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Building a New Colony
The Challenges of Architecture and Inflatable Structures

INTRODUCTION

Travelling the wider outer space has always been a dream of humanity. At the very beginning of recorded history, philosophers and thinkers looked up at the night sky of their time and wrote down with great curiosity whatever tiny lights they found. They followed the movements of these shiny dots and guessed their origins. Later, others simply wanted to go to another place, which meant crossing a river or an impassable ravine. No bridge was to be found for miles, so they began to dream of a new way of transporting their goods to their destinations. Flying.

In the West, it all started with ancient Greek mythology and was followed by other thoughts and plans through the Middle Ages till the beginning of the 20th century when an engineered tool was born and brought a new era in the history of mankind. This was just the first step in a way to conquer the skies but also led to the dream of leaving the Earth's breathable layer. Nowadays, technology has already reached the level to get tourists regularly and safely outside of the Earth's atmosphere and return them. Furthermore, the next destination has already been set, sending people to the Moon and maybe later to Mars.

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BASIC PRINCIPLES OF CONSTRUCTION – LESSONS LEARNED ON EARTH

This chapter aims to make the challenges of architecture for establishing a permanent human presence on another planet more approachable, and more understandable. To approach this problem, architects use the laws of physics, mathematics and the technologies and experience gathered here on Earth. If the exponentially accelerating rate of development of New Space continues, the next challenge will be the housing of people in newly set communities on another planet. Maybe we will name this settlement after someone, who has not yet been born, but will be sent with an expeditionary spaceship to discover new planets and to begin to build new settlements for future generations.

However, the method to reach that location, and the location to create communities on the surface of new planets are still far away and unknown. There were a lot of scientists and thinkers, already back in the 1970s, who were playing with the idea of building permanent facilities for humans under different space circumstances (Johnson–Holbrow 1977).

As the current state and goals of space programs predict, a permanent facility can be built first on the Moon. To construct any in-situ structure far away from the main supply source – Earth – makes solving difficulties a top priority. In such a case, we are talking about some prefabricated container-like rooms that meet the requirements of the Moon, and need to be assembled on site. In the beginning, these will be delivered from Earth to the Moon onboard space cargo vehicles with limited weight and size capacity. At the moment, the SLS rocket used to launch the Artemis I mission (and planned for Artemis II and III) can get around 27 tons of payload with a trans-lunar injection manoeuvre to the Moon. An average five-seater passenger car weighs around 1.5 tons, while a pick-up truck can weigh 2.5 tons. Ten pick-up trucks and one passenger car do not contain that much material in case the aim is to establish a building. If we only talk about metals in their simplest form, one cubic meter of steel weighs 7,850 kg. Titanium is 4,500 kg/m^3, while aluminium is 2,710 kg/m^3. But this is a solid block of metal, and the payload we want to get there is not a homogenous material, but rather all kinds of equipment. This could be good news on the weight side, but not on the size of the equipment, which is also limited. The equipment also needs to safely land on the target planet, which means the payload needs to include a landing module and propellant. The only good news might be that the material transported to the Moon will not need to leave the surface of the planet and get back to Earth.

However, the launch costs for SLS are approximately USD 2 billion. This shows how expensive it is to get materials on the Moon; it also shows the engineering challenges to get light-weight but still very durable and effective equipment to our celestial companion; and underlines how decreasing the launch costs with reusable rockets is of crucial importance.

Based on our experience gathered on Earth and considering the limitations, compact, durable, low-maintenance and highly effective machines, tools, energy sources and equipment need to be taken to the construction site. A modular container system could be suitable for such purposes. As a next step the building site, based on previously gathered data, shall be chosen and set ready to accommodate these containers. After the decision is made on where the containers are to be installed, a soil analysis draws the layers of materials under the designed floor level and sets the parameters of the existing load-bearing capacity of this ground. When the structural analyses of this chosen land are ready and give a positive result to take the forces without any harmful settings of the soil, a correct method of the foundation shall be chosen. This foundation is for the very first time also prefabricated and with space cargo delivered skid-like foot, on which the facility containers *(Figure 1)* are to be mounted.

The prefabrication of such skid structures with those containers in a factory on Earth also requires a well-organised training method for the complete installation on the Moon with the adequate number of astronauts. Personnel must be trained on Earth, and as a result, they will be astronauts, but also skilled in construction and able to improvise building solutions and solve easy or slightly difficult problems during installation procedures.

Figure 1
Skid structure without cover
Source: Oilfield Service Company 2020

The site preparation on Earth is difficult and time-consuming only in extremely bad soil or surface conditions, in other cases it is a simple task to do before the first building process takes place, building the foundations. This same procedure shall be executed on the surface of the Moon with a relatively low or simple set of equipment. So, the start of the construction is the end of a well thought-out and carefully executed process, with all the necessary accessories delivered to the site.

