ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology
No. 4/2023

doi: 10.2478/ACEE-2023-0048

CONCEPTUAL ARCHITECTURAL RESPONSE TO RADIATION ON MARS

Tomasz Eugeniusz MALEC [ab]

[a] Associate Prof.; International University of Sarajevo, Faculty of Engineering and Natural Sciences, Department of Architecture, Hrasnička Cesta 15, Ilidža, 71-210 Sarajevo, Bosnia and Herzegovina

[b] Adjunct; Academy of Silesia, Rolna 15, 40-555 Katowice, Poland
ORCID: 0000-0002-8682-2720

*E-mail address: *tmalec@ius.edu.ba; tomasz.malec1@gmail.com*

Received: 29.01.2023; Revised: 15.09.2023; Accepted: 18.12.2023

Abstract

The climatic conditions on Mars are significantly different from those on Earth, which is the main factor affecting the potential architectural solutions on this planet. Above all, high levels of cosmic radiation of solar and extragalactic origin require specific architectural solutions, such as a safe location and sufficient protection, which are determined by a complex set of factors. These factors include the accessibility of building materials on site, the range and predictability of changes in climatic conditions, and human needs. In this article, the significant influence of radiation on architecture, which should be addressed when planning temporary or permanent resilient settlements on Mars, is examined in the case of manned missions to the planet. For this purpose, a comprehensive literature review is conducted, focused on the latest radiation-related discoveries. As the main outcome, two main schematic architectural solutions are proposed as a step toward more advanced projects. In addition, the gaps that need to be filled in the current approach to the design process, related to the insufficiently strong focus on multidisciplinary site analysis with radiation as its main factor (as is necessary for erecting an inhabitable base) are addressed.

Keywords: **Extraterrestrial architecture; Site analysis; Mars; Martian habitat; Cosmic radiation.**

1. INTRODUCTION

Our solar system consists of 8 (or, hypothetically, 9) planets, 5 dwarf planets, and at least 230 moons [1]. Except for the Earth (with its Moon), only Mars seems to be a reasonable place to develop any kind of artificially supported and temporary inhabited settlements. The proximity of Mars to Earth, and its relatively favorable climatic conditions (in comparison to other planets of the system), should allow humans to send expeditions that could independently survive for some time. The challenges connected with space travel and the inhabitance of Mars primarily originate from the changeable relationship between humans and their environment; human needs are a multi-level response to these circumstances. The environment of cosmic space and the planet are different from the conditions we are used to on Earth. Although early Mars had a thick, Earth-like atmosphere (about 4 billion years ago) and, probably, other similar conditions including liquid water (an ocean in its northern hemisphere, lakes, and rivers) [2, 3, 4], this has drastically changed. The main result of the, practically, lack of atmosphere is the level of radiation on the planet.

The analytical research into the architectural response to cosmic radiation on Mars has revealed general problems that must be addressed in preparation for the manned mission to the planet. They primarily focus on extended site analysis and should be thoroughly analyzed and at least theoretically verified before starting the design of inhabitable buildings. Even though most of them have been well known to scientists representing different fields, there is no confirmation that they have been considered by designers.

Firstly, all of the data collected by rovers, landers, and orbiters so far, and then later analyzed, are different for the various locations and seasons; therefore, the research should be performed on the site of the potential location of the base. This includes levels of radiation at different depths, the thickness and consistency of the regolith and water ice, as well as the types of water ice. Also, seasonal changes in primary and secondary radiation, temperature, and pressure should be measured for the same location throughout the whole Martian year; all of this information is necessary for an extensive architectural site analysis. So far, the current knowledge about Mars seems to be at a relatively early phase but is subject to extensive development that may soon enable much more detailed architectural solutions. Currently, the main problem that should be addressed is the protection from both solar and cosmic radiation, due to the very thin atmosphere and hostile climatic conditions on Mars. On June 22nd 2022, the temperature varied between -6°C and -65°C with air pressure of ca. 875 Pa at Gale Crater [5]. The thin atmosphere of Mars can even significantly increase the problem of radiation due to the production of secondary particles, mainly neutrons [6]. It should be mentioned that some of the solutions used for the protection of humans on spacecraft could potentially be adapted and subsequently applied in the architecture of the settlements on the planet.

The second problem refers to the use of suitable building materials for the construction of the base. So far, Martian concrete made in situ seems to be the best option as a material for structural elements of the base, mainly due to the availability of its components. After comprehensive trials on Earth, the structure with all its anti-radiation protection should be observed, to understand its behaviour over a certain period in the Martian environment.

The third issue remains connected with the organization of the building process on Mars, with the use of robots and artificial intelligence. The first buildings will not need any type of direct human involvement, which will allow for the safe establishment of the base and the collection of data from both the building process and the first period of the existence of a habitable base.

The fourth, and maybe the most important, group of problems refers to manned travel to Mars itself. This includes the progress of the research on active shielding against both galactic cosmic rays (GCR) and solar cosmic rays (SCR) in space, new, more efficient, and reliable propulsion systems for spacecraft (that will allow the length of travel to be shortened), and direct protection of astronauts on Mars (e.g., lightweight magnetic shields).

The fifth group of problems is concerned with the old question: is it reasonable to build a permanent, or even temporary, habitable base on Mars? Based on the scientific analysis that has been undertaken to date, it seems that the importance of the human colonization of Mars lies, rather, in achieving a state of knowledge (through experiments, observation, and analysis) that will contribute to the science and allow for extraterrestrial colonization of other, distant but more suitable, planets. Thus, the construction of temporary human settlements on Mars can be recognized as a significant step towards this aim.

All these groups of problems that must be solved due to the planned inhabitance of Mars, including possible transportation from the Earth and back, result from or indirectly refer to the protection from cosmic radiation.

2. RESEARCH APPROACH

Due to the need for a comprehensive architectural approach to the potential (non)permanent inhabitance of Mars, a thorough research on the most recent data and literature covering the issues of cosmic radiation, the human response to radiation, the problem of magnetic protection of humans, and current knowledge about Martian conditions, was undertaken. The most important part of the article focuses on a proposal of two schematic prototypes of habitable bases on Mars. The main differences between these conceptual designs follow various solutions for protection against cosmic radiation. However, in both cases, deep analysis of the Martian conditions is taken into consideration.

The weak side of the research approach results from the fast-changing information about Martian conditions due to the recent progress in research on site. Nevertheless, the design research must remain accurate, in terms of the main way of thinking about the choice of model and the location of the habitable base on the planet.

