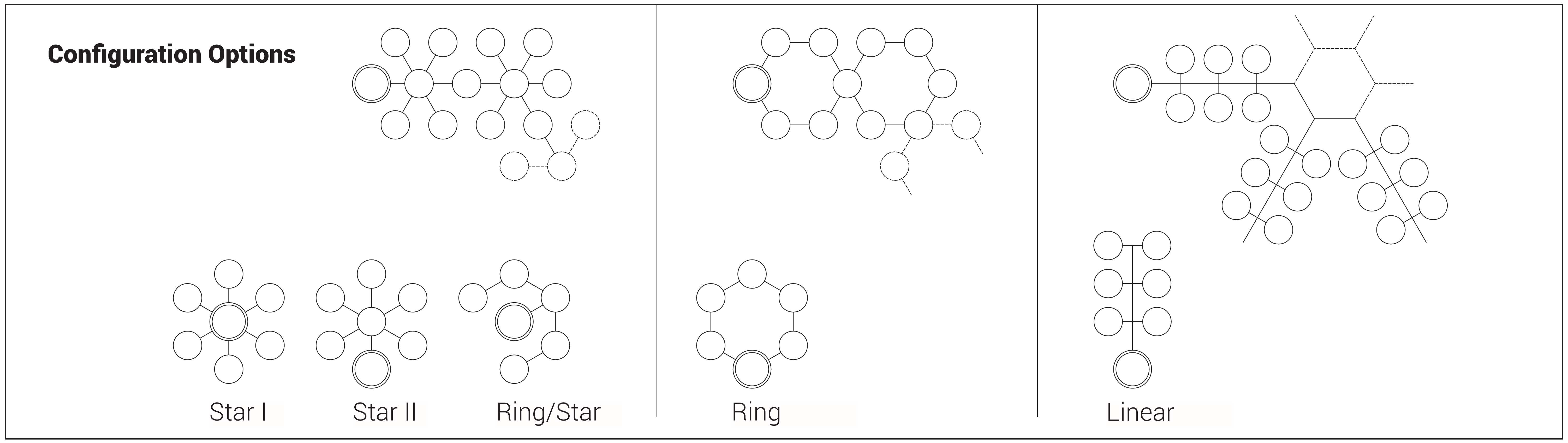
LAVA HIVE

LAVA HIVE | We present the schematic implementation of our proposal. In these sections we will outline aspects relating to the overall vision of our approach, from the novel fabrication process to structural, thermal and interior design aspects.

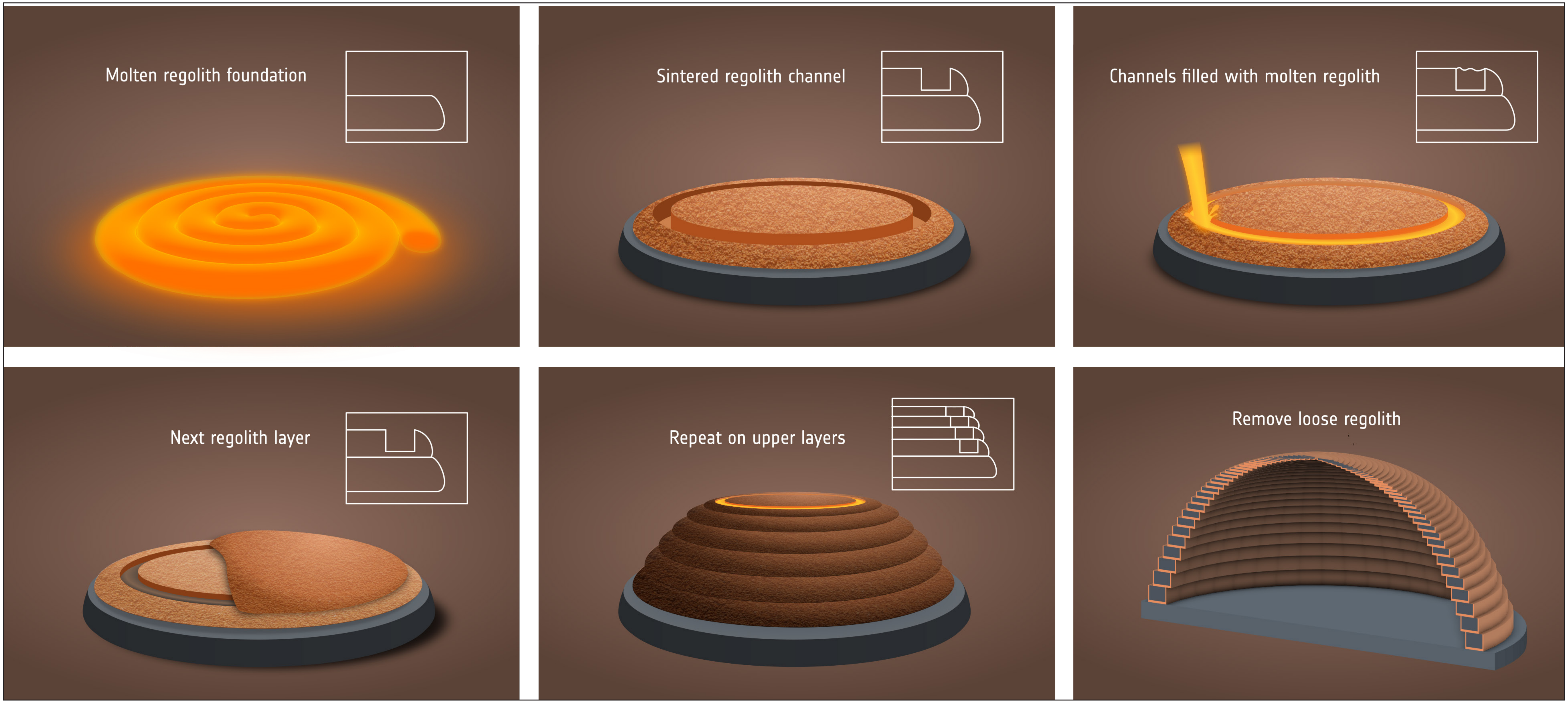
The critical main habitat and other unprintable elements are brought to the surface, while the structural hive elements for the workshop, laboratory and greenhouse are fabricated using a combination of Lava Casting, sintering and finally internal sealing via epoxy.