There will be at least three different sites on the surface of the Moon. The one where all the astronauts will be stationed, possibly in a spacecraft. The second place where the construction will be mounted and finally a direct landing site where cargo will arrive and place the construction material. These places must be optimised in their layout, shortcuts and detours must be designated for a complete and uninterrupted flow of operation processes. Thus, as soon as every participant landed, all equipment unpacked, tested for functionality, the faulty ones got replaced, and the containers also arrived, the construction work can start.

To mount a skid structure, at least one vehicle with a scraping device is necessary to pull the lines next to each other to achieve a uniform surface and to reach the full load-bearing capacity of the ground layer. It is known that in many regions the upper layer of the Moon is made of regolith, which is composed of loose rock and dust that sits atop a layer of bedrock. Contrary to Earth, this does not contain soil, which is a biologically active medium. On the other hand, the Moon's regolith, due to a lack of sedimentary and erosive processes present on Earth, is made of particles which can be extremely sharp. Therefore, Moon dust can be extremely damaging to equipment and as a consequence, the protection of equipment and machinery is a unique problem. This layer needs to be removed or handled in a special way before installing any permanent building elements. Construction vehicles play a key role in the site refurbishing process. The internal uniform plane of the connected rooms in the containers can also be reached within the delivered structure with hydraulic hinges *(Figure 2)* without a uniform ground below, but that would mean extra cargo loads. The installation of a simple vehicle allows its use in the following deployments. Then the unused extra cargo load of built-in hinges can be added to deliver more essential equipment to the construction site.

Figure 2
Hydraulic hinge
Source: http://koltt.com/product/hydraulic-hinges/

This construction vehicle can also be a modular platform which enables the installation of different construction tools such as the mentioned scraper, a simple drilling device, or a crane which can help unload the arriving cargo ships.

Nevertheless, in light of the above, a simple question arises: why do we need flat planes in our transported, prefabricated container laboratories when horizontal–vertical relationships theoretically exist only in the pull of Earth's gravity, where the water level gives mankind a fix and an only reference point in any structure humans ever built. (The Leaning Tower of Pisa is an exception, but it is not used in the right way). There must be a reference point, the Zero, from where you can adjust any activity and process planned in the nearby vicinity. This Zero point determines the final position of the container units prepared for assembly. Even if their connection points and joints are designed to accumulate the hardest geometrical deviations and accuracy, having a Zero point is essential for further developments, corrections or positioning of additional parts or units. Furthermore, if there is a Zero point, an absolute reference coordinate on site of the first construction, the need to use it correctly and efficiently is inevitable and we all know its advantage in any case on Earth. This reference Zero must be created as the very first step with that particular vehicle and will be the second kind of construction element humans ever made in outer space. If we interpret the term in a broad sense, the first kind of 'construction' ever set up by humans on another planet was the rod of the American flag, stuck during the Apollo missions into the cover layer of the surface.

The first steps to mount the prefabricated units in a non-earth environment are done with all the preparation to level the site, the units are mounted together and the usage of these facilities can begin. As continued with some needed expansions of this site, other prefabricated units from Earth can be added. This can lead to a situation where the occupied area reaches its initial terrain limits. The construction vehicle with its terrain-forming shovel tool can easily form the next site by moving the regolith out of the way or handling it as the site requires. This loose regolith of the planet will be collected in a barrow or can be used as filling splits under the new units or set up as a natural barrier around the settlement to give some extra protection.

There is also a limit to predesign a settlement alone from Earth. At a particular size of the enlargement of some jointed skid container structures, an in-situ planning procedure is necessary to adopt. This extra procedure requires significant outlays and extended supply chains. Such necessity can occur, if the terrain turns unfavourable for the project, or the soil under the structure shifts properties. In-situ construction material production might also be necessary. Planning further developments right next to these first human settlements or an expansion of the existing structures (and after several reiterated essential supplements and maintenance parts of these functioning settlements), there will come a point when the decision-makers will realise that further site development with space cargo delivered from Earth is not sustainable anymore. This recognition can be measured by the costs of space cargo, the high frequencies of the supply journeys or the limited time effects for such critical parts of the structures. Therefore, numerous concepts, even for more than a decade, emphasise in-situ construction material building right from the start or the very early stages. One example is regolith foam which could also be used for radiation shielding (Hein et al. 2014).

To support the idea of such settlements with permanent human habitation, there are many well-established, existing examples in the most remote parts of the world, the Arctic and Antarctica *(Figure 3)*. These examples, with all the facilitated features of bases can be considered the starting set for any base or settlement on any planet. Of course, this starting set must be complemented or even multiplied by other service areas for scientists, who must be protected from the external environment in order to concentrate and carry out their scientific tasks. For the first company of such scientists, each incident will be unique and must be resolved promptly, professionally and without critical consequences for the continued use of the settlements.