3. TYPES OF COSMIC RADIATION AND THEIR INFLUENCE ON HUMANS

The two main types of radiation are ionizing (which consists of high-energy particles which can remove electrons from their orbits) and non-ionizing. The latter

consists of low-energy particles and includes ultraviolet (UV), infrared (IF), microwave (MV), radio and extra low frequencies (RF and ELF respectively), and visible light [7]. Of these types of radiation, the most challenging will be the protection against the first one. The ionizing radiation that will affect humans during travel to Mars (and on the planet itself) includes highly penetrative GCR and SCR. Cosmic radiation has been a subject of research since the first half of the 20th century and it is better known because of theoretical research, experimental work (including CERN), and observation (spaceflights, airplane flights). Cosmic radiation of both types (GCR and SCR) comes from the solar system and deep space and consists of high-energy particles that are mostly (89%) protons, nuclei of hydrogen and helium (10%), and heavier nuclei (up to uranium) [8].

On Earth, protective mechanisms include the magnetosphere, ionosphere, and atmosphere. The ionosphere protects the Earth from the GCR and SR. Extending from around 75 to 1000 km from the Earth's surface, the ionosphere possesses particles that are stripped of one or more electrons, due to both types of cosmic radiation. It can be divided into D, E, and F zones, with the latter being characterized by the largest density of electrons [9]. In these earthly conditions, the above-mentioned protons collide with the upper part of the atmosphere and create other, secondary, particles, mainly pions. Pions are short-lived particles which decay fast, creating muons that can penetrate matter; some of them can be found on Earth, a few hundred meters under the ground. Due to the thinner atmosphere on Mars, the secondary radiation creates a much greater danger for astronauts.

GCR is of galactic and extra-galactic origin, like supernova remnants [10], and remains relatively stable, except for supernova flares. The energy spectrum of galactic protons may reach 10^{21} GeV (gigaelectron volt) with very rare particles of high energy (the energy of particles lower than $\sim 10^6$ GeV is considered to be low energy); at an energy $\sim$10 GeV their flux is 1 particle/m^2·s, in PeV (petaelectron volt)-area $\sim$1 particle/m^2·year [11]. SCR originates from the Sun, mostly from coronal ejections. The energy of particles is much lower than in the case of GCR; the spectrum varies by 1–100 MeV (megaelectron volt) particle fluxes, measured from the orbiting Earth IMP-8 satellite [12]. The Sun's emissions increase during solar proton events (SPEs), in terms of radionuclide-production rates on short timescales (up to several orders of magnitude higher than GCR [13]). During periods of low solar activity, which have occurred more often recently, the fluxes of GCR increase significantly. Because of this, Rahmanifard et al. [14] tried to predict a safe manned spaceflight duration. However, it is possible to analyze many possible outcomes of space travel and Mars inhabitance's influence on the human body even from our current perspective, due to ongoing on-ground research and space analogue environments. The most reliable knowledge can only be achieved as a result of direct, long-term experience.

Because the human body has adjusted to earthly conditions, long exposure to both GCR and SCR, as well as the resulting neutrinos, put the health and life of astronauts at risk. The risk is connected with the short and long-term effects of exposure during a stay on Mars. The level of radiation on Mars is much higher than on Earth because of its very thin atmosphere and magnetosphere. Therefore, astronauts are exposed to a total dose of approximately 0.4 mGy/day (miligray/day), where the international system unit 1 Gy (gray) is equal to 1 Sv (sievert), in the case of GCR [15]. According to Paris et al. [16], studies performed on NASA spacecraft have measured radiation levels on the surface of Mars, in the region of Hellas Planitia, to be $\sim$342 μSv/day (mikrosievert/day), which is considerably less than $\sim$547 μSv/day in other regions.

Short-term effects include all the changes in human cells that cause various types of degeneration. In particular, cosmic radiation (consisting of waves or energetic particles, together with secondary particles (mostly neutrons)) can affect DNA bases, including adenine (A), cytosine (C), guanine (G), and thymine (T) [17], damaging the strands. As a result, in the long term, this may inevitably lead to the development of cancer, with problems arising for the cardiovascular and nervous systems [18], increasing in line with the time of exposure.

In terms of cancer, the evidence of risks to humans exposed to radiation is extensive for doses above 100 mSv/year, with uncertainties for lower doses [19] while 2.4 mSv/year is experienced by everyone on Earth [20]. The personal dose limit for radiation workers, averaged over 5 years, is 100 mSv, and for all other people the average is 1 mSv/ year [21]. On the other hand, cardiovascular disease caused by radiation may affect both the heart and all the blood vessels, by narrowing or damaging their surface, while degeneration of the nervous system would critically affect the whole human body.

In particular, light symptoms may be connected with

dementia and involve a much faster weakening of cognitive functions than in the case of typical central nervous system diseases. More severe exposure can cause disruption of the communication between cells, including neurons in the brain, which causes impaired motor coordination and eventually leads to the shutting down of life processes. A similar opinion, based on experimental research on the central nervous system of rodents, was presented by Cekanaviciute et al. [22]. The study highlighted negative influences on the human body, resulting in neuronal damage, neuroinflammation, and cognitive and behavioural changes, mainly associated with loss of social, recognition and spatial memory as a result of the cosmic radiation during space travels outside of areas protected by the shielding atmosphere of Earth.

4. TYPES OF PROTECTION AGAINST COSMIC RADIATION

4.1. Active protection

Due to the knowledge that particles (from helium up to the heavier elements) can penetrate both spacecraft and human bodies, causing serious illnesses and, consequently, the death of astronauts, protection against radiation has been worked on since the end of the 1960s. One of the first ideas for the protection of humans against cosmic radiation was the use of a superconducting magnet, following earlier works from the end of the 1950s, and was based on natural Earth-centric solutions. It was published as early as 1969, by Wernher von Braun, a pioneer of the first rocket and later space technology. Since then, science has made significant progress in different fields connected with the issue of the relationship between radiation and protection from its negative impacts on the human body. Until now, both the EU-funded SR2S project and NASA's Human Research Program (HRP) have been aiming to find the best solutions to this problem. So far, a few main ways to protect the astronauts during their travel and stay on Mars are being actively considered. According to Dobynde et al. [23], aluminium shielding on spacecraft should be ~20-30 g·cm^{-2} thick but not more than ~20-30 g·cm^{-2}, to prevent the production of secondary particles. On the other hand, Rojdev and Atwell [24] claim that nanoporous carbon composites (CNTs) outperform aluminium as a shielding material, remaining material with good structural properties at the same time. Also, Naito et al. [25] theoretically proved much higher anti-radiation shielding efficiency of $^{6}Li^{10}BH^{4}$ (enriched lithium borohydride), ^{6}LiH (lithium-6 hydride), $NH^{3}BH^{3}$ (ammonia borane, a ring structure of boron and nitrogen bound via conjugated double bonds), carbon fibre reinforced plastic and SiC composite plastic, compared to aluminium. However, efficiency will only really be proved in the real conditions of cosmic travel and Mars inhabitance.

