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An ISRU-Based Architecture for Human Habitats on Mars: the 'Lava Hive' Concept

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Abstract. We detail the overall structural architecture for a Class III Mars habitat intended for human exploration missions, constructed utilizing a robust and simple *in-situ* resource utilization (ISRU) approach we have termed 'lava casting'. The habitat concept is based on a hybrid approach, with structural elements of a central habitat arriving from Earth conventionally, while an additive manufacturing (AM) process is used *in-situ* to expand the central habitat workspace using locally sourced construction material, namely Martian regolith soil and sand. The construction process is outlined, with the advantages of our approach elucidated in terms of flexibility, achievability and the ability to provide important protection to surface assets and explorers from the Martian radiation and thermal environment.

1 Introduction

The use of *in-situ* building materials will become increasingly critical as human exploration activities progress beyond low Earth orbit once again, with likely destinations including the Moon and Mars [18, 10]. As human presence on these bodies is expected to follow robotic precursor missions, so must we develop new approaches to structures to accommodate them such as habitats, radiation shelters, laboratory space, greenhouses, etc. It is well understood that the use of *in-situ* resources can significantly offset required launch mass requirements and potentially provide for greater mission sustainability and new capabilities [2, 23], but the use of ISRU represents a paradigm change in mission architecture that has yet to be fully embraced or indeed demonstrated reliably outside of small field test campaigns.

Initial development of ISRU technology has focused heavily on O2 production because it is a substantial constituent of the minerals in both Lunar and Martian regoliths, and it has been shown that a hydrogen reduction process can be used to release it [2, 13]. Upon examination of the regolith composition and atmosphere of Mars, it becomes apparent that there are many resources there that could be exploited to make exploration missions sustainable and affordable. Looking beyond the astronaut's life support, the concept of using local resources for construction processes is equally desirable, with recent work in the domain of 3D printing on the Lunar surface gaining particular attention [4].

Throughout these technologies, however, there runs a streak of design complexity, whether in the chemistry

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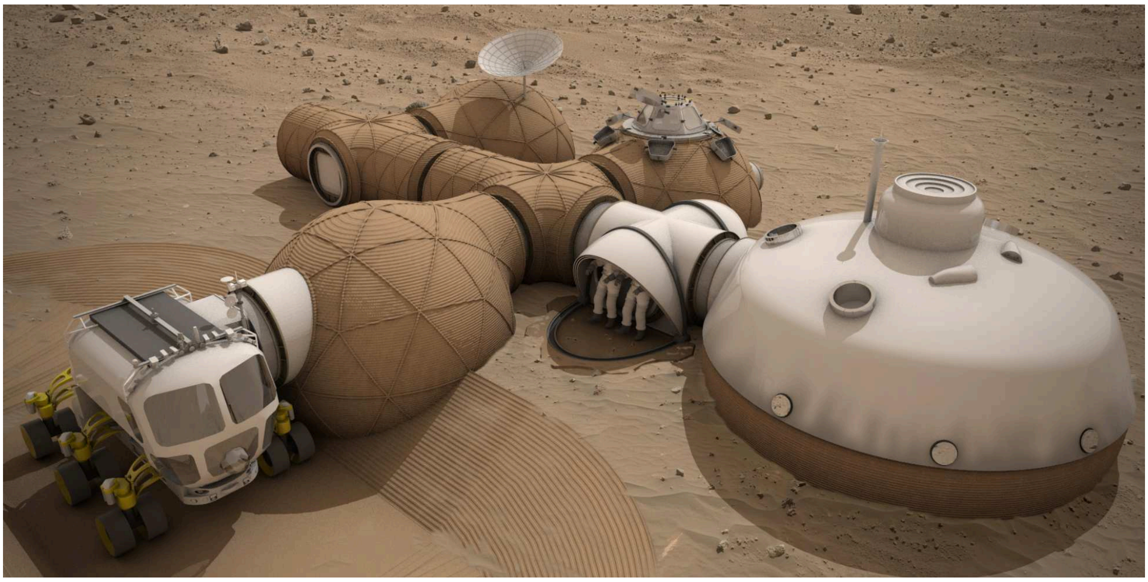

Figure 1. *Render of the Lava Hive concept in its linear configuration. Clearly observable is the central habitat core, with the smaller ancillary 3D printed satellite structures clustered surrounding it. Visualization: René Waclavicek, LSG, 2015*

used to release gas/mineral resources or the engineering concepts needed to access them. In many cases, such concepts require significant development with regards their technology readiness level (TRL), to the point as to exclude them from serious consideration among conservative mission plans in the near or medium term. Exploration demands an expectation of encountering the unknown, but this does not preclude a solid engineering approach to be taken based on best known science as well as a solid design principle such as 'keep it simple and straightforward (KISS)'. With this view, construction processes and technologies can act as simpler *ab initio* validators for ISRU.