Our surface top-down base design is illustrated here. The flexibility of the design allows for variations of the base topography depending on mission requirements and geography of the landing site.



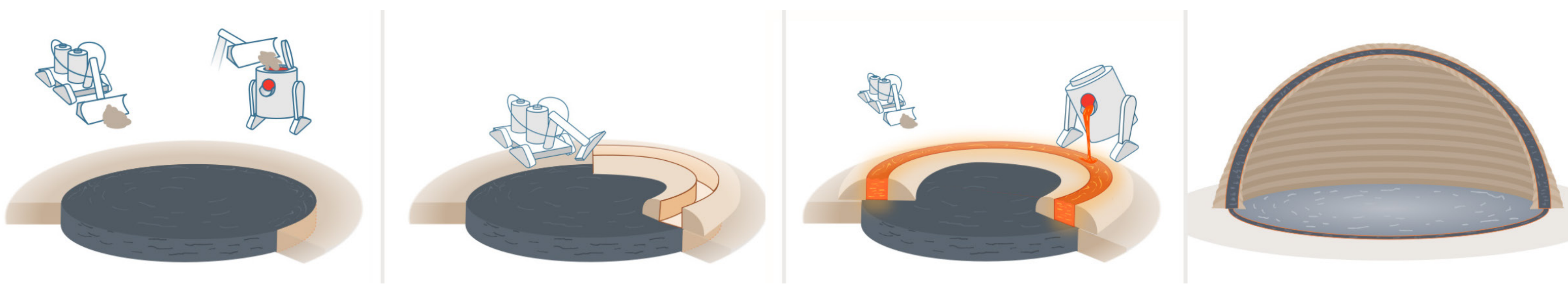


LAVA HIVE CONSTRUCTION PROCESS



LAVA CASTING TECHNIQUE | Our novel lava casting technique, detailed previously, allows for the construction of dome-like structure elements. The sintering of a support channel provides direction for lava when it is poured.