Figure 3
Amundsen–Scott South Pole Station
Source: Wikipedia, Daniel Leussler, CC-BY SA 3.0

Reaching the limits of sustainable resupply of such Lunar bases from Earth is only a question of time. There must be parallel to all scientific research processes a secondary "back office" project, which prepares the base to turn into a self-sufficient habitat, where humans can be humans, men and women live together and form a tiny society with all the necessities of mankind. At that point, the supply connection between the colony's planet (not necessarily the Moon) and Earth would have only secondary meaning. The base can produce and supply most goods. Complete self-sufficiency would be of course much harder to attain.

Needless to say, a self-sufficient habitat complex cannot exist without a source with all the supplements needed for everyday life. The deliveries of all construction parts from Earth have already been completed, so any further expansion of a settlement depends on the properties of that explored planet humans choose to conquer. Suppose we check our timeline from the first skid container-like base to this sophisticated habitat complex, an undisturbed research program shall be discovered. This research program has one aim, and that is to find material in the vicinity which will be good enough to serve as construction material for the habitat.

By the time the built space for humans on a faraway planet reaches its limits, a lot of other scientific, social, legal, ethical, etc. questions must be solved. Only when questions, such as how the new society will look like, what kind of political system they have, are there religions or not, etc. have been answered, can humans live in that habitat long enough to start to use the new resources of the newly accommodated planet. To start a project which has a target that lies outside of the barriers of daily survival challenges, such as who is the leader, who makes decisions, what command routes to follow or is there enough energy reserves, a separated group of people shall exist, who can work independently. Their necessities for existence in an extraterrestrial environment must be provided by others, who can secure a surplus of any existential goods. This independent group of people can overcome the issue of new construction materials for the extension of the habitat without any supplement from Earth. To create a construction material from the surroundings, which can withstand all the challenges of that planet a well-equipped lab, some sort of a test site, lots of independent observation, time and most importantly, enough motivation is needed to continue despite all failures that are granted in any development program.

If we look around in our architectural world today, there are several building materials from which we can build our engineering environment. These materials come directly from nature, like wood and stone or from factories like masonry, concrete, steel or aluminium and their combinations. From this approximate list of materials, only wood and stone can be found as natural resources and these can be used immediately, only with limited additional preparation, as construction materials. That is why one of the first research programs shall be to find out the practical usage of any surrounding material on another planet.

There are programs and investments which are currently analysing the possibilities of using the Lunar regolith with in-situ methods as a construction material. Such investments include 3D printing or the methods used in the processes of the U.S. Army Corps of Engineers, according to a study by NASA focusing on space-based resources for deep space exploration (NASA 2024).

Back to the example of the simple Moon base with that modular vehicle. The vehicle could create a road between two sites (the landing site and home of the astronauts) or build a barrier from the soil of the planet against any currents, winds, etc. of the location. There is another way of using the surrounding regolith of a planet, which is selected for permanent habitat but has a harsh surface "weather" situation to dig into the soil. It is practical against high radiation arriving constantly from outer space. Unfortunately, it is not an optimal long-term solution but helps a lot to gain time for further research to find a way to build facilities on the surface. This version of the structure requires a high knowledge of the regolith or soil at a deeper level. It must be understood how this material will react if a hole is dug or how it reacts as soon as it gets a heavy load from an erected structure, all this in a long-term timeframe. In many cases on Earth, the soil will settle long after the structure is built and can cause damage in the building from a visible scratch to a fatal deformation in the load-bearing system. To handle these kinds of incidents, we have every knowledge and we can design every part of the endeavour to avoid these failures on Earth. Therefore, the regolith used for construction should be well known at the outset and there should be sufficient of that material nearby to be able to complete the project.

Considering all the factors mentioned above, the facility can also be excavated with mining machinery by digging into the deep as planned. In this case, the following issue shall be solved: the route of the mining machinery must be fixed with very massive supporters *(Figure 4)*. In our everyday usage, it is concrete, wood or steel, but in a very large amount, so the newly dug path is safe against the collapse of the above layers.

Figure 4
An ordinary mine route supported with concrete arches
Source: DedMityay – stock.adobe.com

Another method to construct the new base on the surface (or half buried see *Figure 5*) and still use the protecting function of the regolith is the following: a load-bearing structure can be erected as a supporter, then the regolith can be added as a cover layer, as thick as it is needed for the radiation protection. The supporting structure shall be delivered from Earth, which must be strong enough to support the cover. Additionally, for this version of a belated construction of the protective soil layer, all elements of the base must have a radiation shielding layer, as opposed to the first version, where the base will be erected in the already protected tomb or tunnels.

Figure 5
A half-buried home
Source: Yiorgis Yerolymbos, Mold Architects (Barker 2022)

However, building structures and living continuously underground has significant biological and psychological side effects, and solving the problem of exclusion from sunlight can be as complex as finding a solution against radiation for building on the surface.

