Acta Astronautica 107 (2015) 317–326

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

# Utilizing in-situ resources and 3D printing structures for a manned Mars mission

Benjamin Kading [a,*], Jeremy Straub [b]

[a] Department of Mechanical Engineering, University of North Dakota, 243 Centennial Drive, Stop 8359, Grand Forks, ND 58202-8359, US
[b] Department of Computer Science, University of North Dakota, 3950 Campus Road, Stop 9015, Grand Forks, ND 58202-9015, US

ARTICLE INFO

*Article history:*
Received 3 July 2014
Received in revised form
22 October 2014
Accepted 22 November 2014
Available online 2 December 2014

*Keywords:*
Mars exploration
Mars habitation
Mars base
Additive manufacturing
3D printing
Basalt 3D printing

ABSTRACT

This paper presents a manned Mars mission, which is based on the use of in-situ resources for the fabrication of structures. First, it provides an overview of the two-phase mission. In phase one, robotic construction units prepare a functional base for phase-two human habitation. Then, it describes a set of prospective structures that can be created utilizing additive manufacturing (commonly known as 3D printing) techniques and in situ materials. Next, the technological advancements required to allow this type of mission are considered and their feasibility is discussed. Specific focus is given to the topics of basalt 3D printing and the maintenance of the pressure environment. The process of the construction of the base is also discussed. Finally the proposed approach is analyzed through comparison to prior missions, before concluding.



## 1. Introduction

Mars has excited humanity for some time. The prospective benefits, as Ehlmann, et al. note [1], from Martian exploration are significant. Robotic exploration (e.g., [2]) of the planet has enthralled individuals around the globe while collecting preliminary information required to support the development of Mars mission concepts for human exploration. This paper presents one such concept which is based on reducing mission launch and deep space transfer mass and volume requirements via the fabrication of most of the base structures from in-situ resources. This mission concept is not intended as an initial human mission to Mars, but instead as a longer term and larger scale successor mission once several initial missions have been completed.

This mission concept requires technical advancement in several areas beyond those typically required for Martian missions. Specifically, this work requires advancement in the development of basalt additive manufacturing (commonly known as 3D printing) technology and analysis of the produced basalt structures' permeability, ability to maintain a pressurized environment suitable for human habitation and radiation blocking properties. Several approaches which could be utilized, depending on the capabilities of the basalt structures, are considered.

The proposed mission consists of two high-level components. First, an unmanned preparation mission would be sent to build the requisite infrastructure required to support human life. With this infrastructure deployed and validated, a second mission would then be readied for launch. This second mission would carry multiple astronauts to Mars to inhabit the structures built by the robotic assembly vehicles from the first mission.

Several key mission elements are required to sustain life. Key among these are power, water, food, air and waste processing. Power for this mission could potentially be

* Corresponding author. Tel.: +1 218 348 2298.
*E-mail addresses:* benjamin.kading@my.und.edu (B. Kading), jeremy.straub@my.und.edu (J. Straub).

http://dx.doi.org/10.1016/j.actaastro.2014.11.036
0094-5765/

provided in several ways, such as a wireless microwave power system that will stay in orbit and project generated power to a receiving array on the surface (see [3]) – reducing the amount of mass that must be landed – or a solar array on the surface. Water will be brought with the astronauts, reclaimed from waste and generated from in situ materials. Initial food as well as various non-producible items will be brought from Earth. Most food for the mission, however, will be grown in an in situ hydroponics facility. This production could conceivably be mechanized. Air will be brought with the robotic mission and the astronaut-carrying mission, recycled in situ and generated from in situ materials. Waste processing and reclamation will utilize techniques that have been extensively demonstrated in prior space missions (e.g., [4]).

Upon the landing of the first unmanned mission, the spacecraft will be unloaded and prepared for the first phase of printing. Components of the main dome will be printed at this point of the mission. Once the main dome is completed, a basalt 3D printer will be constructed within. This printer will create the living dome structures. These structures will be extracted from the main dome and assembled together to create a base.

This paper continues with an overview of prior work in numerous areas. Following this, the base and its structures are detailed. Then, basalt 3D printing is considered. Next, pressurization strategies are discussed. Finally, the paper discusses the base construction process, before concluding.

## 2. Background

Mars has been an exploration target for humanity and, more specifically, NASA for a long time. The creation of any space mission inherently brings together prior work from multiple disciplines. The design of a Martian base presented herein is no different. This section provides an overview of relevant prior work in several areas.

### 2.1. Martian missions

Key to any Martian mission is transportation. Travel to Mars takes approximately 180 days [5], with several mission durations [6] – including indefinite – possible. In [7], the use of an orbit that intersects with the Earth's and Mars' orbit every 2.5 years is proposed for carrying astronauts and supplies onboard a cyclic orbiting station. Zubrin [5] proposed a "Mars Direct" plan under which an un-manned module would be launched as a precursor to begin converting the Martian atmosphere into rocket fuel, followed by a manned mission. The Mars One concept [8] – which also utilizes robotic precursors – is for a one-way mission. This would be followed by additional manned missions. Other proposals have included a two-craft/two-crew-per-craft mission which would collect in situ resources for its return [9] and a mission concept for a 920–980 day venture (with 420–570 days on Mars) utilizing electric propulsion [10]. Hoffman and Kaplan [11] and Drake, Hoffman and Beaty [12] have developed NASA Martian reference missions.

Much like placing an object into orbit, landing an object safely on Mars is complex and expensive. Various methods have been developed, including drogue chutes, parachutes [5], and retropropulsion [13]. However, numerous entry, descent and landing (EDL) challenges [14] still must be overcome to allow landing of the 20–80 t mass levels projected [14,15] for human Martian missions. While technologies used for prior robotic missions could be used for human missions, Christian, et al. [16] suggest that this may be "insufficient". Korzun, et al. [15] proposed an EDL solution for 20 t of landed, while Steinfeldt, et al. [17] proffer the possibility of a solution for up to 37.3 t of landed mass. For many Mars missions, a primary payload is landed, while a communications satellite continues in orbit to relay communications [18].

### 2.2. Astronaut needs

Astronauts require temperature-controlled and pressurized dwellings and workspaces, breathable air, food, water and other resources. They also require protection from radiation exposure. Finally, astronaut space needs are discussed.

The Martian atmosphere has a pressure of approximately 0.6% of the Earth [19]; clearly, direct exposure to which would cause numerous issues [20]. The planet's temperature, while varying by the season and day cycle, averages $-65\,^{\circ}C$ [19], compared to the Earth's average of $15\,^{\circ}C$ [21]. This limited atmosphere is comprised of 95% $CO_2$ [19], making it unsuitable for breathing, even at higher pressures.