The researchers within the EU-funded SR2S project followed von Braun's scientific approach and proposed a superconducting magnetic shield used as propulsion, as a solution to cosmic radiation. Although this was specifically designed for spacecraft propulsion, the magnetic shield could prove to be useful for the protection of Mars bases from SCR and significantly limit GCR to acceptable levels, by altering the path of energized particles. However, there are still serious drawbacks to superconductive materials. There is currently a lack of a predictable external magnetic field because Mars lost its magnetic field due to hydrogen in the F-S-H core [26] and the production of high currents requires proper advanced support. On the other hand, currently known materials can only sustain the limited current necessary for stable magnetic shield activity [27]. Also, there is a possibility that long-term exposure to GCR, affecting materials that generate the protective field, may reduce magnetic shield efficiency. In Mars conditions, both the stability of the magnetic field and advanced, stable support could be, at least theoretically, sustained. In terms of materials, more theoretical and experimental research is needed. Since living organisms are continuously exposed to a natural geomagnetic field of around 20–70 μT (microtesla) thus 2–7 Gs (gauss) on Earth, this active mechanics-based solution requires in-depth studies on the influence of this specific magnetic field system (superconductive magnets and some of the small, separated magnetic fields on Mars) on the human body, especially taking its neuropsychological response into account. Moreover, a near-zero electromagnetic field could also be dangerous for living organisms [28]. A static magnetic field of 4 T or stronger may, possibly, lead to physiological changes and abnormalities at a cellular level [29]. Also, research on the influence of static magnetic fields on animals confirmed the same value as a threshold of pleasant movement, probably due to its effect on the internal ear [30].

The second quite obvious, but challenging, solution is to create an artificial magnetosphere on Mars that can protect living forms on the planet. Mars has an atmosphere consisting mostly of carbon dioxide and nitrogen that varies in different locations, with an

average pressure of 0.6% of the atmosphere of Earth, an average temperature of -60°C, and dusty airborne storms, influencing air pressure and access to light. According to Bamford et al. [31], the solution presenting the lowest possible power, assembly and mass is to create an artificially charged particle ring around the planet. This could be formed by ejecting matter from one of the moons of Mars, using both plasma and electromagnetic waves to drive a net current in the ring(s), which results in a magnetic field. However, this interesting concept needs to consider many variables, which make it possible, rather than something to expect, in the near future. One of the advantages of terraforming is the opening of a field of large-scale cosmic experiments that may lead to new scientific discoveries and accelerate cosmic expansion.

Both of the active solutions presented above follow an assumption that the development of science may lead to finding the answers to many correlated questions. Therefore, they can be considered to be futuristic plans.

4.2. Passive protection

Passive protection from cosmic radiation, mostly heavy ions, is one of the safest due to its lower complexity than active methods. According to Bloshenko et al. [32], the radiation would be reduced to earth-like intensities for facilities located at a depth of about 2,000 g/cm^2 beneath the surface of Mars. Here, architectural solutions may play an important role because of their relative scientific simplicity. They could be partially applied, because of materials that can be found on Mars, decreasing the possible complications and cost of transport. Also, their preparation may include trials in laboratory conditions on Earth, at least to some extent. For safety reasons, the next step would need to be carried out on Mars with the use of robots and artificial intelligence, before sending humans.

More permanent, predictable, and cheaper protection of habitats against cosmic radiation on Mars could be achieved by the use of protective covers made from ice. The existence of dusty water ice (H_20) [33], especially at high and mid-latitudes [34], in frost patches, frozen lakes, and the north polar cap (dry ice, i.e. frozen CO_2, has been detected at the south cap) could solve the problem of transporting building materials to Mars. A location at a lower altitude could be a good choice because the atmospheric thickness in the valleys can be approximately 10 times higher than in other, higher-located places; thus, protection against cosmic radiation significantly increases. The average pressure on Mars is ca. 753 Pa while, in the valleys and craters, it can reach ca. 800 Pa. This was confirmed by the Curiosity Rover in the Gale Crater in 2012. Atmospheric pressure reaches 1,200 Pa at (even lower) Hella Planitia [35]. However, differences in the levels of ionized radiation reaching the surface of Mars do not differ by more than 10-20%, and so the protection of astronauts remains necessary.

It is important to note that, in the central part of Valles Marineris (a system of canyons that spans ca. 4,000 km, with a maximum width of 200 km and a depth of 10 km [36]), a large amount of near-surface frozen water has recently been found under more than 40% of the area [37]. The water ice on Mars has also been detected in most of the high and mid-latitudes, beneath a centimeters-to-meters-thick covering of lithic material, forming pore ice between grains of soil [38]. The deposit thickness, measured at Utopia Planitia, ranges from ca. 80–170 m and consists of 50–85% water ice mixed with dust (which reduces its albedo) and rocks [39]. Water ice mixed with <1% of dust and small rocks significantly reduces the albedo; however, albedo particles produced on the planet's surface contribute to the radiation environment [40]. Guo et al. [41] claim that this contribution constitutes 19% of the total radiation on Mars.

In the Martian atmosphere, three types of water ice occur in the clouds: hexagonal ice, stacking disordered ice, and low-density amorphous ice (created at temperatures of 88–120 Kelvin (K), 121–135 K, and 140–145 K, respectively [42]). 0 K refers to -273.150°C. This should only be considered as a possible source of water ice on the ground.

It is possible that the amorphous characteristic of water ice on Mars was created by irradiation, as in the case of irradiation caused by electrons or ultraviolet photons. However, it should be underlined that the lower the temperature, the greater the extent of amorphization [43]. The reason for this consideration follows an important feature of the water ice. As water, it can withstand cosmic radiation and serve as a shielding material. In the case of a manned mission, the level of radiation under the layers of water ice, in all its forms existing on Mars, should be checked thoroughly before any human landing. Most probably, the water ice shielding will require at least a few meters' depth in order to perform its protective function.