Apart from this initial use of the surrounding soil, for any other complex material, thorough research programs are needed to find possible and optimal solutions. According to our knowledge and everyday use, steel has very good properties, it is strong enough with relatively thin thickness and optimised geometrical cross-sections (I, U, L, etc.) to withstand torque, tensile or shear effects. Or reinforced concrete to withstand forces of high pressure because of its material consistency or also to withstand load-bearing moments or shear in any designed geometry an architect could imagine. But to be able to use these mentioned materials or create in situ such new building materials easily and readily, a very long and extremely complex parallel and independent development process must take place. These materials are available on Earth, but they are an end product of a very complex and sophisticated supply chain (or rather network) which takes a lot of time and effort to build and maintain. Establishing such a multi-layered and complex industrial base in situ will be extremely difficult if not impossible. Experience is also very important. On Earth, mankind has had to work on countless construction sites, where all the failures and negative properties have come to light and a wealth of experience has been accumulated. The Moon or any other planet has special circumstances and dealing with those with the limited resources available is a tremendous challenge.

Under ideal circumstances, in the first developing stages of extraterrestrial materials, the raw soil or stone samples would be transported to Earth, where scientists could create new construction materials and develop production processes optimised to the conditions of the planet. This includes all production steps from resource extraction, transport and manufacturing to energy supplies. The new materials would be the basis of any construction elements of any structural facility. These construction parts must be able to withstand the loads resulting from the load cases of simple building structures, taking into account local load factors, such as self-loading and additional dead loads (cladding, insulation, HVAC equipment, etc.), imposed loads such as variable loads resulting from the actual use of the structure, thermal loads depending on the circumstances of the new planet, fire loads or any accidental load that may occur during the lifetime of the structures (European Standards [s. a.]). Yet, humanity so far found it difficult to bring back samples for examination from distant planets. We have some samples from the Moon and asteroids, but none from Mars so far. To gather such samples is very expensive and takes a long time with our current technology. A more viable option could be to send robots to the location with onboard laboratories and analysing equipment and transfer the data back to Earth. The drawback is that these onboard laboratories may have a limited capacity and the replicated material created here on Earth would not be the same as on the other planet, it would not be subject to the same gravitational forces as on the other planet, etc.

After reaching the development level of manufacturing new construction materials and the possibility for wide-scale applications opens up, a planetwide construction project can be started. The essential attributes of those who will participate – or better said live – on that planet are the same as those who live on Earth. They need a place to live. After an exhausting shift spent in the research laboratories or their service facilities, these people also need a place where they can recharge for the next day or simply a place called home. Unlike in a scientific research laboratory where scientists only spend a certain time of their lives, these people on a planet will be born and die in those habitats and their lives will take as many twists and turns as those on Earth. These events also need facilities of similar quantity and variety to those on Earth. From a very small habitat base to a complex planetary city, there will be a need for residential areas, working places, health care and recreational places, culture centres, sports facilities, etc.

This base or independent base compounds connected via different routes will be so complex that implementing building regulations will become mandatory. The building regulations will be in power to minimise the risk to the safety of an individual living in the habitat and to annihilate all hazardous events which could lead to a malfunction of the base or turn it into a completely doomed space city.

To implement building regulations on these extraterrestrial habitats, the basic ideas of the regulations obtained on Earth can be used. In the everyday design process on Earth, the building is categorised according to the usage and planning and analysing the risk of having people inside or the importance of that building for the economy and public safety. A good example of such a complex facility is a building with different functions, an administrative building that shall be needed for housing more people. This kind of building scheme was developed in a project where the necessities of 1,000 people on Mars were the task *(Figure 6)*.