Numerous Martian resources can be utilized, however. The soil is well-suited for growing different vegetables [22] and could be fertilized to grow other foods using, for example, a fertilizer derived from the soil's sulfur. Martian soil also contains 1% water which can be extracted via heating [23]. The soil can be used to make concrete [23] and it contains numerous other metal-oxides [23]. It also serves as a basalt supply. Water can be harvested from underground areas through wells [24] and is also present in the northern and southern cap areas [25]. In addition to use, it can also be split into components: the Hydrogen could be used for fuel or to synthesis methane, a fuel that can be used for a rocket [26] and other purposes. The atmosphere can be harvested via electrolysis. The $CO_2$ can be split into CO and O and the oxygen used in the pressurized air mixture while the CO is used as a fuel or to synthesize other fuels [5].

Mars presents a significant challenge to short and long duration exploration, as well as to later prospective settlement. Radiation protection is required, due to Mars having a minimal magnetosphere to protect the planet from sources such cosmic rays and solar radiation [27]. An astronaut on Mars quickly surpasses the US Nuclear Regulatory Commission's 5 rem annual safe exposure limit (see [28]) – potentially in as little as 30 days [29]. NASA's radiation limits are somewhat higher. Currently, NASA allows exposure of 25 rems over 30 days or 50 rems annually [30]. Both limits refer to the blood forming organs and higher exposure limits exist for the skin and eyes. This yearly limit could be exceeded in 10 months [29]. The potentially significant negative effects of excess radiation exposure and uncertainties about its prediction are discussed in [31].

Prior work has considered the space requirements of astronauts. Drake [32] considers the requirements of multiple historic missions and concludes that for long-term missions, crewmembers require 90 $m^3$ per individual. However, the historical analysis also suggests that significantly smaller volume can be utilized for shorter periods. The Mercury, Voskhod, Vostok, Gemini, Apollo LEM, Apollo CM and Soyuz all had less than 10 $m^3$ per person for periods less than 15 days; the STS had just over 10 $m^3$ per individual for nominally longer missions.

## 3. ISRU and 3D printing on Mars

A key component of the proposed mission is the use of in-situ resources and 3D printing. This section describes the properties of basalt, 3D printing technologies and a prospective basalt 3D printing approach.

### 3.1. Properties of basalt

Basalt is very common on Mars. It is an igneous rock that is commonly formed by magma extrusions during a lava flow [33]. It is composed of approximately 52% or less of $SiO_2$ [33] and a selection of other gasses. It has a Modulus of Elasticity at 73 GPa and a tensile strength of 14 MPa [34]. These numbers imply that basalt is more elastic than steel (i.e., 205 GPa for 1018 low-carbon steel [35]) and has similar elasticity to aluminum (i.e., 70 GPa for 7075 aluminum [36]). It also has a stress level breaking point in the range of some plastics, such as low density (11.6 MPa [37]) and high density (26.3 MPa [38]) polyethylene.

Basalt also has properties of radiation resistance, as it is a type of stone [39]. It also has a very high specific heat and a very low permeability constant, so it appears suitable for use in creating pressurized structures [40]. Pressurized structures are discussed in a subsequent section. In addition, basalt can be reheated and cooled at various speeds such that it crystallizes in specific ways, each of which has unique structural properties [40]. For example, if the same magma that forms basalt cools extremely slowly, it forms gabbro [40]. Basalt melts at approximately 1100 °C [33], with the exact melting point being a function of the basalt's composition.

### 3.2. Three-dimensional printing and fused deposition modeling

Three-dimensional printing is a manufacturing technique dating back to 1971 [41]. The basic concept of 3D printing, presented by Kodama in 1981 [42], is well known. The printing process requires the creation of a printing pattern [43] and then, following that pattern, the deposition of filament in multiple, stacked planar layers [44,45] to create the physical object. Berman [46] proffers that 3D printing represents a “new industrial revolution”, with it finding use in the creation of numerous items on a bespoke basis. Its use in a planetary mission may have a similarly beneficial outcome.

This drastically reduces the manufacturing cost of some parts. Methods using laser sintering and baked powders have also been employed [46]. A very common method that is used, however, is the fused deposition modelling (FDM) [46]. FDM is performed by using computer numerical control (CNC), to precisely force molten material through a die (a process called extrusion) to specific places in layers. The molten material flows onto existing material and the new and existing material fuse together as the material freezes or solidifies (much like the welding process) [46]. This approach is commonly used to print thermoplastics such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS). Advances in 3D-printing have allowed great improvements in the manufacturing process.

The basic FDM technique has been augmented through an increase in the materials that can be printed and the use of multiple techniques. For example, in addition to printing the common rigid objects using plastic [47] and metal [48], a technique for printing soft and interactive objects has recently been proposed [49]. Three-dimensional printing has also been used for textile production (e.g., [50]). Larger scale printing of models such as houses has proven to be feasible using a fast setting masonry [51].

### 3.3. Basalt 3D printing

Kelso, in [52], suggested the notion of the 3D printing of basalt, but provided an insufficient explanation of the operations of a basalt 3D printer. Cesaretti, et al. [53] and Benvenuti, Ceccanti and De Kestelier [54] have considered the concept of 3D printing with lunar regolith. Their approach, however, utilizes the D-shape process and a chemical reaction between a pre-deposited mixture of “granular material” and metal oxide and a sprayed chemical [53].

Basalt is abundant on Mars [55] and present across the entire surface of the planet [56]. Mars is, in fact, very well suited to the use of Basalt 3D printing because, as McSween, Taylor and Wyatt [56] note, it has a higher concentration of basalt content as compared to the other “rocky” planets in the solar system. This presents various advantages from its use via the FDM method. First, the melting point of this substance is not so high such that this is simply impossible. The material's use for extrusion presents two main considerations: heat and die pressure. Heat needs to be added in sufficient abundance; however, care must be taken in design to protect parts of the machine that cannot withstand this level of heat. The die also needs to be able to sustain the level of heat and pressure of the molten material being extruded [57]. Basalt's abundance on Mars removes material transportation costs. The use of 3D printing for structures is also advantageous because the structures are ready for use almost immediately after they are done printing.

Basalt also has a comparatively low permeability constant, so using it to contain the atmosphere combined with the pressurization techniques, discussed in Section 4, appears feasible. The structure of the printed dome would help with maintaining the structure of the air bags (if required); it would also support insulation material.