In this paper we discuss the concept for our ISRU enabled Mars habitat, which we have named 'Lava Hive', and how our approach provides a potentially robust and simple approach to producing structures on Mars.

2 The Lava Hive Concept

Lava Hive is a modular additive manufactured Martian habitat concept using a proposed novel 'lava-casting' construction technique, utilizing recycled spacecraft materials and structures, and represents a Class III ISRU derived structure as defined by NASA [5]. The impetus for this work was our response to the NASA Centennial Challenge, calling for approaches to 3D-Printing a Mars Habitat, which was run in 2015 [19]. Key design requirements for this competition were to address ISRU and 3D printing combined, re-use or recycling of existent spacecraft structures, mission concept and overall architectural quality. This concept was awarded third place in September 2015.

Our proposed habitat concept has a number of key design elements:

- 'Re-use' of commonly discarded entry-descent-landing (EDL) systems, the reentry back plate, as part of the central habitat section, providing the housing for mission critical mission elements and personnel
- 3D printed satellite structures feeding off from the main central habitat, with configurable orientations to suit the mission requirements
- Unique use of regolith sintering combined with the novel 'Lava Cast' methodology to produce solid basalt structures for enhanced protection from the Martian radiation and thermal environment

An architectural interpretation of our concept can be seen in the Figure 1. A primary central dome, housing crew areas and mission critical systems such as life support, is connected to a number of smaller ancillary dome

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Figure 2. *The Namib dune periphery, visited by NASA Curiosity rover in January 2016, illustrating the ease of availability of well understood construction resources.*

structures. This central element will be brought from Earth and forms the core of the habitat. The smaller domes, connected via 3D printed passageways to the central dome, house laboratories, workspaces, garage airlock and other required mission specific areas. Our understanding and examination of state of the art technologies led us to develop a concept and fabrication approach that would erect freestanding 3D printed structures using direct energy input to Martian regolith and sand material as shown in figure 2. 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 [15, 14]. A combination of sintering and melting of Martian regolith and sand emerged as our process of choice.

Architecturally, our inspiration was driven by beehive huts (Clochán) of the Irish monastic sites and by the traditional South Italian's "Trulli", Apulia's domed houses with prehistoric origins built using the abundant stone materials from the surrounding land, a true example of 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.

2.1 Mission Concept

On arrival to the Mars orbit, the spacecraft will detach the EDL payload 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 utility rovers will also be included in this payload, which will be used for the 3D construction process to follow.

When the re-entry capsule (Fig. 3) comes to rest on site, the underside inflatable habitat will deploy, as seen in Fig. 4. 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 ancillary 3D printed satellite domes, we assume 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 subsystems like environmental control and life support (ECLSS) as well as providing a reliably sealed environment. It can also act as the initial habitat for astronauts as the construction work is carried out, as opposed to remaining in orbit.

The back-shell from the EDL heat shield will be recycled as the roof of this central habitat, to reinforce and protect the inflatable structure that deploys under-

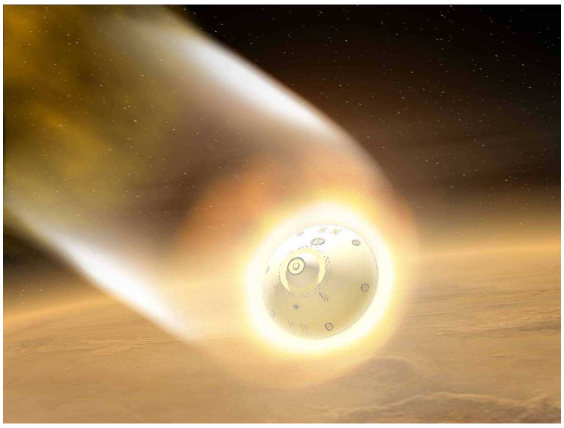

Figure 3. *Mars Exploration Rover aeroshell (artistic rendition [20])*

neath from hazards such as micrometeorites and radiation. Landing within range of our targeted site, the tele-operated utility rovers will be utilized to begin the preparation of the area for the expansion of the base.

2.2 Martian ISRU Construction Material

The surface of Mars yields a number of potential construction resources that can be readily accessed, chiefly among them is the regolith and sand. Sand dunes are among the most widespread Aeolian features present on the surface, manifesting readily as large fields or within sheltered crater impact sites. In addition to the loose surface regolith, they represent an excellent building construction material consisting of a narrow range of well-sorted, unconsolidated particles mostly comprised of pyroxene, olivine and basaltic sands.