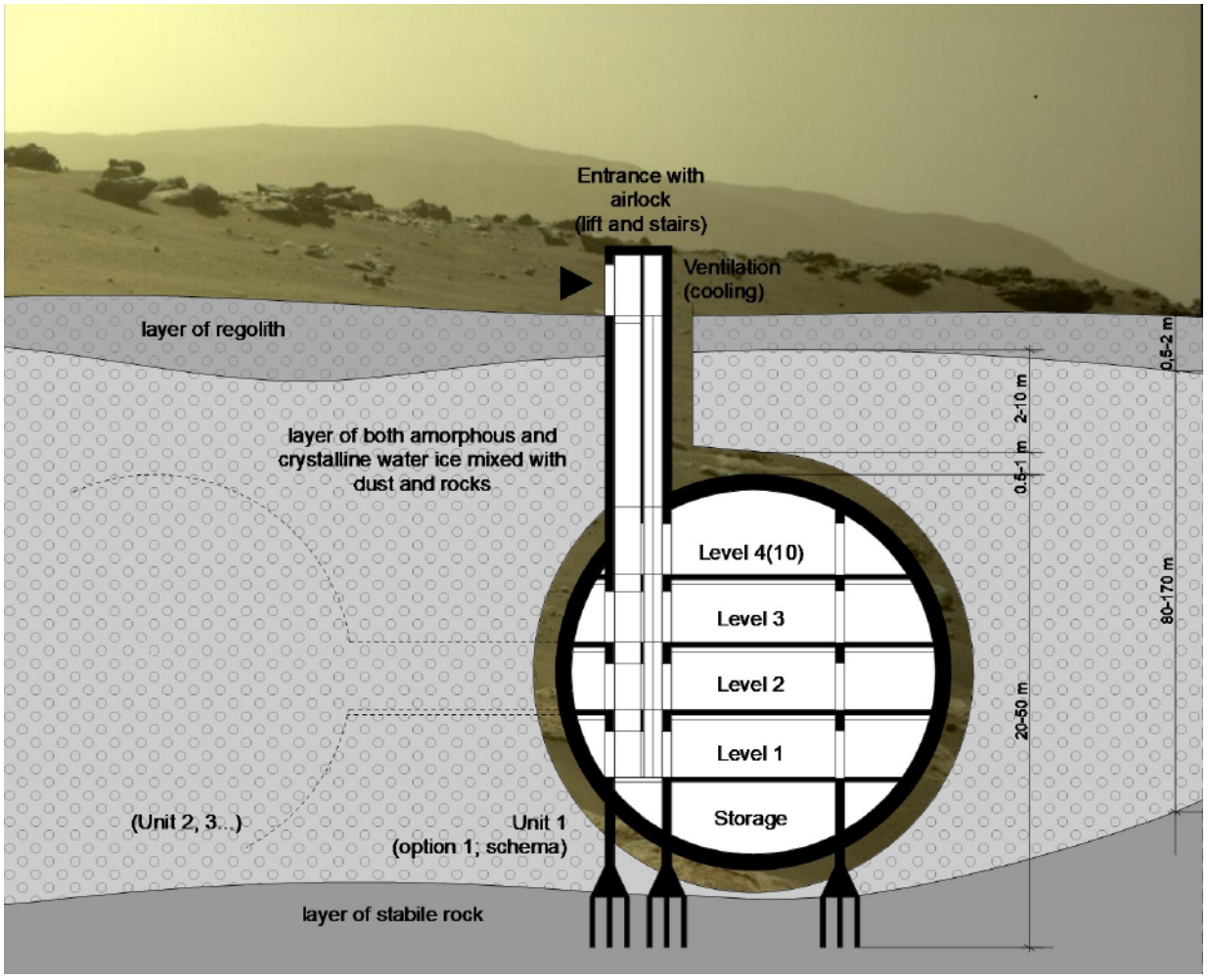


Figure 1.
Schema of protection of the habitable undersurface base (in the background: NASA/JPL-Caltech (2022). Martian landscape made on 2-8.01.22 by Perseverance rover [Photograph]. https://mars.nasa.gov/mars2020/multimedia/raw-images/image-of-the-week/week-47)

As it is reasonable to use a Mars-originating material for the protection of astronauts in potentially habitable bases, there are two main options that should be analyzed. In each case, the main aim is to keep at least two independent types of protection against radiation: an active and passive one. If one of them fails due to an unpredictable event, the other one can still perform its function.

5. ARCHITECTURAL RESPONSE TO THE COSMIC RADIATION ON MARS: THE TWO PROPOSALS

Architecture is a human response to the environment that enables survival in various types of conditions. Therefore, multidisciplinary site analysis is the key component of architectural design. This also applies to the architecture-to-be on Mars and, later, other planets. It follows that the main goal of architecture is to improve already existing living conditions to the highest possible extent; the more hostile the extraterrestrial environment, the more important the architecture becomes. Current Martian environmental conditions would allow humans a semi-open type of living that requires continuous protection. This limits the possibilities for the development of Earth-like infrastructure, requiring a different attitude. As a first step, after precisely locating properly chosen settlement areas by using unmanned orbiters and landers, the bases could be built. The second step is to build a temporary base for qualified, trained professional staff, including researchers. If this succeeds, there is still time to decide about the potential evolution of the base or the construction of new, self-sustaining habitable structures.