The proposed 3D printer would be housed, initially, inside a large dome (in construction mode, this is discussed in subsequent sections). Fig. 1 shows the printer

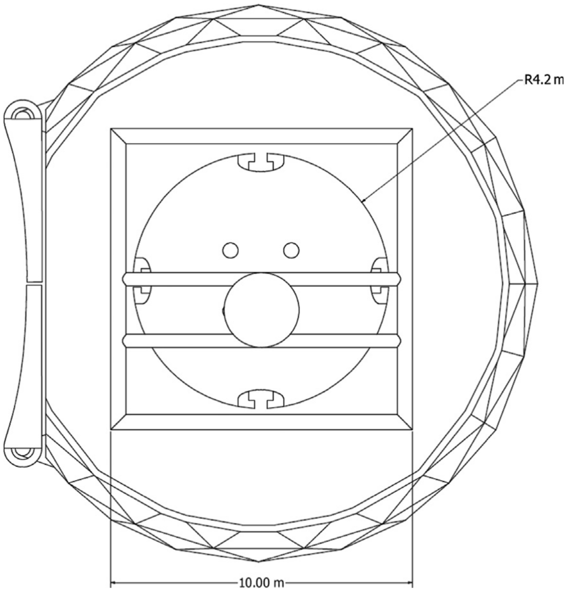


**Fig. 1.** Large dome with 3D printer and smaller dome shown.

inside the dome with one of the smaller domes shown within its print area, for reference. The printer's dimensions are 10 m × 10 m × 6 m and it has a usable print area of 9 m × 9 m × 5 m (the smaller dome has a diameter of 8.4 m and a height of 4.5 m).

The heating elements would be primarily electric heating coils. Once the basalt has been heated to a molten state, it will be extruded using a screw-style auger similar to the approach discussed in [58]. Further advancement of the proposed basalt 3D printing technique will serve as a subject for future work.

## 4. Pressurization

Pressurization is necessary to sustain astronauts life and make living and working spaces comfortable for astronauts (i.e., so they do not have to wear pressure suits). This section discusses the creation of pressurized structures and strategies for their fabrication.

### 4.1. Pressurized structures

Martian human exploration requires structures to be erected on the Martian surface. Creation of a rigid structure with a significantly greater internal pressure (compared to external pressure) has historically proven to be costly. Rigid structures have typically been employed due to their ability to maintain their form across a variety of pressures. Traditional space-based habitable structures have been made using a rigid structural approach as well [59]. This is suitable from a utilization, protection and safety perspective; however, the level of mass required by this approach precludes many mission concepts. In an environment, like space or a planetary surface, where external and internal pressures are reasonably constant, a lightweight expandable pressurized structure can be utilized instead [60]. Similar to the approach proposed by Bigelow [61,62], the structures discussed in [60] use a multilayer protective system that uses constant positive pressure to maintain the rigidity of the structure. These can be used to replace rigid structures by using pressure differentials to create the structure [60], allowing the same structural volume to be created at a fraction of the mass, cost and volume.

### 4.2. Pressurization strategies

Maintaining a pressurized living and working environment within the structures is critical. Several considerations are presented by the use of the 3D printed basalt structures which must be overcome to ensure their utility. These are now discussed and prospective solutions to each challenge are provided.

First, a question as to the permeability of the 3D printed basalt walls exists. Prior work [63–65] has characterized the permeability of basalt; however, this work did not consider the specific compositions of basalt found on Mars (see [66]) nor its use in the Earth-to-Martian atmosphere pressure differential or their relative compositions (see [67] for a discussion of the Martian atmosphere). Thus, several possible scenarios exist: the basalt may be suitably impermeable such as to prevent the substantial loss of the breathable air as printed, it may be suitably impermeable but the printing leaves gaps through which significant air escapes or it may be too permeable for this use. In the latter two cases, there is the potential that post-printing chemical treatment (such as suggested in [39]) with another chemical may make the basalt suitable for use in this way.

If the basalt is suitable for atmosphere retention, the doors present another challenge. It is planned that a Mylar-based door mechanism could be attached to the basalt walls (though further characterization of the properties of the basalt that would be utilized is needed to inform attachment strategies). One concept for this was developed by Bigelow Aerospace: an inflatable airlock [68], though the version used in conjunction with the basalt structure would necessarily differ in design and attachment mechanism.

If the Basalt fails at sufficiently containing air (as anecdotal evidence from terrestrial 3D printing suggests might occur), a second solution has been demonstrated in the design of Bigelow's inflatable spacecraft [61,69]. In this design a bladder-style air barrier [62] is used to retain air within the spacecraft. This could be inflated within the basalt structures (with the bladder being designed to perfectly align with the structure). The basalt structure would provide protection from the exterior elements, radiation shielding and insulation, while the bladder retained the atmosphere. A similar door to what is described for use without the bladder could still be utilized; however, its design would differ in that it would connect to the interior Mylar bladder, in addition to the basalt structure.

## 5. Phase 1: base & structure design and manufacturing

When the primary payload of the phase one mission lands, an autonomous robot will unload all of the necessary components for the deployment and erection of the base. Inside the spacecraft, a 3D printer will be prepared to begin printing with basalt collected by the robotic craft. The robots collect basalt rocks and load them into a hopper, from which they will be fed into a furnace to be melted for printing. The first structure which will be created will be a large dome, which will be used to 3D print the other smaller domes. After this dome is constructed, the large basalt 3D printer will be constructed within. This printer uses heavy parts carried by the rocket from Earth such as the print head, print mechanisms and heating elements. The print head and heating elements will also be used for the original in-craft printing. The remainder of this section discusses all of the structures which will comprise the base.

### *5.1. Agriculture/construction dome*

To facilitate in-situ resource utilization (ISRU) for the agriculture/construction dome (ag dome) without a larger structure to print it within, it will be produced in pieces. Triangles with a height of 2.4 m will be printed (or cast) inside the landed spacecraft and constructed into a large multipurpose ‘ag-dome’. This dome will be comprised of about 100 of these triangles. A diagram of the dome is presented in Fig. 2. It will be constructed by the robots and temporary scaffolding will be used for support during its construction. At this point, an airtight seal is not needed. The dome's primary function now is to shield the 3D printer from the elements on Mars. An outer double door helps – additionally-with protection and allows for smaller printed domes to be moved out upon completion without having to disassemble the ag dome.

After a sufficient amount of smaller domes are produced, the dome will be converted into an agricultural area. A number of the basalt structural triangles will be replaced with translucent or transparent panels to allow sunlight to enter the dome. The double doors will be replaced with a permanent wall containing a door compatible with the common connector unit described in Section 5.3.2. Once the tiles and doors are replaced, a seal will be created using a polymer similar to Fix-a-Flat or Tire Jack [70] or using an inflatable bladder and the structure will be pressurized.

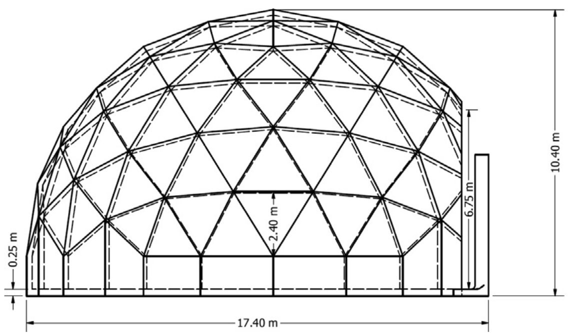


**Fig. 2.** Agriculture/construction dome diagram.

### *5.2. Modular work & living units*

Smaller 3D printed domes will be created to provide considerable living and research space. These domes have four connection ports which are sealed with a Mylar like material with bulkheads on the ends. In addition, the domes would be printed under conditions that make a seal and provide a low permeability. On the top of the dome, four service ports are included for communications, power and other various uses. A diagram of this dome is shown in Fig. 3. A variety of internal configurations of these domes can be created using easily adjustable partitions and movable fixtures. Domes can, thus, be easily reconfigured as mission needs change.