The material within these Aeolian dunes and beds are well understood in terms of their particle size distributions from thermal inertia measurements (500 ± 100 μm, medium to coarse sand [8]), as well as from terrestrial numerical and empirical modeling of their morphology [21]. The particle size and characteristics are an important consideration for understanding the dynamics of any sintering process that would be employed, and we can thus empirically validate our process with simulants found terrestrially.

The utility rovers deployed will identify and collect from the loose regolith or sand from dunes present in craters, natural beds or depressions. Transporting these to the base site, the utility rover, capable of a sintering process, will begin the production of the foundations for the smaller habitat sections.

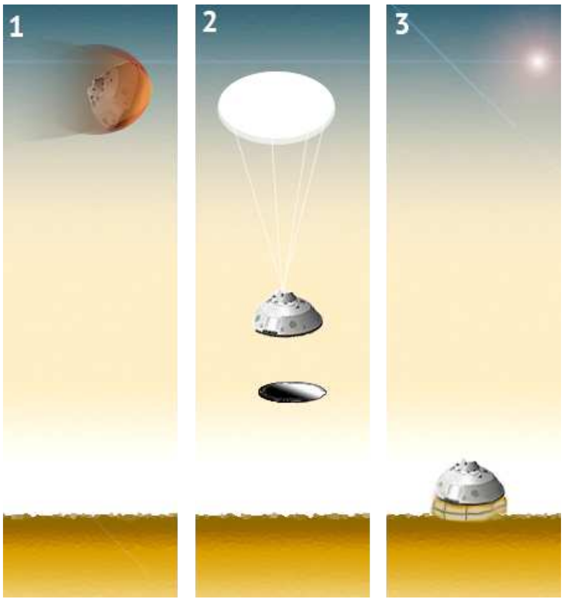

Figure 4. *Illustration of main habitat deployment below the back shell*

2.3 Fabrication via Lava Casting and Thermal Sintering

Our AM inspired fabrication process uses two distinct methods to produce a final structure. The lava-casting fabrication process is inspired by naturally occurring terrestrial processes and its feasibility has been confirmed by small-scale demonstration projects terrestrially [9]. The second process, thermal sintering, involves using heat and/or pressure to fuse fine particles and it is a well defined material process, even being demonstrated to be effective with planetary regoliths [1]. The two techniques would be used in tandem, with the sinter process producing flow channels for the lava cast technique – essentially a guide path for the basalt liquid melt 5.

Sintering of the flow channel for the Lava Cast technique would likely best be achieved via a thermal sintering approach, with a strong candidate being a laser sinter system [17, 11]. 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.

When one cast layer has cooled, the rover begins the layering of more regolith/sand and a new channel is sin-

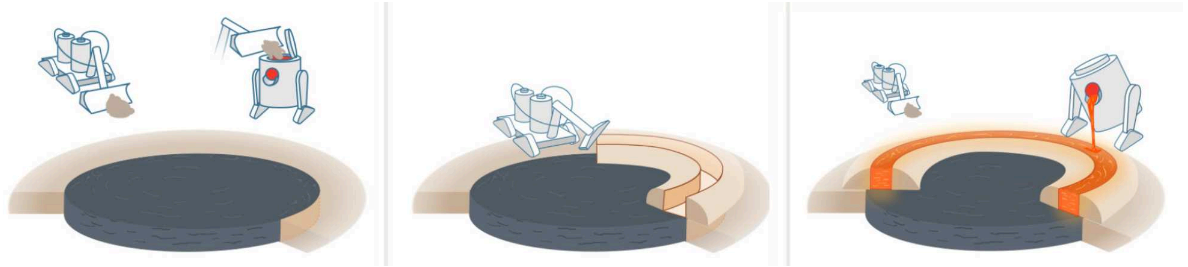

Figure 5. *Illustration of the flow channel construction process, whereby the utility rover produces a controlled path within which the lava melt can flow and be constrained.*