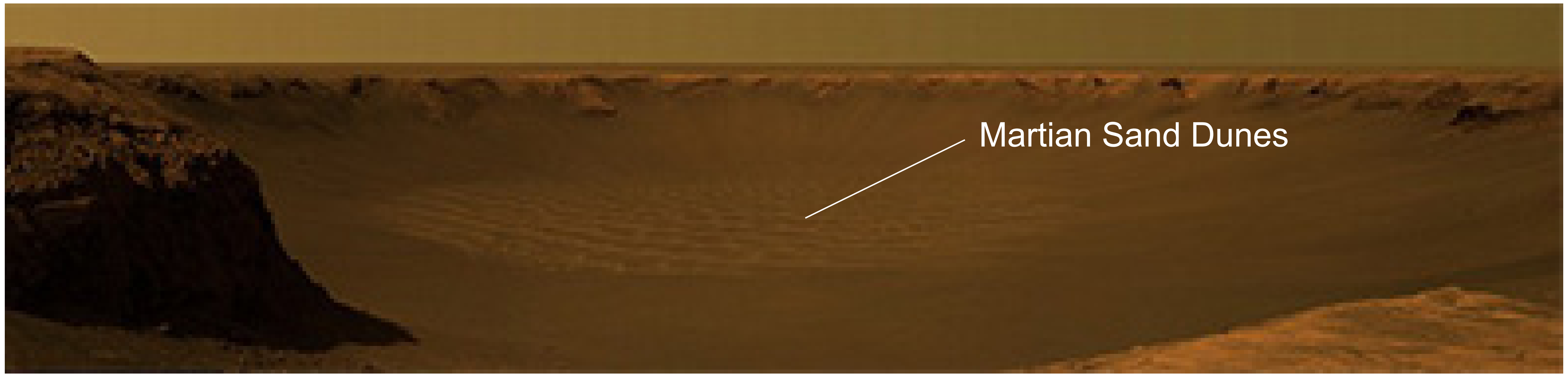
ROBOT WORKFLOW | Our concept uses two rovers operating in tandem to produce a dome structure. They can also be used for other base features such as creating foundations, support structures or base roadways.



LAVA HIVE STRUCTURE & ENVIRONMENT ASPECTS

STRUCTURE | The habitat structures are based on a dome shape. Structural analysis of the dome indicated that the largest forces occur at the base of the dome. In order to carry the weight of the top portion of the dome and to provide a good resistance to tensile hoop stresses, the lower part of the dome will be built with a thicker layer of material. On the other hand, the top part of the dome is subject to lower stresses and therefore will be built with a thinner layer of material [5].

THERMAL | On Mars, the main heat transfer mechanisms are radiation and conduction. The high thermal inertia of basalt type rocks, which our lava cast process would produce, will have significant thermal benefits in terms of retaining heat for the crew and the overall energy efficiency of the base



SITE | Our approach will require access to aeolian deposited regolith, of which there are many available in our targeted site. Known research on the particle size of such deposits allows terrestrial testing of the sintering process