### *5.3. Services and connection units*

In addition to the primary construction/agriculture and modular living/work units, several support structures are required. These are now discussed.

#### *5.3.1. Sub-surface units*

The collection of basalt to supply the raw material for printing will result in excavated areas. Additional cylindrical units could be placed underneath the dome shaped units described in Section 5.2. These could be used for storage or as additional work or living areas.

#### *5.3.2. Connector units*

Connector units will be used to interlink the domed structures. One prospective configuration showing the ag dome before its conversion from printing to agriculture is shown in Fig. 4. These units will be printed separately and will connect to the ports of each door, crest a doorway and maintaining the structure for a Mylar liner that has an integrated bulkhead. Domes would not all be able to have direct and level connections with each other. A connector would be able to be made to bridge between two units in an irregular configuration.

#### *5.3.3. Command unit*

A command unit will be constructed to oversee the communications, life support, and various other services that require a pressurized environment. These services will include a central air exchange system, sewer, water recycling, communications and other various functions.

#### *5.3.4. Services unit*

One or more general services units will be created, with a size that is slightly larger than the standard unit, to conduct the various services that do not require a pressurized environment. These services include power conditioning, storage, and ISRU.

### *5.4. Manufacturing strategies*

This section considers logistical aspects of the construction of the Ag Dome and smaller domes. First, the robotic

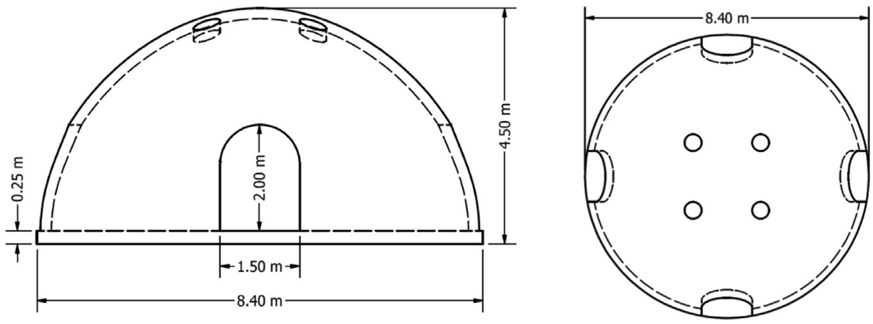


**Fig. 3.** Modular work & living units.

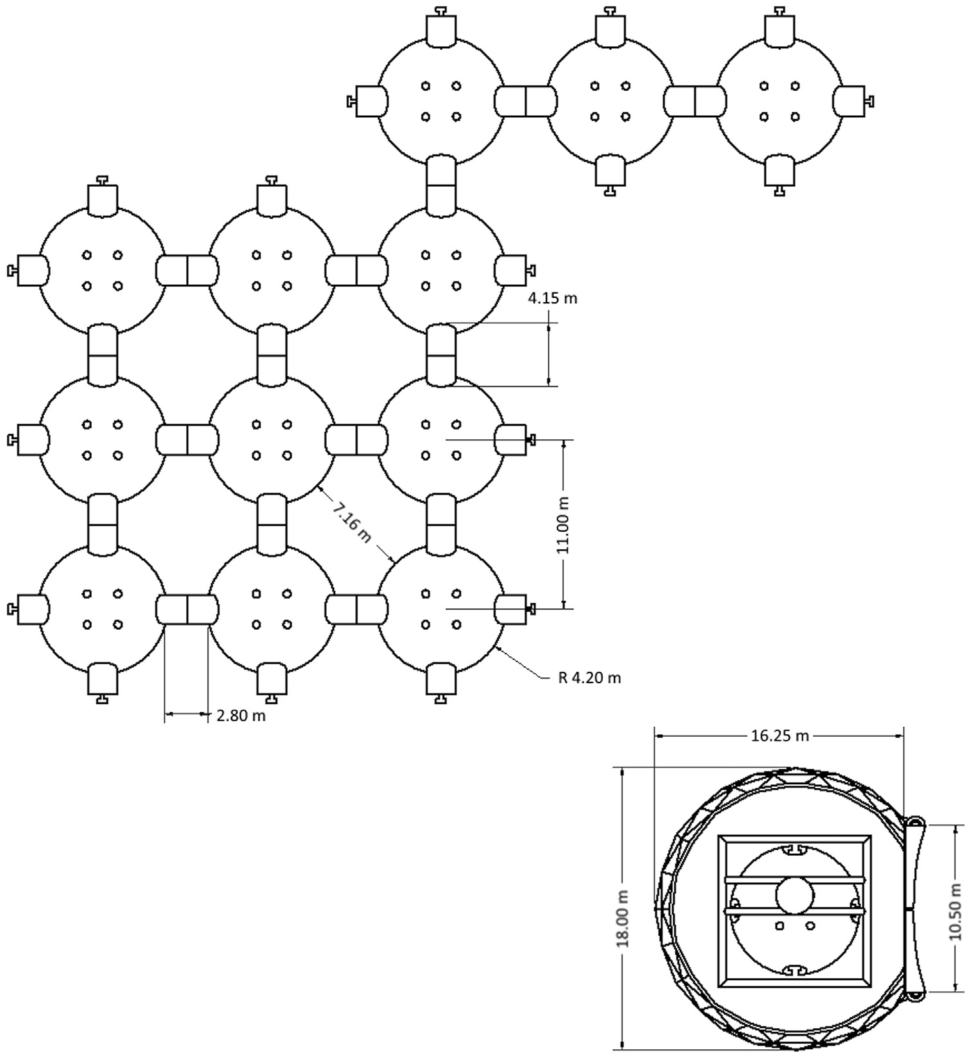


**Fig. 4.** Example base configuration midway through construction.

construction techniques utilized for the Ag Dome are discussed. Then, the robotic system for collecting Basalt is considered. Next, the printing time required for the smaller domes is characterized. Finally, the logistics of moving the smaller domes to their final location are discussed.

The Ag Dome is constructed by two robots. The first is a (comparatively) large robot, which is also utilized for basalt collection and moving the smaller domes. This robot clears the ground, as required, for the Ag Dome, lays the bottom layer and lower levels of truss. A second robot is utilized to place the upper layers of truss (which are out of reach of the larger robot) and to place (and replace, as part of the construction configuration to agricultural use configuration conversion) the panels within the truss. This smaller robot is designed to move along the truss and will, thus, utilize the lower levels of the structure to provide access to place the higher levels of the structure. This robot will also perform maintenance on this structure throughout its lifetime.