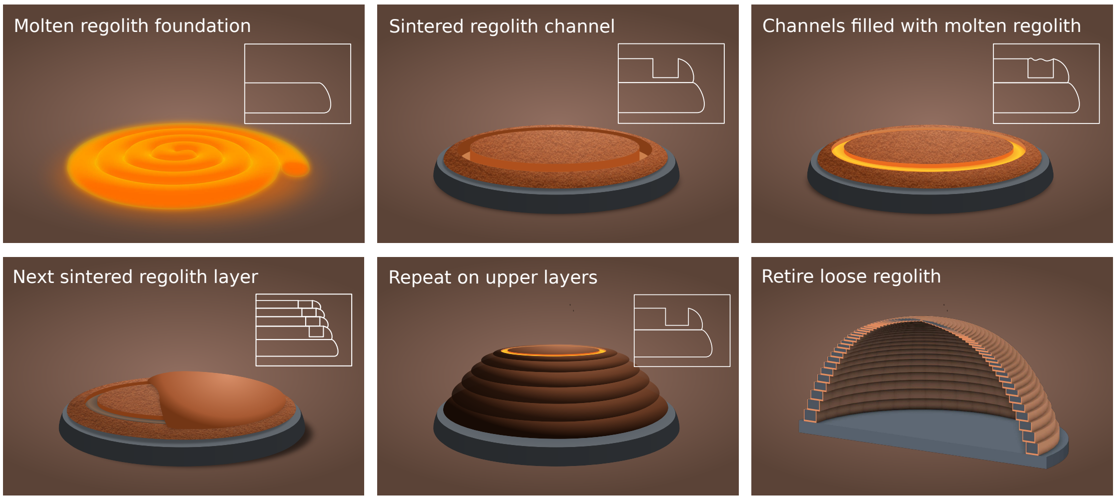

Figure 6. *Stepwise illustration of the lava casting process to produce a hemispherical shape habitat section (inset represents cross section of the process): (1) deposition of foundation base, (2) regolith is gathered and sintered to produce a flow channel, (3) molten basalt from the sand/regolith is poured into the channel and allowed to solidify, (4) the next layer of regolith is spread across, and another channel sintered, (5) layer by layer the structure is constructed, (6) loose, un-sintered regolith is excavated from the structure, revealing the completed dome.*

tered 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 properties and final morphology [9]. The presintering of the channel would also likely reduce outgassing events during the lava pour, which could affect the porosity of the basaltic lava. 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 thixotropy and shear thinning characteristics [3]. A full schematic of the fabrication process can be seen in Fig. 6.

It is envisaged that astronauts will then perform final operations either autonomously/tele-robotically from Mars orbit or from the surface (e.g. from the central habitat), installing mission elements brought from orbit (such as airlocks, internal fittings, 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, forming a sealed environment with the main habitat.

3 Advantages of Lava Casting Approach

A number of advantages are realized by utilizing this casting approach and the final basaltic rock building elements. Firstly, as a building material in terms of structural strength, it is superior to thermally induced sintered material [1]. The thermal inertia of the regolith is a key parameter that drives the surface-atmosphere exchange processes [22]. The thermal inertia is defined as $I = \sqrt{\rho \cdot c \cdot \kappa}$, being ρ the density, c the heat capacity and κ the thermal conductivity. Compared to dust and sand, Martian rocks present a higher thermal inertia due to their higher κ conductivity and density. Figure 7 compares the influence of the thermal inertia on the surface temperature on Mars. It can be seen that because of the high inertia of the Martian rocks (around 1500-1700 $\frac{J}{m^2 \cdot K \cdot s^{0.5}}$), the temperature swing experienced between day and night within such material would be much more moderate than in the case of sand, having a much lower thermal inertia (around 300 $\frac{J}{m^2 \cdot K \cdot s^{0.5}}$).

The higher density of the basaltic lava would have considerable benefits in terms of providing radiation shielding on the surface environment, from galactic cosmic rays (GCR) and solar proton events (SPE). The permeability of basalt stone [24] is also superior to that of a sintered process, which is an important consideration for forming a hermetic seal. Studies of GCR penetration into Martian regolith have been numerically studied, with peak dose found to be 40 cm within the regolith (density of 1.6 $\frac{g}{cm^3}$) and attenuation to 2% initial dose 5 m subsurface [16]. The basaltic lava rock would have a higher density ($\sim 3.3 \frac{g}{cm^3}$) and would be a stronger candidate for radiation protection then loose regolith alone. The inner polyethelyne (CH_2) based sealing epoxy can also act as an additional radiation attenuator [12], where the hydrogen-rich nature of this material make it suitable for passive radiation shielding. The accurate GCR and SPE dose modeling of the basaltic layer and epoxy sealant is continuing work at this time.