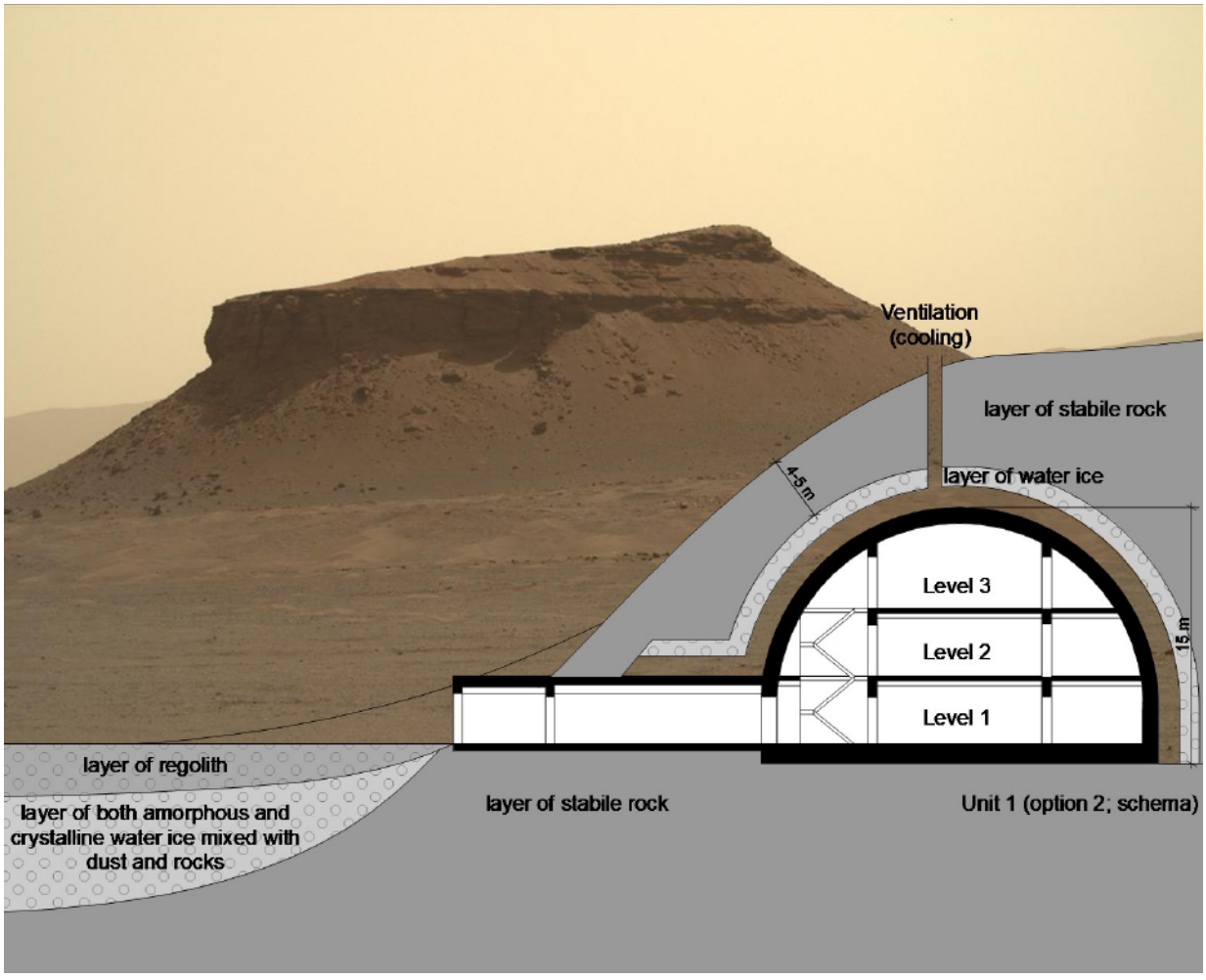


Figure 2.
Schema of protection of the habitable base inside the mountain cave (in the background: NASA/JPL-Caltech (2022). Martian landscape made on 10-16.04.22 by Perseverance rover [Photograph]. https://mars.nasa.gov/mars2020/multimedia/raw-images/image-of-the-week/week-61)

Therefore, the first option is based on building a subsurface base that could be temporarily inhabited by humans. Active protection could be formed by an artificial magnetic field of a limited range that both creates gravity and protects against radiation. Passive protection would rely on the location and the materials which the habitable premises are built from. Therefore, the base can be located under the regolith (inorganic layers of dust and rocks) and inside a thick layer of water ice, mixed with dust. The Mars Ice Home project proposed by NASA Langley Research Center in 2016 in collaboration with SEArch+ and CloudsAO also utilizes water as a shielding material [44]. Currently, this solution seems not to be feasible due to its above-ground location, which cannot protect its inhabitants from any kind of meteorite impact until a very effective active shield is discovered.

In the case of an underground structure, the protection against the charged particles and potential meteorite impact is sustained and the regolith protects the outer layer of water ice from evaporating or melting (Fig. 1). If water ice melts and the water evaporates, the partially damaged layer will be re-made by extracting water from ice and freezing it in the required place and form. The underground caves that could serve this purpose (or rather, the potential caves) were described by Cushing [45], with entrance typologies including lava tube skylights, deep fractures, pit craters, and various void spaces in karst-similar terrains. However, some of the caves may still not be visible, with hidden entrances; this is particularly true of mountain caves.

Locating the base deep under those layers has one more function as it protects astronauts from the

impact of meteorites, which are more common than on Earth, due to the thin atmosphere on Mars. On the other hand, the weak gravity field (with an acceleration of 0.38 times that of the Earth [46]) decreases the strength of the potential impact. The issue of potential meteorite impacts on the surface needs further investigation, following the existing research.

Here, the plan is to use water ice, closely surrounded by ventilated and cooled buildings, as anti-radiation protection but not for the entire base structure, as was proposed by Van Ellen and Peck [47] and others. Therefore, the structure is proposed to be made with the use of 3D printing, consisting of hydrogen-rich materials (including fibre [48]), biocomposites [49], mixed Martian soil (with a plant-based bioplastic called polylactic acid [50]), or other non-plastic materials, such as concrete. The use of a 3D printer has already been proposed during the NASA-organized 3D-Printed Habitat Challenge completed in 2019 [51], where similar methods were proposed and, by contrast with many other competitions focused on function and form, the solutions were mainly focused on the structure form relationship. The autonomously constructed structures were evaluated based on their durability, strength, leakage, and material mix. Even though all of them included above-ground structures, the solution has the potential to be applied for the purpose of structures located underground or in caves.

The materials available on Mars should take a strong form, such as a ball or cone, that is relatively resilient to any sudden or unpredictable outer impacts. The foundations of the whole structure should reach the stable rock under the layer of water ice. Strong forms were presented in some of the projects such as those presented in the above-mentioned competition or Experimental Bio-Regenerative stations with low-gravity food production designed by the Interstellar Lab [52]. This solution remains so far, the best option to apply in the environment of Mars, which still requires better recognition and understanding.

The proposal is to make concrete in situ, due to its simplicity and the potential advantages (strength, availability, and cost of materials). Since the Martian regolith mostly consists of silicon dioxide and ferric oxide, with a fair amount of aluminium oxide, calcium oxide, and sulphur oxide [53], the idea is to heat up sulphur to about 240°C, so that it becomes liquid. Later, it can be mixed with Martian soil, which acts as an aggregate, and cooled. Eventually, the sulphur solidifies, binding the aggregate and creating concrete [54].