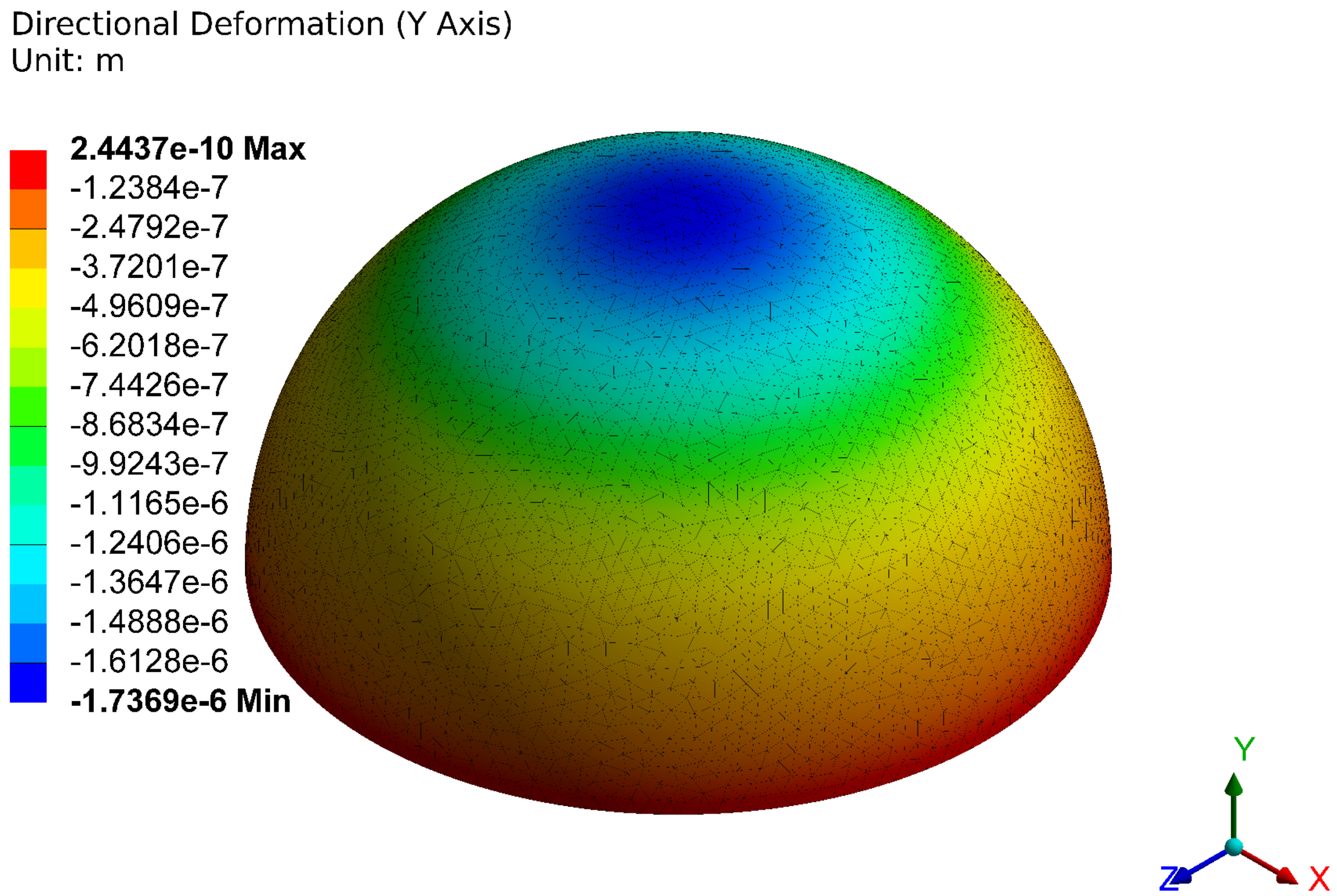


Figure 1: Directional deformation for a basalt like Lava-Cast dome structure

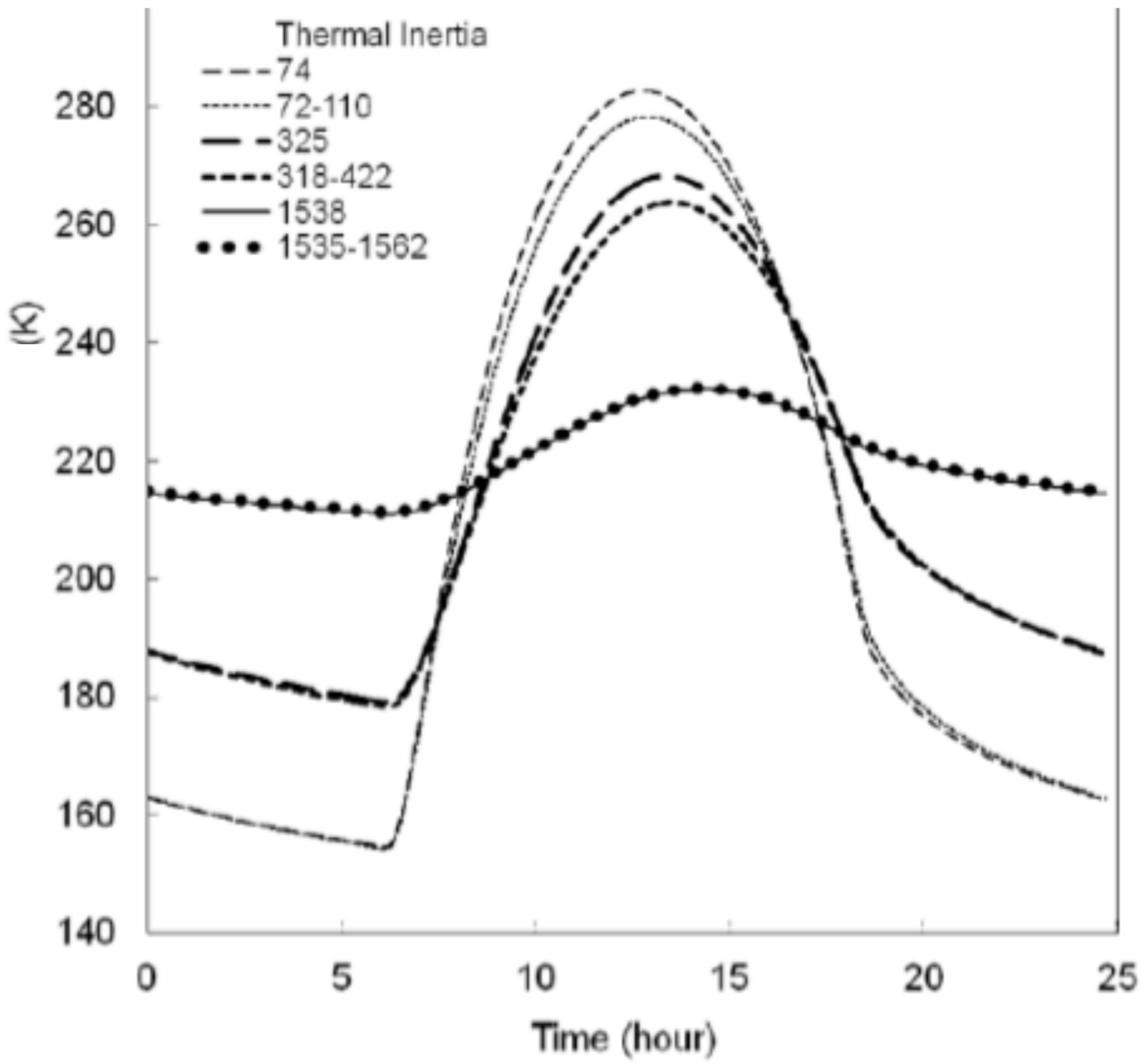


Figure 2: Surface temperature differences of dust (low thermal inertia, ±1500), sandy and rocky surfaces (high thermal inertia ±74) on Mars. The units of thermal inertia for the values in the legend are $J{\cdot}m^{-2}{\cdot}K^{-1}{\cdot}s^{-0.5}$. [4]