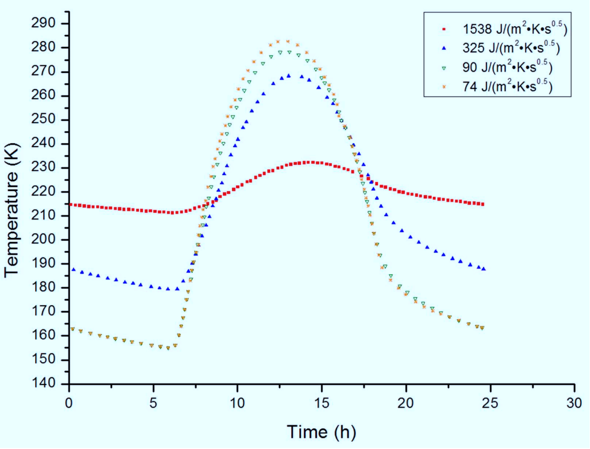

Figure 7. *Surface temperature profile of dust (low thermal inertia), sandy and rocky surfaces (high thermal inertia) on Mars, results based on the equations presented by Paton, M. et al. [22]*

4 Overall Layout Design Considerations

At a building scale, the 3D printed approach of this concept allows for a great deal of extensibility. Figure 8 below shows how the ancillary hive areas can be arranged in a linear manner, however the interconnections could be arranged in a web or ring configuration also depending on the mission scenario or local surface topography. In Figure 8, different layout configuration options ranging from "star", to "ring star", only "ring" and "linear" can be compared. The "star" option can expand on limited area and has drawbacks from a circulation point of view. There would need to be many habitation volumes, not just connecting tunnels, which serve as circulation space. The modules need to have numerous doors to the other modules, necessitating such structures being brought as payload. The efficient use of interior space is thus limited. The "ring" configuration uses necessary circulation space more efficiently; only two connection doors are necessary. However, the layout of the modules requires a circulation path right through the module and this space functions are limited and may only be used as public zones. The linear configuration allows a module to only have one exit and entrance, which might pose a safety concern in case of an emergency such as fire. This linear layout allows different functions and spaces such as a greenhouse and a laboratory to be used efficiently since there is no circulation path leading through this module. Each module is essentially self-contained and if malfunctioning, can be disconnected and does not disturb the functioning of the other modules or hinder the crew to reach other modules.

5 Habitat Design Considerations

The central habitat section (see Figs. 9 and 10) is housed under the re-used back shell and is an inflatable structure. Attached to this central section is an airlock node,

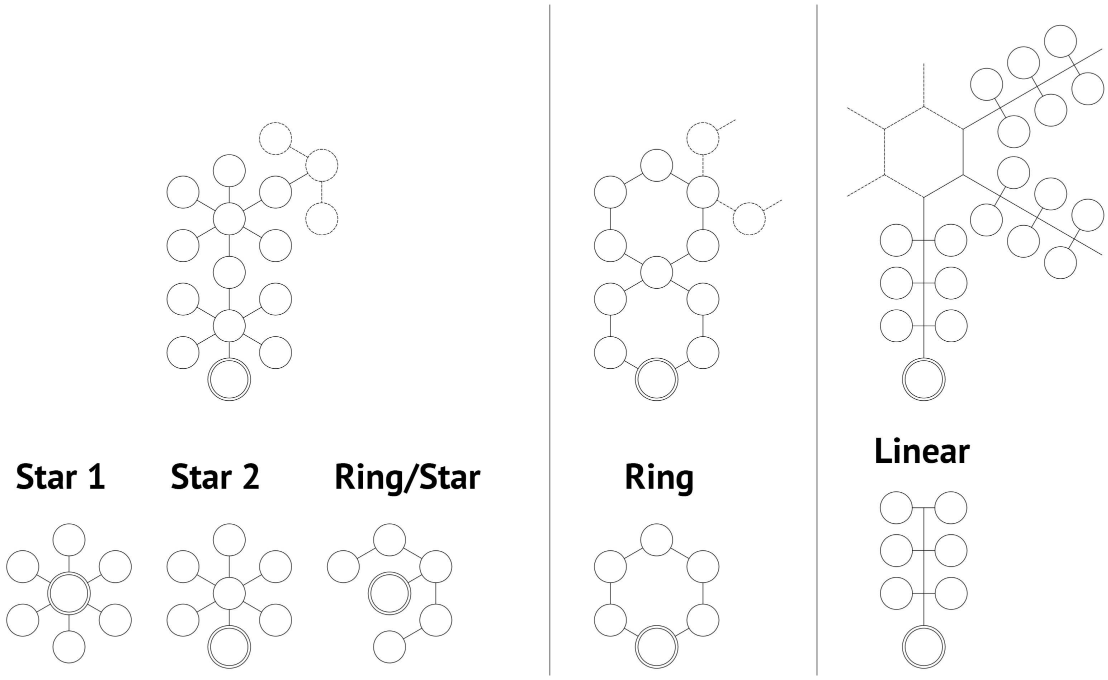

Figure 8. *Overall configuration options ranging from circular to linear extension possibilities. Visualization: René Waclavicek, LSG, 2015*

which then interfaces with the 3D printed ancillary structures. The airlock or suitport node allows for the capability to egress and ingress the habitat.