The direct protection of the habitable premises is able to preserve an acceptable pressure and maintain breathable air components so the outer layer can also be made of Martian-made concrete. Moreover, dust storms occur on Mars so protection from dust is also necessary. These dust storms are more dangerous than those on Earth because of their higher levels of acidity, which can cause potentially life-threatening problems with respiratory diseases, immunological diseases [55], and carcinogenic chronic inflammation; the effects depend on the length of exposure.

There is one more condition that has to be taken into consideration: the toxicity of the Martian regolith. Regolith is highly toxic due to the existence of chlorine compounds which, under the influence of UV, may produce toxic substances. This toxicity, however, should not be a problem, in terms of locating the base inside Martian rock.

The second design proposal is based on the use of already existing caves in mountains or making them by drilling into hills or mountains for the purpose of protection from cosmic radiation. A similar solution was researched for Earthly conditions, as claimed earlier by Paris et al., confirming the protective characteristic of lava tubes that can serve as natural radiation shielding. Moreover, a proposal to focus on the use of underground tunnels was suggested by Bier et al. [56]. In this case, the 3D-printed concrete made with the use of regolith mixed with cement could be sprayed as structural support for those tunnels, enabling the creation of an artificial atmosphere. This solution, despite not taking into consideration the impact of meteorites, seems to be reasonable due to the recognition of the importance of other factors, such as radiation and temperature. On the other hand, the application of HVAC systems seems to be necessary for any kind of habitable Martian structure.

According to mentioned earlier Chen et al., in order to limit the level of cosmic radiation to 1 mSv/year, the thickness of the Martian soil needs to be greater than 3 m, since the effective dose of radiation is predicted at 2.7 ± 1.0 mSv/year at this depth; here, 4 to 5 m could be proposed as a sufficient barrier. The variable that has to be taken into further consideration is the potential production of secondary particles by this thickness of soil. If this is confirmed to be unsafe, the protection of the base can be strengthened by an additional layer of ventilated and cooled water ice above the building (Fig. 2). Caves can also protect astronauts from UV radiation.

Both options presented above should have a limited number of floors; the first aim is to check their

durability, so the level of safety remains low at the beginning of the process. Although the protective qualities of water ice are currently being researched, the behaviour of the substance needs to be checked under Martian conditions; above all, its long-term anti-radiative durability should be proved in situ. After finishing the building process, the protection against cosmic radiation should be thoroughly monitored before human inhabitation; this includes the production of oxygen, water, and waste economy.

It should be underlined that the solutions presented above mainly address the problem of protection against radiation and related issues such as potential meteorite impact; in the case of considering other conditions, including human needs, they need further development and verification in subsequent design steps.

7. CONCLUSIONS

The analytical research presented in this article results in two ideas for passive architectural solutions to the problem of cosmic radiation on Mars. Both of them, however, require further investigation and verification in real conditions. It should be noted that both discussed solutions theoretically prove the sustainability of controlling cosmic radiation, according to the current state of knowledge. Therefore, they present architectural responses to the environmental conditions that have been recognized and analyzed. In the near future, it could be that, due to the development of the research on Mars' climatic conditions and geology, as well as research into advanced materials for protection against cosmic radiation, new possibilities will appear. The proposed options for passive architectural protection should remain compatible with the results of in situ analysis, as far as possible. Additionally, proper planning of the future Martian habitats as well as their design and, eventually, construction should be divided into subsequent phases, relevant to environmental requirements and human needs; the research presented above on radiation could provide an example. This approach requires an organized process with specialized research and design teams focused on particular problems such as travel to Mars, the above-described protection against radiation, management of the on-site construction process, production of building materials, oxygen, and food, satisfying the psychological needs of inhabitants, etc.

In recent years, new solutions to the challenging problem of the colonization of Mars have been presented in various papers, competitions, and discussions and they have originated in different fields of science. However, the analysis of active and passive protective anti-radiation solutions has highlighted the fact that there is still a lack of comprehensive knowledge about the specific location that would be suitable for the establishment of a habitable, safe base for astronauts on Mars. Therefore, although an enormous and exciting amount of research has been carried out on the topic so far, it still needs significant enrichment, focusing on the architecture with all its scientific methodology.

REFERENCES

[1] NASA Science. (2022, May 5). *Solar System Exploration*. https://solarsystem.nasa.gov/

[2] Jakosky, B. M. (2019). The $C0_2$ inventory on Mars. *Planetary and Space Scienc*e, 175, 52–59. https://doi.org/10.1016/j.pss.2019.06.002

[3] Kurokawa, H., Kurosawa, K., & Usui, T. (2018). A lower limit of atmospheric pressure on early Mars inferred from nitrogen and argon isotopic compositions. *Icarus*, 299, 443–459. https://doi.org/10.1016/j.icarus.2017.08.020

[4] Scherf, M., & Lammer, H. (2021). Did Mars Possess a Dense Atmosphere During the First ~ 400 Million Years? *Space Science Review*, 217. https://doi.org/10.1007/s11214-020-00779-3

[5] NASA Science. (n.d.). Mars Weather. Retrieved June 23, 2023, from https://mars.nasa.gov/msl/weather/

[6] Zhang, J., Guo, J., & Dobynde, M. I. (2023). What is the Radiation Impact of Extreme Solar Energetic Particle Events on Mars? *Space Weather, 21*(6), 1–13. https://doi.org/10.1029/2023SW003490

[7] United States Department of Labor (n.d.). Non-Ionizing Radiation. https://www.osha.gov/non-ionizing-radiation

[8] European Organization for Nuclear Research [CERN]. (n.d., May 13). Cosmic rays: particles from outer space. https://home.cern/science/physics/cosmic-rays-particles-outer-space

[9] Stanford Solar Center [SSC]. (n.d., May 14). Tracking solar flares. http://solar-center.stanford.edu/SID/activities/ionosphere.html

[10] Thoudam, S., Rachen, J. P., van Vliet, A., Achterberg, A., Buitink, S., Falcke, H., & Hörandel, J.R. (2016). Cosmic-ray energy spectrum and composition up to the ankle: the case for a second Galactic component. *Astronomy & Astrophysics, 595*(A33). https://doi.org/10.1051/0004-6361/201628894

[11] Obodovskiy, I. (2019). Radiation Fundamentals, Applications, Risks, and Safety. Elsevier. https://doi.org/10.1016/C2016-0-02609-8