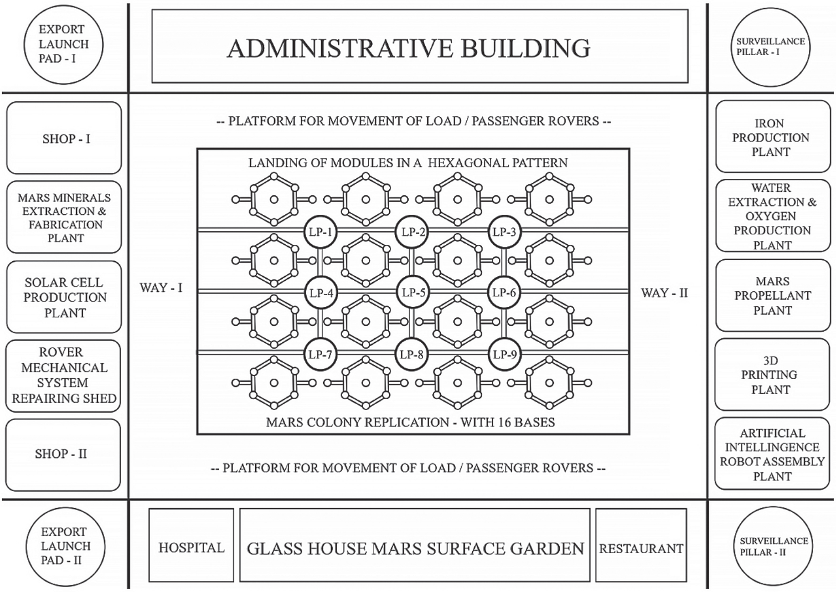

Figure 6
Facilities of a Martian colony
Source: Biswal et al. 2019

Knowing the extended boundaries for complex buildings is important for the detailed planning procedure and has a significant effect on the construction design. Such an example is to compare a single family house with a public building. The method to build a house for a family is based on their budget and the readiness and professional expertise of the construction company but it contains simple technical solutions and minimal living spaces. It is often built for a lifespan of approximately 50 years at most, but in this short lifetime, it needs to be renovated a couple of times. A public building with an expected capacity of 1,000 people has wider corridors, additional service spaces, greater rooms or an event hall which requires complex load-bearing structures. The extra housing services such as HVAC or electricity are also on a different scale and in all cases require additional spaces in the building. For such a structure all the required dimensions and building concepts are defined and with the correct execution, the building will have a much longer life-cycle. Similar and even more strict regulations will be needed when a large-scale construction or expansion starts on other planets.

After introducing the reader to some obstacles and basic principles of construction work, the chapter continues with the description of a possible solution for solving the weight and cargo space problem, while providing a good starting point for the base of operations at the early stages of a space colony.

INFLATABLE STRUCTURES IN SPACE EXPLORATION

Since the heroic age of space exploration, virtually every structure that has crossed the Kármán line and officially reached outer space has been built of metal. By the time of World War II, the durability, strength and lightness of aluminium and titanium alloys had supplanted almost all other materials in aircraft construction. Thus, when the first space technology developments were underway, all engineers and researchers naturally used these metal alloys to design and build spacecraft.

However, in the meantime, thanks to the progress of organic chemistry and plastic industry research, materials have become available that surpass these metals in many of their properties. Polymer plastics such as Kevlar or Dyneema are much lighter than the above metal alloys, but at the same time, their tensile strength is much higher than that of the metals. It is not surprising that these materials have found their way to space applications. However, they are currently used only as outer shells of metallic devices, where they act as a kind of "bulletproof vest" to protect the spacecraft from the damaging effects of micrometeorite impacts. Unfortunately, however, the protection cannot be perfect, as certain devices – solar panels or cooling radiators – cannot be covered with a cover made of such materials, as this would hinder their operation. However, reports of unprotected, and thus leaking cooling equipment clearly show that most spacecraft are effectively protected by these plastic covers.

Although even experienced pilots and astronauts are averse to structures made of plastic, development has now reached the point where the International Space Station has been boasting an inflatable plastic module for a few years now. The inflatable module of Bigelow Aerospace went into space in 2016 and docked with the space station. The largely empty module is serving mainly experimental purposes. On the one hand, the durability and pressure resistance of the structure can be checked during several years long use. On the other hand, this module also allows astronauts to get used to living in such structures when in space. In other words, the attachment of this module is intended to demonstrate that astronauts can safely use the volume provided by the inflatable modules for a long time and that their aversion to such an unconventional structure is just a habit that can be overcome.

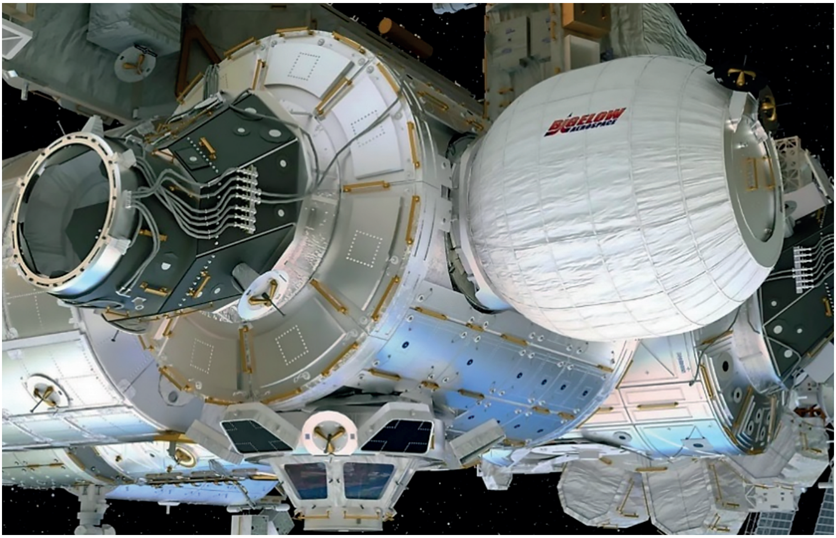

Figure 7
The inflatable module of Bigelow Aerospace docked at the ISS
Source: FOUST 2022

Since the module of Bigelow Aerospace has been providing a stable and safe living space for ISS astronauts for 7 years, other private companies have also started to plan to launch such structures into space (Seedhouse 2014). When Bigelow Aerospace was liquidated due to the economic crisis during the Covid pandemic, a significant number of specialists were employed by the Sierra Space Corporation. So, it is not surprising that this company is planning to build the so-called Orbital Reef space station in partnership with the rocket manufacturer company, Blue Origin. This space station would consist largely of inflatable modules, with metal parts only in the structure connecting them. Sierra Space and Blue Origin plan to launch the parts of the space station into orbit in 2025 with Blue Origin's New Glenn rocket, which is supposed to be operational to that date (Williams–Mosher 2022).