If mission planners will decide on a conventional airlock or on suitports is still open, the most likely scenario is to have both options. The suitport as the nominal way of stepping onto the Martian surface preventing cross contamination and an airlock in case of an emergency, e.g. should an injured astronaut need to be recovered and brought into the habitat and cannot step backwards from the suit through the port into the habitat.

The core habitation zone, depicted in Figure 9 and 10, houses private crew quarters for a nominal size of a four person crew. These offer a bed, a desk and some storage accommodation. The infrastructure parts such as the hygiene facility and the galley are in the centre of the module separating the private zone from the public area including a main installation shaft connected to the ECLSS which are located under the backshell roof. The habitation module can serve as a minimal base for the first crew.

Essential are the suitports and the workshop where a pressurized rover can be docked. The workshop can also be used as a multi-purpose space, where goods, spare parts can be stored or other activities can be performed. Since the floor is lower than in the other modules, the ceiling is higher and thus this part offers more volume.

Some of the interior might be deployable and being stowed under the backshell. Some of the interior for the laboratory (Fig. 12), or the greenhouse could be transported from the lander to the modules with a pressurized rover and installed using the docking port to reach the interior of the base.

It will become an important issue in the preparation of such missions to find efficient ways of packing and deploying interiors, even transforming some parts from other missions into usable gear. One could think of “transformers” which have different purposes, being used in a different function before becoming interior installations.

Imperative for the survival of humankind on Mars is also a greenhouse (Fig. 11). Although the size of the greenhouse envisioned for this concept is probably too small, exact growth areas are still to be determined by experts working on this topic – we need to develop robust nutrition capabilities before we can stay on Mars for longer periods.