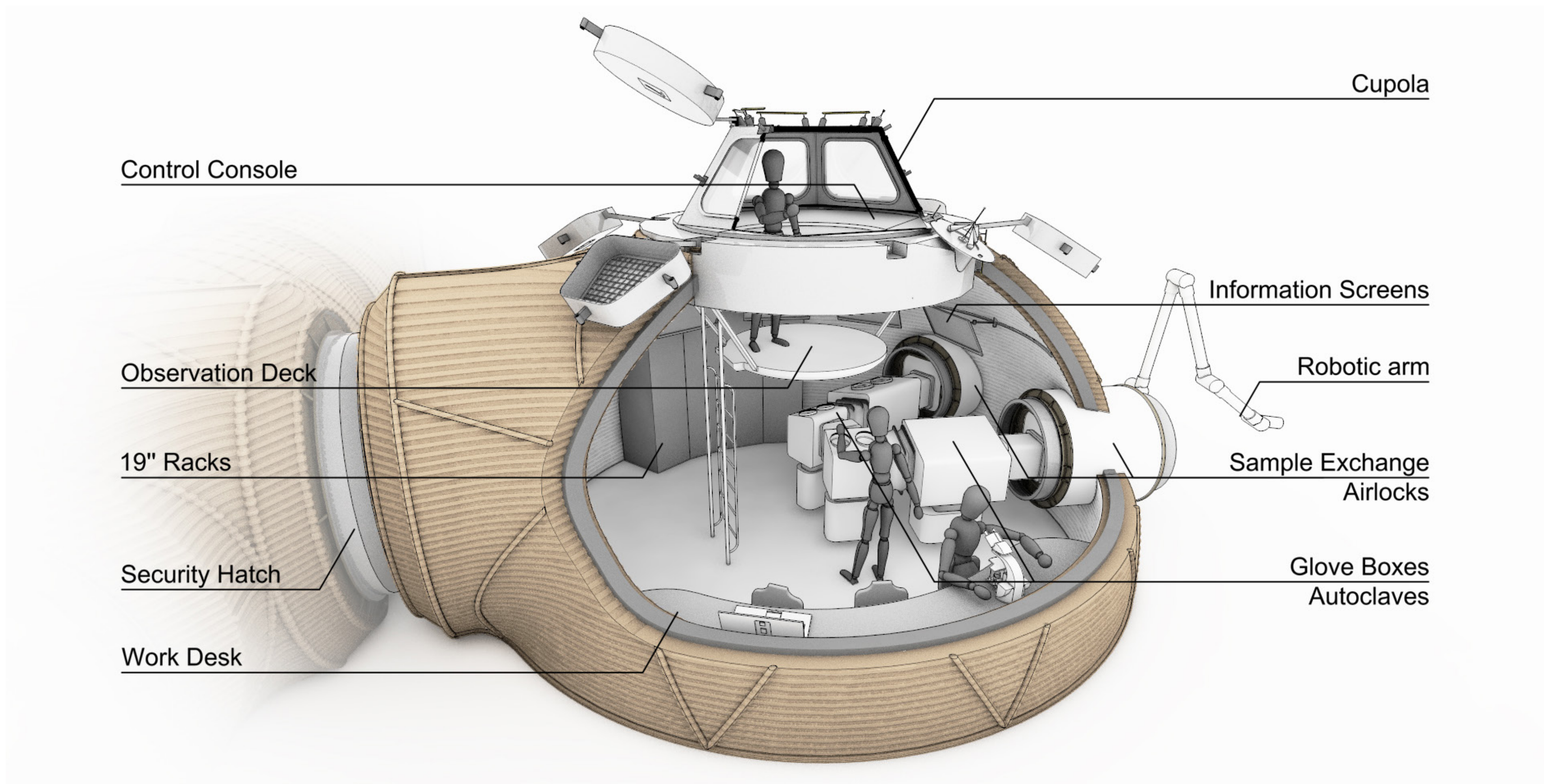
LAVA HIVE ELEMENTS

ARCHITECTURE | The main habitation unit is connected to the sub-habitat section by an airlock module, which also houses suitports providing ingress and egress to all four crewmembers.

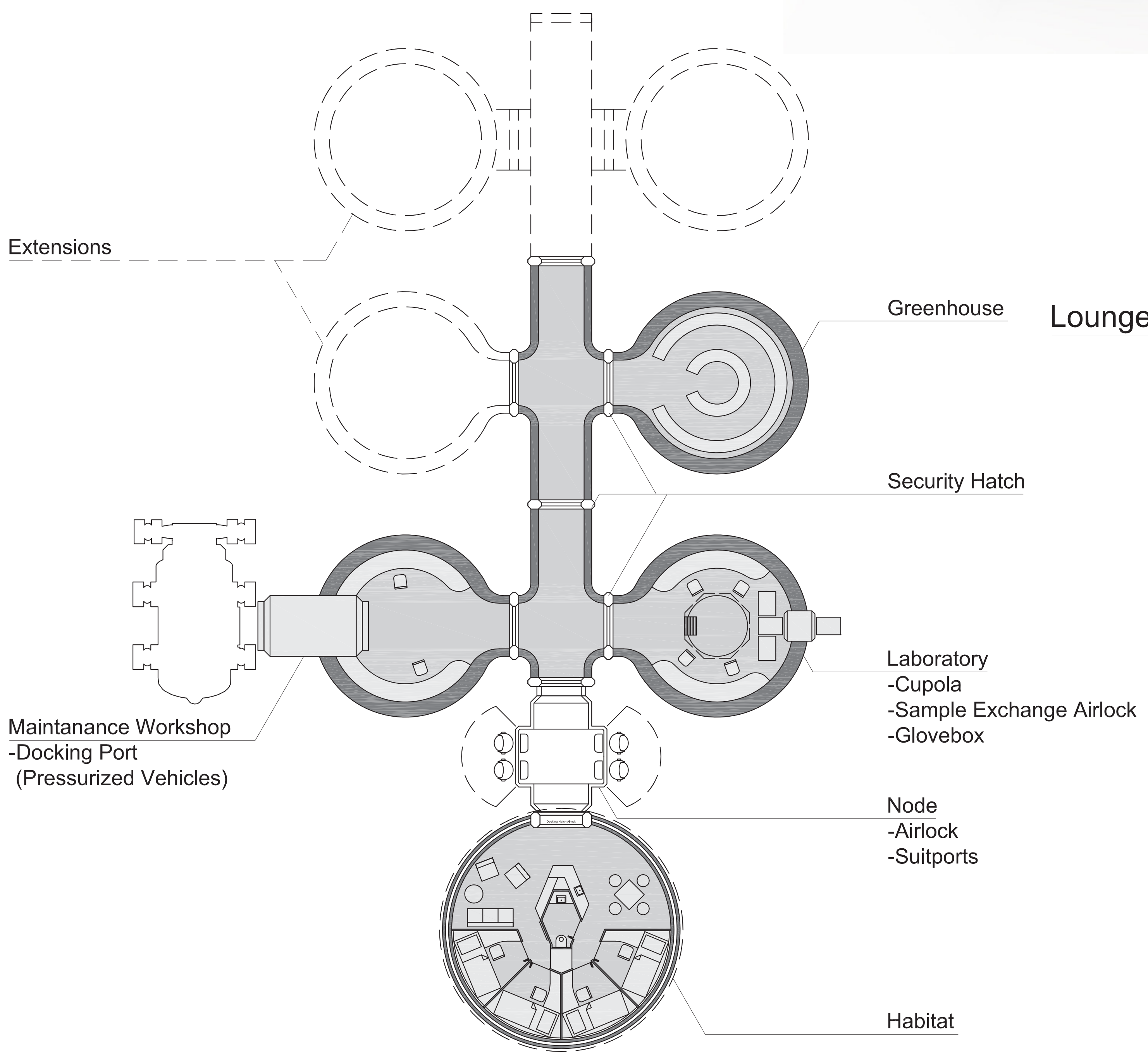
The maintenance workshop and docking port connects to mobile pressurized elements such as a rover. Located opposite is the laboratory with a viewing cupola. It also houses sample exchange airlocks to analyse matter taken from Martian surface expeditions.