The biggest concern regarding the use of inflatables is proper pressure retention. Since the air pressure in outer space is practically zero, and in the inflated module a pressure of at least 0.7–0.8 bar must be ensured for comfortable breathing, the wall of the module is subjected to enormous forces. At a minimum of 0.7 bar, 70 kN is exerted on each square meter of the wall, and at the usual atmospheric pressure – at 1 bar – even more, 100 kN/m^2, is exerted from the inside to the outside. For comparison, the same force would be exerted on the wall, if we put 7 or 10 tons of weight under normal earthly conditions to every square meter. The latter is equivalent to the weight of two adult elephants, on each single square meter of surface. The wall of the inflatable module should resist these enormous forces: the deformation of the elastic material counterbalances the force exerted by the air pressure. For example, in case of a module with a diameter of 5 m and an inner pressure of 1 bar, each meter-thick strip of the wall is pulled by a force of 500 kN in opposite directions (see *Figure 8*).

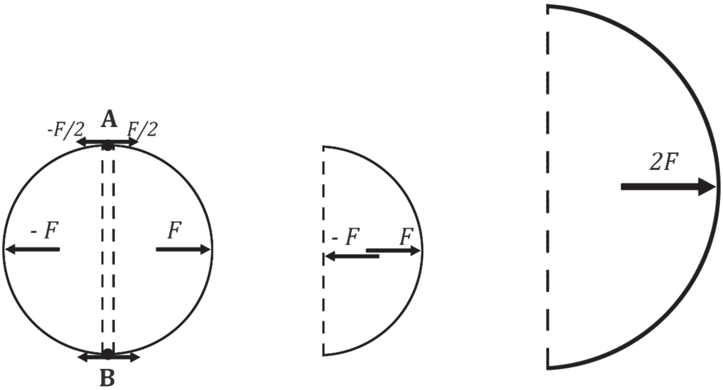

Figure 8
Pressure retention of inflatable modules in space
Note: The tensile forces arising in the wall of the cylindrical modules result from the difference between the internal and external pressure. Since the external pressure in space is practically zero, the internal "comfortable" air pressure creates enormous forces in the walls of the module. Only metals and plastics with high tensile strength can withstand these forces.
Source: Compiled by the authors

(If we imagine the inflated module shown in *Figure 8* to be cut in half between points A and B, then one half of the module is pushed to the right by the force *F* resulting from the internal air pressure, while an opposite but equal force –*F* pushes the other half to the left. The material behind the A and line B points is pulled apart by an F/2 and –*F*/2 force pair. The middle picture demonstrates that in the half module, on the side opposite to the force *F*, a force –*F* is generated due to the pressure.

In this case, however, the surface is flat, so it is easy to calculate that the force created by the air pressure is the product of the pressure [*P*] and the surface [A]: $F = P \cdot A$. But the surface created by cutting the module in half is the product of the length [*L*] and diameter [*D*] of the module: $A = L \cdot D$. Thus, the force is $F = P \cdot L \cdot D$, i.e. the product of pressure, length and diameter. This means that at a given pressure and given length, the magnitude of the force that pulls apart the walls will be proportional only to the diameter of the module. So, if we double the diameter the force is also doubled, and with three times the diameter, the force will be three times larger.)

Since the force arising in the wall increases with the diameter of the module, we might reach the tensile strength of the material in case of a large diameter module. Therefore, it is not common to design modules with a diameter larger than 5 meters for use in space. Of course, the same reasoning applies to modules made of metal, which is why metal spacecraft or space station modules are usually not more than 5 meters in diameter. But other pressure resistant containers, such as rockets used in space navigation, do not exceed 10 meters in diameter due to the cracks that occur due to the resulting tensile forces. Other pressurised vessels, such as rockets used in spacefaring, also do not exceed the 10 meters limit in diameter, since the tensile forces the pressure generates would cause the failure of the material (Bihari–Herzig 2021).

In science fiction literature, we often come across ideas in which the base built on other celestial bodies is covered by a dome, which protects the inhabitants of the base from external air pressure or the lack of air pressure, or even from a toxic atmosphere. Such a dome, however, is rarely a realistic construction. As the people living in a base covered by such a dome are used to a normal pressure of 1 bar, the internal pressure should be between 0.7 and 1.2 bar, so that too low or too high an air pressure does not cause breathing difficulties for the occupants. By changing the oxygen content of the air, it is possible to achieve different pressure values: for example, if the concentration of oxygen is increased from the usual 21% to 35%, breathing difficulties do not occur even at a relatively low pressure of 0.5 bar. But if the external pressure is practically zero, as in the case of Earth orbit or on the surface of the Moon or Mars, 0.5 bar pressure will only enable the construction of a dome with a diameter of 10 meters using the typical inflatable materials.