[12] Logachev, Yu. I., Zeldovich, M. A., Surova, G. M., & Kecskemety, K. (2003). Energy Spectrum of Galactic 10–100 MeV Protons in Quiet Sun Periods. *Cosmic Research* 41, 13–18. https://doi.org/10.1023/A:1022395311635

[13] Muscheler, R. (2013). Ice Core Methods | 10Be and Cosmogenic Radionuclides in Ice Cores. In Elias S. A. & Mock C. J. (Eds.), Encyclopedia of Quaternary Science (Second edition) (353–360). https://doi.org/10.1016/B978-0-444-53643-3.00328-9

[14] Rahmanifard, F., de Wet, N., W. C., Schwadron, A., Owens, M. J., Jordan, A. P., Wilson, J. K., Joyce, C. J., Spence, H. E., Smith, C. W., & Townsend, L. W. (2020). Galactic Cosmic Radiation in the Interplanetary Space Through a Modern Secular Minimum. *Space Weather, 18*(9). https://doi.org/10.1029/2019SW002428

[15] Hassler, D. M., Zeitlin, C., Wimmer-Schweingruber, R. F., Ehresmann, B., Rafkin, S., Eigenbrode, J. L., Brinza, D. E., Weigle, G., Böttcher, S., Böhm, E., Burmeister, S., Guo, J., Köhler, J., Martin, C., Reitz, G., Cucinotta, F. A., Kim, M.-H., Grinspoon, D., Bullock, M. A.,…Moores, J. E. (2014). Mars' Surface Radiation Environment Measured with the Mars Science Laboratory's Curiosity Rover. *Science, 343*(6169). https://doi.org/10.1126/science.1244797

[16] Paris, A. J., Davies, E. T., Tognetti, L., & Zahniser, C. (2019). Prospective Lava Tubes at Hellas Planitia. Journal of the Washington Academy of Sciences.

[17] Blanchett, A. (2017, September 19). Space Radiation is Risky Business for the Human Body. NASA. Human Research. https://www.nasa.gov/feature/space-radiation-is-risky-business-for-the-human-body

[18] NASA. (2018, June 8) Space Radiation (HRP Elements). https://www.nasa.gov/hrp/elements/radiation/risks

[19] International Commission on Radiological Protection [ICRP]. (n.d.). Recommendations. https://www.icrp.org/consultation_viewitem.asp?guid=%7B012C4E04-7B2F-4A2E-B010-B7F614B3BEE0%7D

[20] World Nuclear Association. (2022, October). *Radiation and Health Effects.* World-nuclear.org. https://world-nuclear.org/information-library/safety-and-security/radiation-and-health/radiation-and-health-effects.aspx

[21] International Atomic Energy Agency [IAEA]. (n.d.). *Radiation in Everyday Life*. https://www.iaea.org/Publications/Factsheets/English/radlife

[22] Cekanaviciute, E., Rosi S., & Costes, S.V. (2018). Central nervous system responses to simulated galactic cosmic rays. *International Journal of Molecular Sciences 19*(11). https://www.mdpi.com/1422-0067/19/11/3669/htm

[23] Dobynde, M. I., Shprits, Y. Y., Drozdov, A. Y., Hoffman, J., & LI, J. (2021). Beating 1 Sievert: Optimal Radiation Shielding of Astronauts on a Mission to Mars. *Space Weather, 19*(9). https://doi.org/10.1029/2021SW002749

[24] Rojdev, K., & Atwell, W. (2015). Hydrogen-and Methane-Loaded Shielding Materials for Mitigation of Galactic Cosmic Rays and Solar Particle Events. *Gravitational and Space Research, 3*(1). https://doi.org/10.2478/gsr-2015-0006

[25] Naito, M., Kodaira, S., Ogawara, R., Tobita, K., Someya, Y., Kusumoto, T., Kusano, H., Kitamura, H., Koike, M., Uchihori, Y., Yamanaka, M., Mikoshiba, R., Endo, T., Kiyono, N., Hagiwara, Y., Kodama, H., Matsuo, S., Takami, Y., Sato, & T., Orimo, Si. (2020). Investigation of shielding material properties for effective space radiation protection. *Life Sciences in Space Research*, 26, 69–76. https://doi.org/10.1016/j.lssr.2020.05.001

[26] Yokoo, S., Hirose, K., Tagawa, S., Morard, G., & Ohishi, Y. (2022). Stratification in planetary cores by liquid immiscibility in Fe-S-H. *Nature Communications 13*(644). https://doi.org/10.1038/s41467-022-28274-z

[27] Yao, C., & Ma, Y. (2021). Superconducting materials: Challenges and opportunities for large-scale applications. *iScience, 24*(6), 102541. https://doi.org/10.1016/j.isci.2021.102541

[28] Lutz, K., Cadiou, H., Trevino, T., & Cinelli, I. (2021). Electromagnetic Fields to Sustain Life on Earth, in Space, and Planets. 72nd International Astronautical Congress (IAC), Dubai. https://www.researchgate.net/publication/356474843_Electromagnetic_Fields_to_Sustain_Life_on_Earth_in_Space_and_Planets

[29] Norimura,T., Imada, H., Kunugita, N., Yoshida, N., & Nikaido, M. (1993). Effects of strong magnetic fields on cell growth and radiation response of human T-lymphocytes in culture. *Journal of UOEH, 15*(2), 103–112. https://doi.org/10.7888/juoeh.15.103

[30] Saunders, R. (2005). Static magnetic fields: animal studies. *Progress in Biophysics and Molecular Biology, 87*(2-3), 225–239. https://doi.org/10.1016/j.pbiomolbio.2004.09.001

[31] Bamford, R. A., Kellett, B. J., Green, J. L., Dong, C., Airapetian, V., & Bingham, B. (2021). How to create an artificial magnetosphere for Mars. *Acta Astronautica*, 190, 323–333. https://doi.org/10.1016/j.actaastro.2021.09.023

[32] Bloshenko, A. D., Robinson, J. M., Colon, R. A., & Anchordoqui, L. A. (2021). Health threat from cosmic radiation during manned missions to Mars. Proceedings of Science, 37th International Cosmic Ray Conference, 15–22 July, 2021, Berlin. https://doi:10.5281/zenodo.4327684

[33] Khuller, A. R., Christensen, P. R., & Warren, S. G. (2021). Spectral Albedo of Dusty Martian H2O Snow and Ice. *Journal of Geophysical Research: Planets, 126*(9). https://doi.org/10.1029/2021JE006910