The larger robot is also responsible for basalt collection. To this end, it will go to collection locations, break the basalt apart as necessary and place it into the robot's storage bin. Once returned to the printer's location, the basalt will be further processed by the printer system for use. Mining robots have been discussed extensively in [71,72]. The detailed design of both robots will serve as a subject for future work.

While the exact characteristics of the basalt 3D printer are unknown and will be a product of ongoing work into this technology, the impact of printing speed on dome construction has been considered. Table 1 characterizes the production time of the domes as a function of the flow rate (a combination of the extrusion speed and size) of the molten basalt.

Considering the times presented in the table, it appears that only the lowest four (bottom four rows) would be desirable, as these require between 7.3 days and 8.7 h for structure production. For the 12-dome base presented in Fig. 4, this would take between 87.6 and 4.3 days. The next slowest would require 36.4 days per structure (or 1.2 years for the 12-strucutre base). Mission timing and base size requirements would drive requirement decision making, in this regard. The cooling speed of the basalt must also be considered (to ensure that the prior layer is cool enough for another to be deposited upon it). This becomes particularly important towards the top of the domes, where the layer size is smaller. The movement speed possible for the print head (considering mass and volume tradeoffs) and temperature gradients across the print head mechanisms may also constrain printing speed. The potential to utilize a less-than-complete fill (i.e., an internal lattice structure) will also be considered as part of the characterization of the material and basalt 3D printing technology relative to its ability to contain atmosphere and provide radiation resistance.

Once printed, the smaller domes will be removed from the Ag Dome by the larger (basalt collector) robot and dragged to their final location. A dolly mechanism may be required, depending on the rockiness of the base-site's terrain.

**Table 1**
Characterization of flow rate and small dome production time.

| Flow Rate ($m^3/s$) | Time (s) | Time (h) |
|---|---|---|
| $1.00 \times 10^{-6}$ | $3.14 \times 10^{7}$ | 8730 |
| $5.00 \times 10^{-6}$ | $6.28 \times 10^{6}$ | 1750 |
| $1.00 \times 10^{-5}$ | $3.14 \times 10^{6}$ | 873 |
| $5.00 \times 10^{-5}$ | $6.28 \times 10^{5}$ | 175 |
| $1.00 \times 10^{-4}$ | $3.14 \times 10^{5}$ | 87.3 |
| $5.00 \times 10^{-4}$ | $6.28 \times 10^{4}$ | 17.5 |
| $1.00 \times 10^{-3}$ | $3.14 \times 10^{4}$ | 8.73 |

### 5.5. Base configuration

As a modular structure, the base can be configured to meet particular mission science and other needs as well as to conform to terrain features. One prospective configuration is presented in Fig. 4 which demonstrates how a row could be offset to avoid a terrain feature or to place multiple air-locking doors between a hazardous area and the rest of the colony.

The construction of the base will be a multi-phase process. First, construction is designed to be performed primarily by robots sent on an unmanned phase 1 construction mission. As has been discussed, robots will, upon landing, configure the basalt 3D printer and print and deploy the base structures. These robots will be designed to operate autonomously with minimal teleoperation and oversight required. The second mission may carry additional structural elements and equipment to augment or replace these deployed during the phase 1 mission as required.

The process of basalt collection, structure production and structure deployment will be concurrent. Some of the areas that the basalt is mined from could be used to house cylindrical underground units, which a surface unit can be placed on top of and latched to. This facilitates the re-use of the areas that are mined for basalt as well as sharing the excavation expense between the basalt collection and structure deployment processes. As underground structures will benefit from the surrounding soil's insulating and radiation–resistance properties, their use is desirable.

Robotic construction of the base will take two forms: the 3D printer, housed in the agriculture/construction dome (shown in Fig. 5), will be a stationary robot, which will print ready-to-use smaller structures. These will be moved (and the agriculture/construction dome initially constructed) by construction robots. The design of these robots is beyond the scope of this paper (and has been considered extensively: e.g., [73–76]); certainly, however, they will need to work collaboratively (see [77,78]) to move the structures and to (individually as part of a coordinated group) to assemble the agriculture/construction dome.

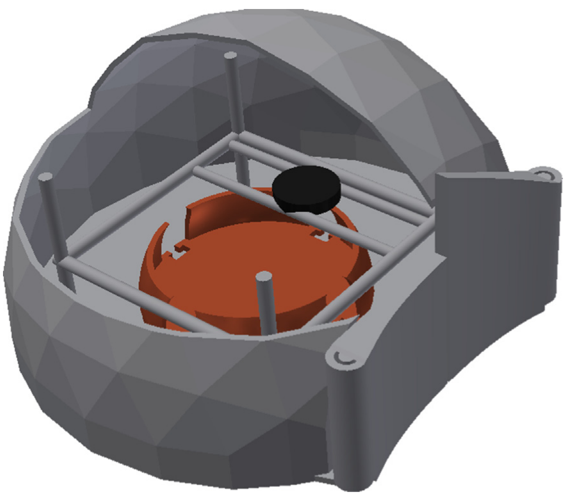

**Fig. 5.** 3D printer deployed inside ag dome.

## 6. Phase 2: human arrival

The human occupants-to-be of the basalt-printed base should arrive to find the structures close to ready for their occupation. They will need to descend in a lander module that can also serve as temporary housing. The exact requirement for this temporary human housing, while any basalt-printed structures are completed is unknown. Several factors must be considered. As was described in Section 2.2, the volume of space required for astronauts varies significantly based on mission duration. The tasks that the astronauts are required to perform in this space also, obviously, drives space needs.

Given this, the level of completeness of the structures for human occupation will be a key factor in how much temporary housing space is required. If complete automation was possible (and no safety margin was required), then the lander could provide only seating and spacesuit storage space and an airlock for the astronauts to exist. Alternately, if the astronauts will be required to perform treatment activities on the basalt structures to make them capable of pressurization or inflate bladders within them to this end and install pluming, cabling and electronic components, significantly more time (and thus more space) will be needed. The tasks that require completion would also dictate whether humans could focus on completing one pod at a time (and thus allowing it to be used immediately) or whether activities would be more effective if they proceeded in parallel. If the lander craft was to be insufficient to support the astronauts for the remainder of the mission, consideration must be given to how landing in an incorrect location would be dealt with. For landings within a drivable distance from the base, the rover and excavator/construction robot could be sent to collect the astronauts and supplies from the landing site. A landing at a distant site might represent a critical mission failure that could result in the loss of the crew and, as such, appropriate safety measures must be taken to keep the landing site within a coverable zone.

Present-day robotic capabilities would likely limit the ability to automate building construction completely; however, advances in general robotics and robotics for space applications (e.g., [79]) suggest that robotic capabilities may develop to a point where complete or near-complete automation is feasible prior to other logistical challenges to a long-duration Mars mission being resolved.