A large dome can only be feasible if the internal pressure is not significantly different from the external pressure. Such circumstances exist in the high atmosphere of Venus, where the air pressure is about 1 bar at an altitude of 50 km and the temperature is also acceptable, around 30°C. Here, we can think of an inflatable structure of almost any size since the air pressure can be the same outside and inside – the wall merely prevents the mixing of the external Venusian carbon dioxide atmosphere and the internal oxygen-nitrogen air. Another such possibility in the Solar System is Saturn's moon Titan, which has a surface pressure of 1.5 bar. On the surface of this moon, there are 5 km high mountains with a pressure of about 1.2 bar – still a comfortable pressure for humans. An inflatable structure of any size is therefore possible to build here, but since Titan's atmosphere is composed of nitrogen and methane, such an inflatable dome is needed to prevent the mixing of toxic external gases with the internal air.

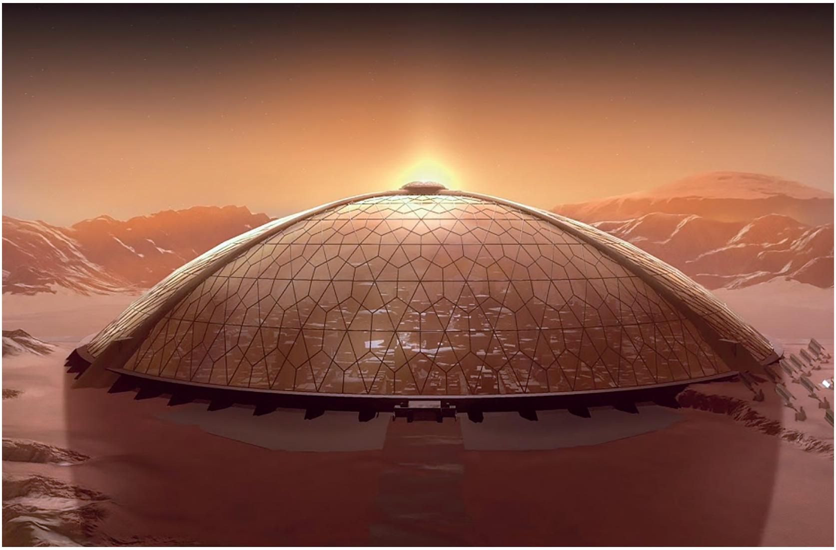

Figure 9
Protective domes in space
Note: On other celestial bodies, the construction of large domes is only realistic if there is a part of the celestial body where the air pressure is almost the same as the comfortable 1 bar pressure for us. Otherwise, enormous forces would be exerted on the dome, which would result in a large wall thickness and very large mass. However, such conditions prevail only in the upper atmosphere of Venus or on the surface of Saturn's moon Titan.
Source: Bihari – Herzig 2021

However, on other well-known celestial bodies, such as the Moon, Mars, or Mercury and the moons of Jupiter, the surface pressure is zero or very low, so the forces generated by the internal air pressure limit the size of the structures that can be built, whether they are made of metal or some kind of durable plastic. For example, in case of a 100-metre-diameter dome, which is by no means large, only a wall about 10 cm thick could withstand the forces. However, taking into account the properties of the known materials, the weight of the dome would still be several hundred tonnes, which shows that such an idea is not realistically feasible in most cases.

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In the next few decades, humanity is expected to return to the Moon and establish a permanent base there. The current political climate suggests that there will not be one such base on the Moon, but probably two, thanks to the renewed space race. One of these bases will be built by the U.S. space agency, NASA, and private U.S. companies such as SpaceX, Blue Origin and Sierra Space, in partnership with the European Space Agency and the space agencies of India, Canada and Japan. The other base will be built mainly by China and Russia, with several associated countries, Iran and other Middle Eastern countries.

The main reason for building a permanent lunar base will be to exploit the water ice reserves at the Moon's poles and the opportunities it offers. Previous studies have detected the presence of water ice, and the hydrogen of the water molecule using various methods, such as neutron backscattering, radar echo intensity analysis and the emission spectrum of the gas cloud produced by the impact of an artificial object. This water ice is expected to be found in craters close to the poles, the depths of which are never illuminated by sunlight. Due to the lack of illumination, these craters are among the coldest regions of the Solar System, where temperatures have been around –150 and –200 °C for billions of years (Lawrence, 2017).