Crucial to the crew apart from food is also sensible

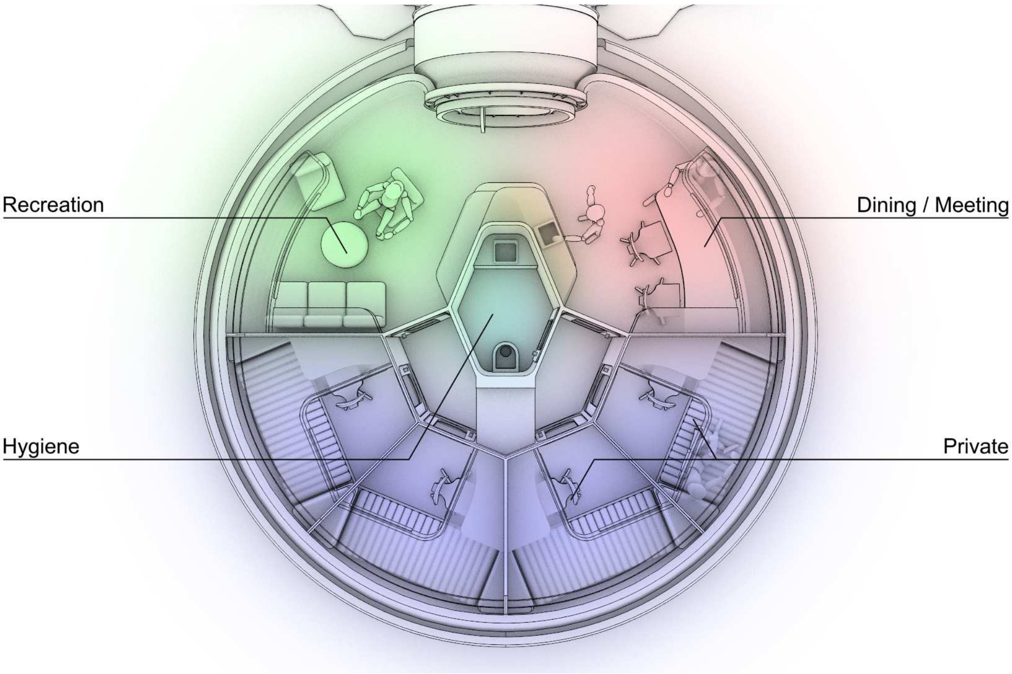

Figure 9. *Habitation module. Visualization: René Waclavicek, LSG, 2015*

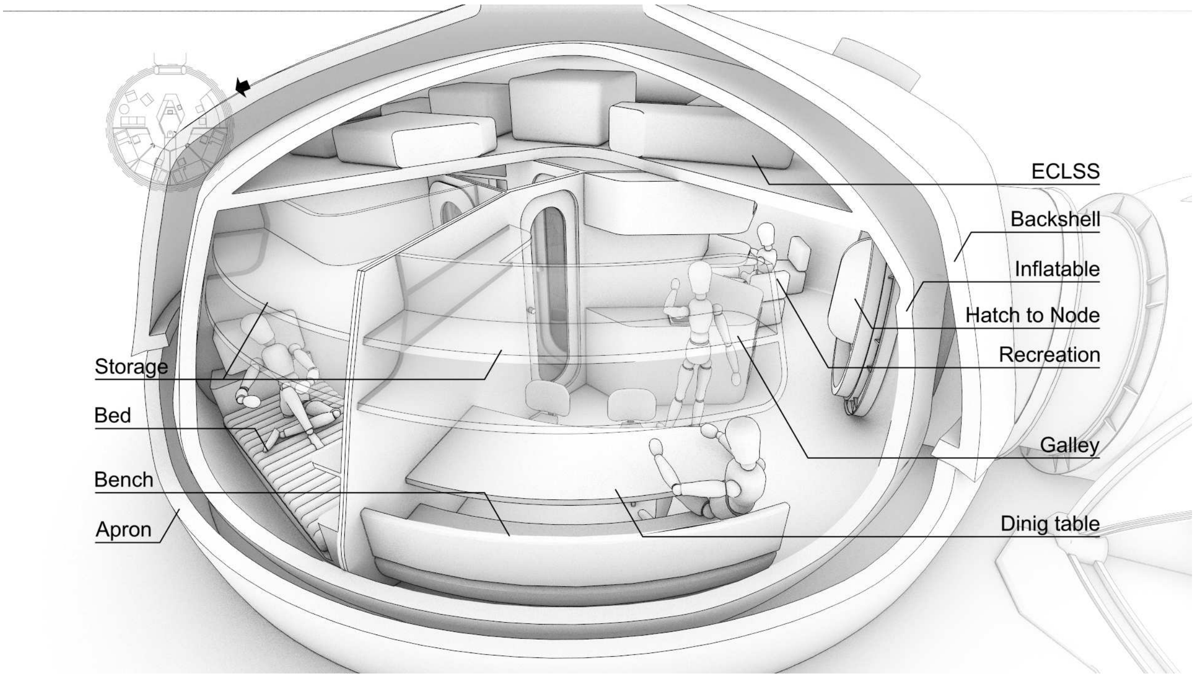

Figure 10. *Interior cutaway showing the living area and on the left a view into a crewquarter. Visualization: René Waclavicek, LSG, 2015*

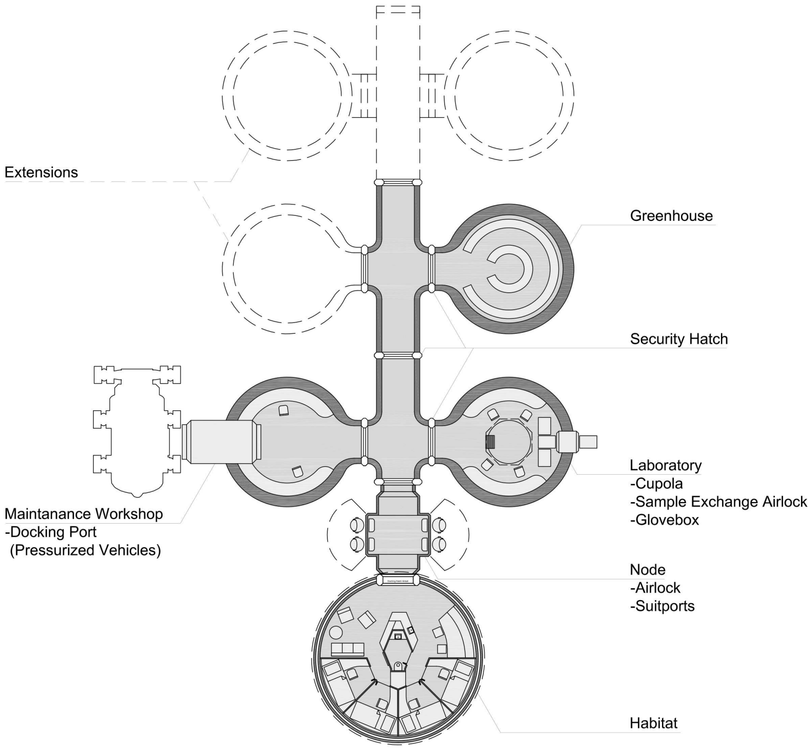

Figure 11. *Linear layout of Lava Hive concept, stemming from the habitat section. A pre-fabricated airlock node acts as the interface between the terrestrially delivered structures and the in-situ 3D printed elements. Visualization:René Waclavicek, LSG, 2015*

work to do. While Extra Vehicular Activities (EVAs) provide only for one end of scientific investigations the astronaut team will also need some facility within the habitation zone to analyse samples.