With a volume per-smaller dome of 128 $m^3$, the 12-dome base could support approximately 17 individuals, based on the 90 $m^3$ per person estimate. Given the need for additional use of space for hallways and such in a larger base, as well as the limited utility of some areas of the domes (such as close to the sides or the top – though both could be used for storage), a nominal figure of 14–15 inhabitants is projected (with the actual number dependent on base configuration and science mission/laboratory needs).

## 7. Evaluation of proposed approach

This section considers the suitability of the proposed approach in the context of several prior missions. It compares the mass requirements of other mission approaches with the in-situ basalt material 3D printing proposed herein. This comparison is, of course, of particular interest given the correlation between mass, launch costs and overall mission costs.

**Table 2**
Mass components (in kg) for proposed mission approach.

| | Proposed approach |
|---|---|
| **Surface systems** | 39,200 |
| Science | 1000 |
| Robotic rovers | 1500 |
| Human rovers | 5000 |
| Habitat | 4600 |
| Power system | 16,600 |
| ISRU | 2000 |
| Basalt printer | 5000 |
| Other | 3500 |
| **Ascent stages** | 0 |
| **Consumables** | 4000 |
| **Trans Mars Hab.** | 40,000 |
| **Total** | 83,200 |

The total mass of the mission is clearly within a launchable range. Excluding return ascent stage mass, the proposed mission has a projected mass of 83,200 kg (based on other missions, it would be between 96,000 and 116,000 kg with the ascent stage). Table 2 provides a mass source breakdown. Given other total masses, such as 115,670 for DRM-5 [12], 98,600 for STCAEM NEP [80], 99,500 for STCAEM NTR [81], 60,840 for Mars Direct, 114,100 for the 1997 NASA Reference Mission [82] and 109,981 for 2009 NASA DRA5-Adden [83], the proposed approach would appear to fall towards the middle of the pack.

These mass comparisons should not be taken as a direct assessment of this mission, however. Most of the prior missions were based on short term visit-and-return scenarios (the Mars One mission proposes long-term habitation and colonization, though). Given this, the size and configuration of the base required for these missions differs significantly from that required for the proposed longer-term mission. However, even with this, the proposed approach fares well in terms of overall mass requirements. It should be noted that the return ascent stage mass has been omitted from the proposed design (in alignment with the longer-term nature of the mission). When this is added to the total mass, the solution falls into the middle of the range of the others, in terms of projected mission mass (while offering significantly greater usable space.

A number of specific differences exist, for example, in the proposed mission: different robotic rover capabilities are required for the construction of the ag dome and movement of the habitat/workspace domes. In addition, rover capabilities are needed to harvest the basalt required for printing the various structures. In DRM-5 and many other missions, a pressurized and unpressurized rover are used. In this approach (due to the robotic pre-construction of the base), the initial settlement does not need a large pressurized rover; rather, an unpressurized rover will be sufficient.

For the proposed mission, the habitat mass was projected based on the development of a base comprised of 12 smaller domes with 15 door bulkheads and 4 service bulkheads being required. These units were estimated to have masses of 100 kg and 50 kg, respectively. The mass of the printer was estimated based on its projected size and the mass of the materials that will be required for its construction (it needs several very large steel components to deal with extruder heat).

The mass noted in the table for habitat is inclusive of the items that are required to prepare these printed structures for astronaut use. This includes life support systems, wires, plumbing hardware and electrical components. A nominal mass for inflatables or chemicals to treat the structures has also been included. The actual solution chosen may change the weight somewhat. In addition, the duration of time that astronauts must be housed in landed accommodations may also necessitate additional mass requirements. The ongoing enhancement of robotic capabilities should reduce the items that must be performed manually for structure completion, over time. Additional housing requirements, thus, must be considered in the context of when the mission is actually undertaken.

Given the foregoing, it appears that the basalt printing solution would have a similar level of mass requirement to prior mission approaches, while providing the benefit of a significantly greater amount of usable space. Given the properties of basalt, these structures would also be durable and able to support mission (and prospectively follow-on mission) needs for an extended period of time.

## 8. Conclusions & future work

This paper has provided an overview of a prospective approach to Martian exploration via utilizing in-situ resources to reduce launch and deep space transit mass and volume requirements. It has described a prospective mission design and the structures that could be constructed utilizing 3D printing of the common Martian in situ resource basalt. It has identified and analyzed two area of particular technical concern (basalt 3D printing and maintaining the base's pressure environment). In the case of the base's pressure environment, several prospective solutions (dependent on the characterization of the Martian basalt composition) have been presented. Strategies for base construction have also been discussed.

Immediate future work will focus in two areas. First, work is planned on the refinement of the basalt 3D printer (which may have terrestrial – in addition to extraterrestrial – applications) and the demonstration of a working prototype. Second, work will be performed on the characterization of several basalt compositions to better understand its utility as a pressurized structure and to ascertain the best approach to attach objects (e.g., the airlocks/doors) to it.

## Acknowledgments

Thanks are given to Kirt Leadbetter for providing information and advice related to evaluating the feasibility of 3D printing of basalt. Some facilities and equipment used for this work were provided by the UND Department of Computer Science and North Dakota EPSCoR (NSF#EPS-814442).

Thanks are also given to the anonymous reviewers who provided a number of suggestions that have significantly enhanced this paper.

## References

[1] B.L. Ehlmann, J. Chowdhury, T.C. Marzullo, R. Eric Collins, J. Litzenberger, S. Ibsen, W.R. Krauser, B. DeKock, M. Hannon, J. Kinnevan, Humans to mars: a feasibility and cost–benefit analysis, Acta Astronaut. 56 (9) (2005) 851–858.

[2] J.P. Grotzinger, J. Crisp, A.R. Vasavada, R.C. Anderson, C.J. Baker, R. Barry, D.F. Blake, P. Conrad, K.S. Edgett, B. Ferdowski, Mars science laboratory mission and science investigation, Space Sci. Rev. 170 (1-4) (2012) 5–56.

[3] J.O. McSpadden, J.C. Mankins, Space solar power programs and microwave wireless power transmission technology, Microw. Mag. IEEE 3 (4) (2002) 46–57.

[4] D.S. Parker, E.W. O'Connor and R. Bagdigian. ISS water reclamation system design, in: Proceedings of the 29th International Conference on Environmental Systems, 1999.

[5] R. Zubrin., The Case for Mars: The Plan to Settle the Red Planet and Why we Must 2011.

[6] B. Griffin, B. Thomas, D. Vaughan, B. Drake, L. Johnson and G. Woodcock. A comparison of transportation systems for human missions to mars. AIAA Paper 3834, 2004, pp. 40.

[7] D.V. Byrnes, J.M. Longuski, B. Aldrin, Cycler orbit between earth and mars, J. Spacecr. Rocket. 30 (3) (1993) 334–336.