To supply sufficient food a greenhouse is located at the rear end of the connecting tunnel. Further docking ports for extending the configuration in the future are foreseen, allowing for future expansion of the base in a modular manner.

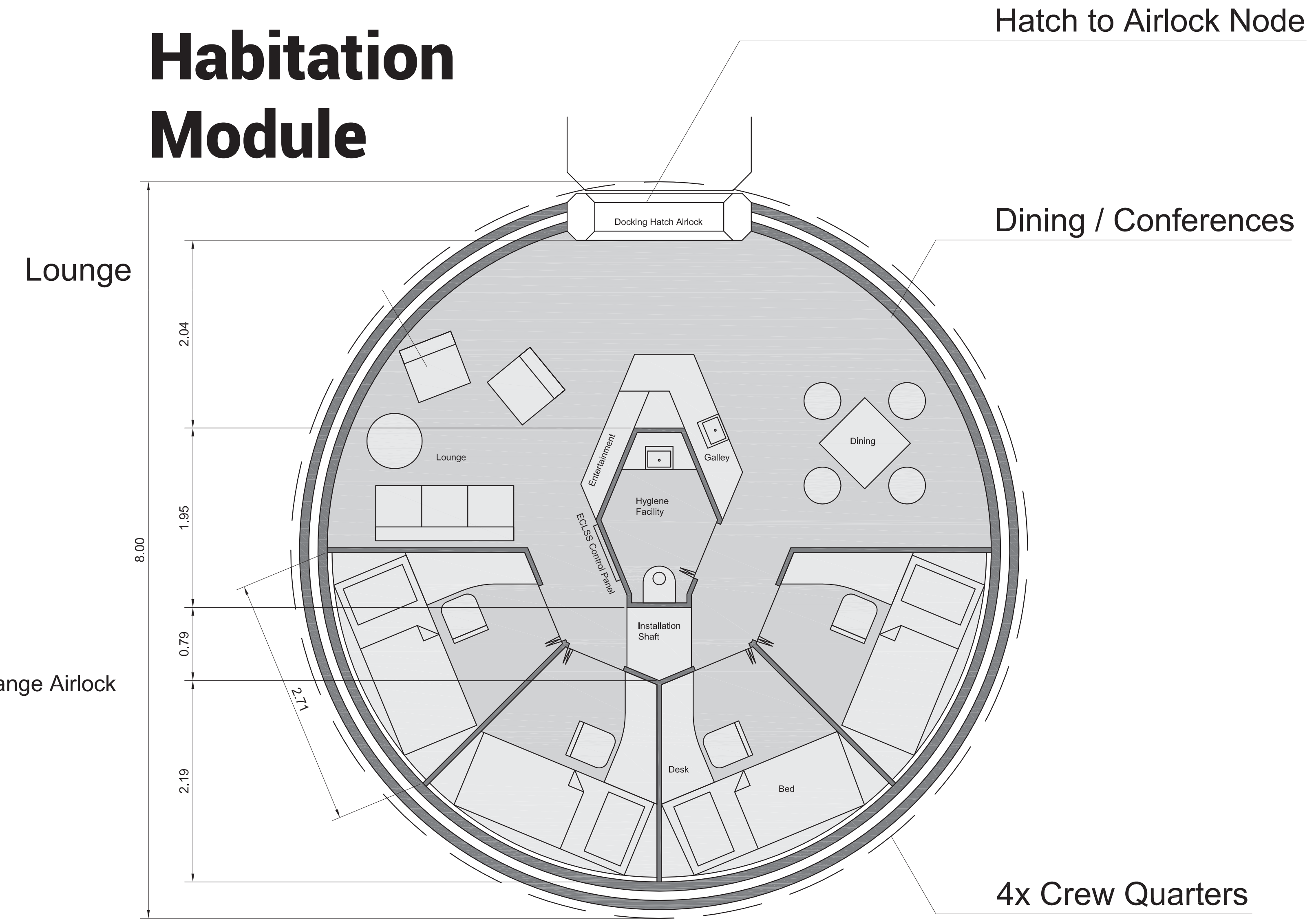
Laboratory HIVE



Overall Configuration

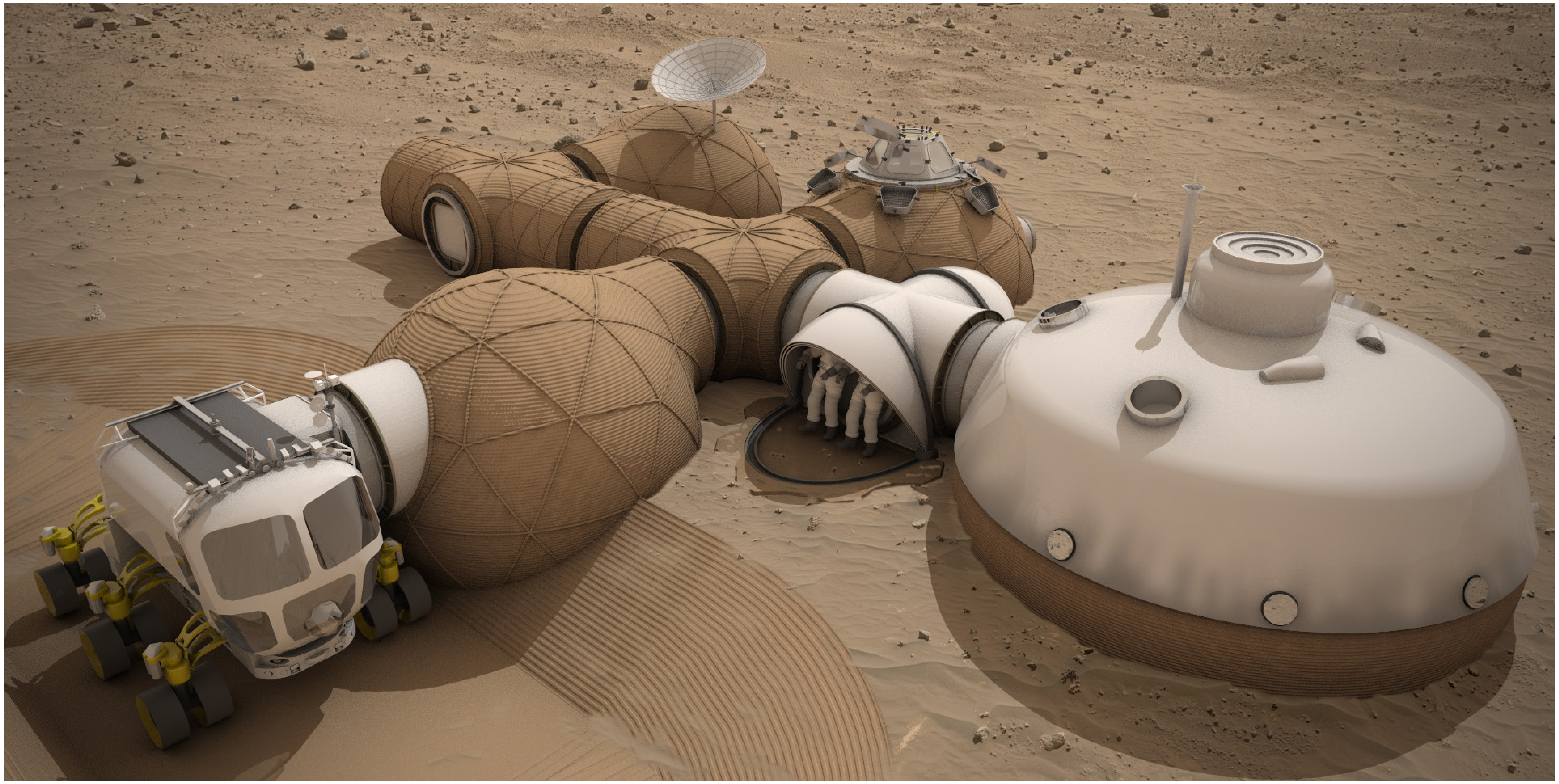


Habitation Module



ECLSS and Storage space underneath backshell roof

LAVA HIVE OVERALL CONFIGURATION



OVERALL CONFIGURATION | The overall configuration forsees an inflatable habitation module covered in combination with the recycled backshell of the entry capsule and a sintered apron of martian soil.

Connected to the habitat will be an array of smaller satellite habitats, containing all functions for research, surface operations, and a greenhouse. Different configurations have been proposed, taking into consideration mission requirements, extendability and safety. To start with a linear configuration would be the safest, most effective and most flexible option, when considering larger base footprints.