Here the authors suggest an astrobiology laboratory as described by Marc Cohen [6, 7]. The visualization in this paper is the first in a real scenario modelled after Cohen. The layout and tools are required to prevent cross-contamination. The samples would be handled by a robotic arm (see Fig. 12) and taken through a sample exchange airlock into autoclaves and glove-boxes for inspection. Some of the samples would also be taken out again since it is assumed that only particular samples would make it back to Earth. Work desks, racks and an observation deck would complement the laboratory.

To which extent the crew will be able to directly view the outside needs to be discussed since the radiation levels on Mars might be still too high to allow real windows. In specific dedicated areas, certainly not in the habitation module, a direct observation option might prove useful and not too dangerous if shutters can be closed for more solid protection against radiation.

Additional functions to be manufactured to extend the base or to add other parts could be a non-pressurized wind and dust shelter, a sort of garage to protect tools, machinery and vehicles from the Martian environment.

6 Conclusion

In this paper we discuss the Lava Hive concept, a novel 3D printed habitat made from sintered and molten Martian regolith/sand. We detail the construction process using readily accessible resources, and outline the merits of our approach in terms of achievability and specific advantages. It is a modular design for an initial surface habitation mission, with the ability to expand

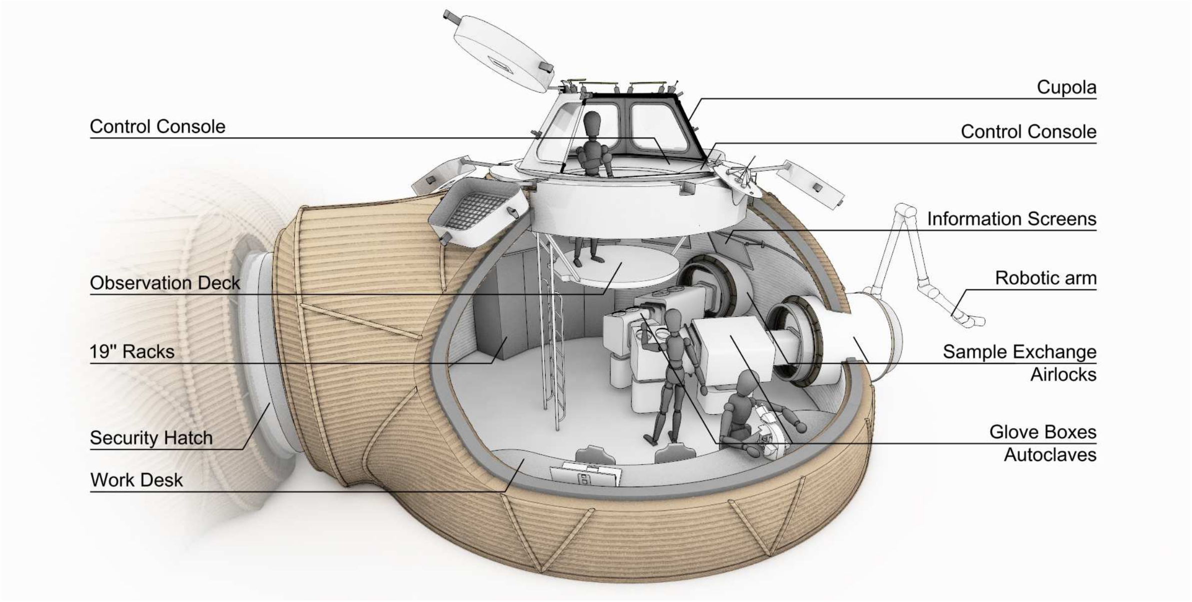

Figure 12. *Cutaway imaging of the laboratory space, with embedded cupola for site observation, sample load locks and work area. Visualization:René Waclavicek, LSG, 2015*

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, demonstrating a new approach to a Class III habitat design realized via AM and a simple resource utilization process. The main habitat houses crew living areas and critical subsystems with the subhabitats used for experiments, Martian surface exploration preparation and maintenance. With some development, we believe this approach can be terrestrially validated using simulant regolith or sand, opening up the possibility for future mission scenarios to utilize derivations of our concept. It is planned to demonstrate aspects of the lava casting process on a small scale in order to derive material characteristics and validate the fabrication approach.

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