[8] H. Keller, "Mars One: exciting adventure or hoax?", Educ. Technol. Chang. (2013). (April 8). Available: < http://etcjournal.com/2013/04/08/mars-one-exciting-adventure-or-hoax/ > .

[9] J. Marc Salotti, Simplified scenario for manned mars missions, Acta Astronaut. 69 (5) (2011) 266–279.

[10] M.S. Konstantinov, V.G. Petukhov, The analysis of manned mars mission with duration of 1000 days, Acta Astronaut. 73 (2012) 122–136.

[11] S.J. Hoffman, D.I. Kaplan, Lyndon B Johnson Space Center. Human exploration of mars. 1997.

[12] B.G. Drake, S.J. Hoffman and D.W. Beaty. Human exploration of mars, design reference architecture 5.0, in: Proceedings of the 2010 IEEE Aerospace Conference, 2010.

[13] A.M. Korzun, J.R. Cruz and R.D. Braun. A survey of supersonic retropropulsion technology for mars entry, descent, and landing, in: Proceedings of the 2008 IEEE Aerospace Conference, 2008.

[14] R.D. Braun, R.M. Manning, Mars exploration entry, descent, and landing challenges, J. Spacecr. Rocket. 44 (2) (2007) 310–323.

[15] A.M. Korzun, G.F. Dubos, C.K. Iwata, B.A. Stahl, J.J. Quicksall., A concept for the entry, descent, and landing of high-mass payloads at mars, Acta Astronaut. 66 (7) (2010) 1146–1159.

[16] J.A. Christian, G. Wells, J.M. Lafleur, A. Verges, R.D. Braun, Extension of traditional entry, descent, and landing technologies for human mars exploration, J. Spacecr. Rocket. 45 (1) (2008) 130–141.

[17] B.A. Steinfeldt, J.E. Theisinger, A.M. Korzun, I.G. Clark, M.J. Grant and R.D. Braun. High mass mars entry, descent, and landing architecture assessment. AIAA Paper 6684, 2009.

[18] C.D. Edwards, P.R. Barela, R.E. Gladden, C.H. Lee and R. De Paula. Replenishing the mars relay network, in: Proceedings of the 2014 IEEE Aerospace Conference, 2014.

[19] April 25, 2014. Mars Fact Sheet. Available: 〈http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html〉.

[20] R.W. Bancroft, J.E.I. Dunn, Experimental animal decompressions to a near-vacuum, U.S. Air Force, , 1965 (Technical Report N66 14341, 9 April 1965).

[21] July 1, 2013. Earth Fact Sheet. Available: 〈http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html〉.

[22] R.A. Kerr, Growing prospects for life on mars divide astrobiologists, Science 330 (6000) (2010) 26–27, http://dx.doi.org/10.1126/science.330.6000.26. ([doi]).

[23] C. Stoker, J. Gooding, T. Roush, A. Banin, D. Burt, B. Clark, G. Flynn, O. Gwynne., The physical and chemical properties and resource potential of martian surface soils, Resour. Near-Earth Space (1993) 659–707.

[24] J.S. Lewis, Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets, Reading, MA: Helix Books, 1997.

[25] T.N. Titus, Mars: Water, water everywhere, Nature 428 (6983) (2004) 610–611.

[26] May 4, 2007. Methane Blast. Available: 〈http://science.nasa.gov/science-news/science-at-nasa/2007/04may_methaneblast/〉.

[27] G. De Angelis, M. Clowdsley, R. Singleterry, J. Wilson, A new mars radiation environment model with visualization, Adv. Space Res. 34 (6) (2004) 1328–1332.