[34] Khuller, A. R., & Christensen, P. R. (2021). Evidence of exposed dusty water ice within martian gullies. *Journal of Geophysical Reasearch: Planets*, 126. https://doi.org/10.1029/2020JE006539

[35] Zhang, J., Guo, J., Dobynde, M. I., Wang, Y., & Wimmer-Schweingruber, R. F. (2022). From the Top of Martian Olympus to Deep Craters and Beneath: Mars Radiation Environment Under Different Atmospheric and Regolith Depths. *Journal of Geophysical Research: Planets, 127*(3). https://doi.org/10.1029/2021JE007157

[36] Tillman, N. T. (2017, December 9). Valles Marineris: Facts About the Grand Canyon of Mars. Space.com. https://www.space.com/20446-valles-marineris.html

[37] Mitrofanov, I., Malkhov, A., Djachkova, A., Golovin, D., Litvak, M., Mokrousov, M., Sanin, A., Svedhem, H., & Zelenyi, L. (2022). The evidence for unusually high hydrogen abundances in the central part of Valles Marineris on Mars. *Icarus*, 374. https://doi.org/10.1016/j.icarus.2021.114805

[38] Butcher, F. E. (2022). Water Ice at Mid-Latitudes on Mars. Oxford Research Encyclopedia of Planetary Science. Oxford University Press. Retrieved 24 June 2022, from https://oxfordre.com/planetaryscience/view/10.1093/acrefore/9780190647926.001.0001/acrefore-9780190647926-e-239

[39] NASA. (2016, November 22) Mars Ice Deposit Holds as Much Water as Lake Superior. https://www.nasa.gov/feature/jpl/mars-ice-deposit-holds-as-much-water-as-lake-superior

[40] Chen, J. L., Yun, S. J., Dong, T. K., Ren, Z. Z., & Zhang, X. P. (2022). Studies of the radiation environment on the Mars surface using the Geant4 toolkit. *Nuclear Science and Techniques 33*(11). https://doi.org/10.1007/s41365-022-00987-2

[41] Guo, J., Khaksarighiri, S., Wimmer-Schweingruber, R. F., Hassler, D. M., Ehresmann, B., Zeitlin, C., Löffler, S., Matthiä, D., Berger, T., Reitz, G., & Calef, F. (2021). Directionality of the Martian Surface Radiation and Derivation of the Upward Albedo Radiation. *Geophysical Research Letters, 48*(15). https://doi.org/10.1029/2021GL093912

[42] Mangan, T. P., Plane, J. M. C., & Murray, B. J. (2021). The Phase of Water Ice Which Forms in Cold Clouds in the Mesospheres of Mars, Venus, and Earth. *Journal of Geophysical Research: Planets, 126*(3). https://doi.org/10.1029/2020JE006796

[43] Mifsud, D.V., Hailey, P.A., Herczku, P., Juhász, Z., Kovács, S. T. S., Sulik, B., Ioppolo, S., Kaňuchová, Z., McCullough, R. W., Paripás, B. & Mason, N. J. (2022). Laboratory experiments on the radiation astrochemistry of water ice phases. *The European Physical Journal D* (76)87. https://doi.org/10.1140/epjd/s10053-022-00416-4

[44] NASA. (2016, December 29) A New Home on Mars: NASA Langley's Icy Concept for Living on the Red Planet. https://www.nasa.gov/feature/langley/a-new-home-on-mars-nasa-langley-s-icy-concept-for-living-on-the-red-planet

[45] Cushing, G. E. (2015). Mars Global Cave Candidate Catalog PDS4 Archive Bundle. PDS Cartography and Imaging Sciences Node (IMG). https://doi.org/10.17189/1519222

[46] Williams, M. (2016, December 19). How strong is the gravity on Mars? Universe Today. https://www.universetoday.com/14859/gravity-on-mars/

[47] Van Ellen, L., & Peck, D. (2018). Use of in situ ice to build a sustainable radiation shielding habitat on Mars. 69th International Astronautical Congress, Bremen. https://www.researchgate.net/publication/342145558_Use_of_in_situ_ice_to_build_a_sustainable_radiation_shielding_habitat_on_Mars

[48] Blachowicz, T., & Ehrmann, A. (2021). Shielding of *Cosmic Radiation by Fibrous Materials. Fibres, 9*(60). https://doi.org/10.3390/fib9100060

[49] Roberts, A. D., Whittall, D. R., Breitling, R., Takano, E., Blaker, J. J., Hay, S., & Scrutton, N. S. (2021). Blood, sweat, and tears: extraterrestrial regolith biocomposites with in vivo binders. *Materials Today Bio*, 12. https://doi.org/10.1016/j.mtbio.2021.100136

[50] Shiwei, N., Dritsas, S., & Fernandez, J. G. (2020). Martian biolith: A bioinspired regolith composite for closed-loop extraterrestrial manufacturing. *PLoS ONE 15*(9). https://doi.org/10.1371/journal.pone.0238606

[51] NASA . (2019, May 4) Teams 3D Print Planetary Habitats, Awarded $700K in NASA Challenge. https://www.nasa.gov/directorates/spacetech/centennial_challenges/3DPHab/19-017.html

[52] Designboom (2023, February 17). Interstellar shoots for the Moon, Mars, and more. https://www.designboom.com/architecture/interstellar-lab-self-sustainable-space-pods-dassault-systemes-02-17-2023/

[53] Savage, N. (2017, December 27). To build settlements on Mars, we'll need materials chemistry. Chemical & Engineering News. https://cen.acs.org/articles/96/i1/build-settlements-Mars-ll-need.html

[54] Wan, L., Wendner, R., & Cusatis, G. (2016). A novel material for in situ construction on Mars: experiments and numerical simulations. *Construction and Building Materials*, 120, 222–231. https://doi.org/10.1016/j.conbuildmat.2016.05.046

[55] Esmaeil, N., Gharagozloo, M., Rezaei, A., & Grunig, G. (2014). Dust events, pulmonary diseases and immune system. American Journal of Clinical and Experimental Immunology, 3(1), 20-29. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3960758/

[56] Bier, H., Vermeer, E., Hidding, A., & Jani, K. (2021). Design-to-Robotic-Production of Underground Habitats on Mars. SPOOL, 8(2), 31-38. https://doi.org/10.7480/spool.2021.2.6075