[28] Friday, June 28, 2013. Information for Radiation Workers. Available: ⟨http://www.nrc.gov/about-nrc/radiation/health-effects/info.html⟩.
[29] D.M. Hassler, C. Zeitlin, R.F. Wimmer-Schweingruber, B. Ehresmann, S. Rafkin, J.L. Eigenbrode, D.E. Brinza, G. Weigle, S. Bottcher, E. Bohm, S. Burmeister, J. Guo, J. Kohler, C. Martin, G. Reitz, F.A. Cucinotta, M.H. Kim, D. Grinspoon, M.A. Bullock, A. Posner, J. Gomez-Elvira, A. Vasavada, J.P. Grotzinger, MSL Science Team, Mars' surface radiation environment measured with the Mars science laboratory's curiosity rover, Science 343 (6169) (2014) 1244797, http://dx.doi.org/10.1126/science.1244797.
[30] July 30, 2014. NASA Space Flight Human-System Standard Volume 1, Revision A: Crew Health. Available: ⟨https://standards.nasa.gov/documents/viewdoc/3315622/3315622⟩.
[31] F.A. Cucinotta, W. Schimmerling, J.W. Wilson, L.E. Peterson, G.D. Badhwar, P.B. Saganti, J.F. Dicello, Space radiation cancer risks and uncertainties for Mars missions. Radiation Research 156 (5) (2009) 682-688.
[32] B.G. Drake, Reference Mission Version 3.0: Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team, 1998.
[33] 30 March 2014. VHP Photo Glossary: Basalt. Available: ⟨http://volcanoes.usgs.gov/images/pglossary/basalt.php⟩.
[34] R.A. Schultz, Brittle strength of basaltic rock masses with applications to venus, J. Geophys. Res.: Planets (1991–2012) 98 (E6) (1993) 10883–10895.
[35] AISI 1018 Steel, cold drawn. Available: ⟨http://www.matweb.com/search/DataSheet.aspx?MatGUID=3a9cc570fbb24d119f08db22a53e2421⟩.
[36] Aluminum 7075-T6; 7075-T651. Available: ⟨http://www.matweb.com/search/DataSheet.aspx?MatGUID=4f19a42be94546b686bbf43f79c51b7d⟩.
[37] Overview of materials for Low Density Polyethylene (LDPE), Molded. Available: ⟨http://www.matweb.com/search/DataSheet.aspx?MatGUID=557b96c10e0843dbb1e830ceedeb35b0&ckck=1⟩.
[38] Overview of materials for High Density Polyethylene (HDPE), Injection Molded. Available: ⟨http://www.matweb.com/search/DataSheet.aspx?MatGUID=fce23f90005d4fbe8e12a1bce53ebdc8⟩.
[39] M. Kim, S.A. Thibeault, J.W. Wilson, L.C. Simonsen, L. Heilbronn, K. Chang, R.L. Kiefer, J.A. Weakley, H.G. Maahs, Development and testing of in situ materials for human exploration of Mars, High Perform. Polym. 12 (2000) 13–26. (2000).
[40] F.J. Turner and J. Verhoogen. Igneous and Metamorphic Petrology 1960.
[41] A. Bowyer, 3D printing and humanity's first imperfect replicator, 3D Print. Addit. Manuf. 1 (1) (2014) 4–5.
[42] H. Kodama, Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer, Rev. Sci. Instrum. 52 (11) (1981) 1770–1773.
[43] C. W. Hull, Apparatus for production of three-dimensional objects by stereolithography, Mar 11, 1986. Patent US4575330 A, 1986.
[44] R.F. Housholder, Molding process, Jan 27, 1981). Patent US4247508 A, 1981.
[45] P. L. DiMatteo, Method of generating and constructing three-dimensional bodies, Jan 20, 1976). Patent US3932923 A, 1976.
[46] B. Berman, 3-D printing: the new industrial revolution, Bus. Horiz. 55 (2) (2012) 155–162.
[47] H. Lipson, M. Kurman, Fabricated: The New World of 3D Printing, 2013.
[48] L. Wang, J. Liu. Liquid phase 3D printing for quickly manufacturing conductive metal objects with low melting point alloy ink. Science China Technological Sciences 57 (9) (2014) 1721–1728.
[49] S.E. Hudson. Printing teddy bears: a technique for 3D printing of soft interactive objects, in: Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems, 2014.
[50] A. Taylor and E. Unver. 3D printing-media hype or manufacturing reality: textiles surface fashion product architecture. 2014.
[51] M. Goldin, April 28, 2014. Chinese Company Builds Houses Quickly With 3D Printing. Available: ⟨http://mashable.com/2014/04/28/3d-printing-houses-china/⟩.
[52] R. Kelso. Expanding the planetary analog test sites in hawaii-planetary basalt manipulation. Presented at AGU Fall Meeting (Abstracts), 2013.
[53] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, L. Pambaguian, Building components for an outpost on the lunar soil by means of a novel 3D printing technology, Acta Astronaut. 93 (2014) 430–450.
[54] S. Benvenuti, F. Ceccanti, X. De Kestelier, Living on the moon: topological optimization of a 3D-printed lunar shelter, Nexus Netw. J. 15 (2) (2013) 285–302.
[55] G. Dreibus, H. Wanke., Mars, a volatile-rich planet, Meteoritics 20 (1985) 367–381.
[56] H.Y. McSween Jr, G.J. Taylor, M.B. Wyatt, Elemental composition of the martian crust, Science 324 (5928) (2009) 736–739, http://dx.doi.org/10.1126/science.1165871.
[57] G. Dieter, Mechanical Metallurgy, McGraw-Hill, New York, NY, 1961.
[58] R. A. Barr and C. I. Chung, Auger-type extruder Jan 6, 1970. Patent US3487503 A, 1970.
[59] National Aeronautics and Space Administration, "Reference guide to the international space station," (Technical Report NP- 2010-09-682-HQ), National Aeronautics and Space Administration, Washington, DC, 2010.
[60] D. Cadogan, M. Grahne and M. Mikulas. Inflatable space structures: a new paradigm for space structure design, in: Proceedings of the 49th International Astronautical Congress, 1998.
[61] R. T. Bigelow. Inflatable satellite bus, November 8, 2005. US Patent 6962310 B1, 2005.
[62] R. T. Bigelow, Air barrier for use with an expandable structure, Feb 5, 2013. US Patent 8366051 B2, 2013.
[63] N.I. Christensen, R. Ramananantoandro, Permeability of the oceanic crust based on experimental studies of basalt permeability at elevated pressures, Tectonophysics 149 (1) (1988) 181–186.
[64] A.T. Fisher, Permeability within basaltic oceanic crust, Rev. Geophys. 36 (2) (1998) 143–182.
[65] M.O. Saar, M. Manga, Permeability-porosity relationship in vesicular basalts, Geophys. Res. Lett. 26 (1) (1999) 111–114.
[66] N.J. Tosca, S.M. McLennan, D.H. Lindsley, M.A. Schoonen, Acid-sulfate weathering of synthetic martian basalt: the acid fog model revisited, J. Geophys. Res.: Planets (1991–2012) 109 (E5) (2004).
[67] H.B. Franz, M.G. Trainer, M.H. Wong, H.L.K. Manning, J.C. Stern, P.R. Mahaffy, S.K. Atreya, M. Benna, P.G. Conrad, D.N. Harpold, Analytical techniques for retrieval of atmospheric composition with the quadrupole mass spectrometer of the sample analysis at mars instrument suite on mars science laboratory, Planet. Space Sci. 96 (2014) 99–113.
[68] J. Ingham and E. Haakonstad. Inflatable airlock, Patent US20120318926 A1, 2012.
[69] D. M. Barenett, Inflatable satellite, Mar 25, 2003. US6536712 B1, 2003.
[70] D. Pittman, Fix-a-flat, Chem. Eng. News (2010) 39.
[71] R.P. Mueller, P.J. Van Susante, A review of lunar regolith excavation robotic device prototypes. , Space (2011).
[72] K. Zacny, G. Mungas, C. Mungas, D. Fisher and M. Hedlund. Pneumatic excavator and regolith transport system for lunar ISRU and construction, in: Proceedings of the AIAA SPACE 2008 Conference & Exposition 2008.
[73] C.A. Parker, H. Zhang and C.R. Kube. Blind bulldozing: multiple robot nest construction, in : Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003.
[74] T. Huntsberger, G. Rodriguez, P.S. Schenker, Robotics challenges for robotic and human mars exploration, Proc. Robot. (2000) 84–90.
[75] M. Cohen and K.J. Kennedy. Habitats and surface construction: technology and development roadmap, in: NASA Conference Publication, 1997.
[76] B. Khoshnevis, Automated construction by contour crafting—related robotics and information technologies, Autom. Constr. 13 (1) (2004) 5–19.
[77] J. Wawerla, G.S. Sukhatme and M.J. Mataric. Collective construction with multiple robots, in: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2002.
[78] J. Straub, Command of a multi-tier robotic network with local decision making capabilities. Int. J. Space Sci. Eng. 2 (3), 2014.
[79] G.V. Tzvetkova, Robonaut 2: mission, technologies, perspectives, J. Theor. Appl. Mech. 44 (1) (2014) 97–102.
[80] G.R. Woodcock, Space transfer concepts and analyses for exploration missions: nuclear electric propulsion implementation plan and element description document (Boeing Technical Report NAS8-37857, March 8), 1991.
[81] G.R. Woodcock, Space transfer concepts and analyses for exploration missions: nuclear thermal rocket implementation plan and element description document boeing aerospace and electronics (Technical Report NAS8-37857, March 8), Boeing Defense and Space Group, 1991.
[82] S.J. Hoffman, D.I. Kaplan, Human exploration of mars: The reference mission of the NASA mars exploration study team (NASA Special Publication 6107, July), National Aeronautics and Space Administration, Washington, DC, 1997.
[83] B.G. Drake, Human exploration of mars design reference architecture 5.0 addendum (Technical Report NASA/SP–2009–566-ADD, July), National Aeronautics and Space Administration, Washington DC, 2009.