While the depths of the craters in the north and south polar regions of the Moon are extremely cold, the protruding peaks of these areas are called the Mountains of Eternal Sunshine. On these mountain peaks and plateaus, the Sun can be seen almost continuously, since the Sun moves around the horizon in polar regions. This unusual natural phenomenon – the eternally dark craters and the constantly illuminated mountain peaks – provides a unique opportunity for mankind to establish the first outposts on the Moon. The energy supply of the base built in these permanently illuminated areas would be ensured by solar panels and unlimited sunlight. But continuous sunlight offers the possibility of plant cultivation as well. The deep craters shrouded in darkness, on the other hand, offer the possibility of mining water ice. Extraction of the latter would not only provide drinking water to the personnel of the base but would also supply the crew with oxygen – i.e. breathable air – and food through the irrigation of plants. The hydrogen and oxygen produced by splitting water could be used also as propellants for rockets.

All this means that the lunar water resources are of extreme strategic importance. Extracted water ice can be used to create a self-sustaining base on the Moon that can also produce rocket propellants. This will give the future lunar base a role as a kind of gas station. In other words, the lunar base is the springboard for exploring and colonising the rest of the Solar System. Any country or major corporation that is the first to mine ice on the Moon could gain a strategic advantage that could make it the winner of the space race and the sole ruler of Earth's economy in the 21st century.

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When designing a human habitable structure on other celestial bodies, it is very important to consider the environmental hazards of outer space. Among these sources of danger, radiation is the most significant: numerous astronomical objects in our galactic environment shower us with a diverse array of radiation. While we are on the surface of the Earth, we are protected from the vast majority of cosmic rays by the Earth's atmosphere and magnetic field. The latter deflects electrically charged particles so that most of them are absorbed by the molecules of the atmosphere around the uninhabited poles of the Earth, creating the phenomenon of the aurora borealis and australis.

Particles deflected by the Earth's magnetic field create the Van Allen radiation belts around the Earth (see the chapter on space weather.) Everything below these belts is largely protected from radiation since these high-energy particles can no longer get down there. Since space stations in low Earth orbit are also below the Van Allen belts, astronauts are still protected by the Earth's magnetic field. In the belts and above the belts, however, astronauts are exposed to the full spectrum of cosmic radiation, whether these are the solar wind protons, or X-rays from the Sun, or even high-energy particles from distant quasars. If we want to create a habitable space for humans anywhere in space beyond the Earth's magnetic field, we need to isolate that habitable space from the radiations of outer space with thick radiation shields.

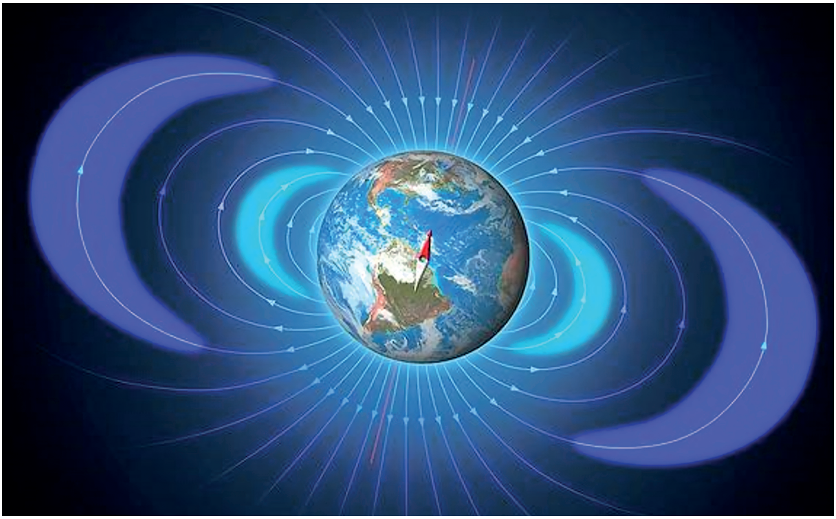

Figure 10
The Van Allen radiation belts around the Earth, shown to scale
Note: In the immediate vicinity of the Earth, at an altitude of only a few hundred kilometres from the surface, space station crews are largely shielded from the radiations by the Earth's magnetic field, although the dose rates are higher than those at the surface, where the atmosphere also has a shielding effect. However, this magnetic protection disappears further away from Earth.
Source: Evans 2018

Micrometeorites are another very serious source of danger in outer space. These tiny dust particles are usually very small, and most of them fall into the microgram range. They are usually released when comets disintegrate or when larger meteorites collide. Their velocity relative to a human habitable base to be defended can be very high, whether it is a space station orbiting the Earth or a building on another celestial body. Comets can reach speeds of up to 40–50 km/s in their orbits close to the Sun, which means that any dust grain that break away from them and move in a similar orbit will have the same speed and significant kinetic energy. For example, a grain with a diameter of less than a millimetre and a mass of a milligram can have tens of kilojoules of kinetic energy at this speed – the energy of the most powerful armour-piercing and sniper rifle projectiles.

Thus, in space architecture, the limiting factor is not only the material strength and the forces that arise from the large pressure difference but also the harmful levels of radiation and the danger of impacting micrometeorites. All these factors are threatening the living organisms in the building. On most celestial bodies – especially those without a significant atmosphere, such as the Moon or Mars – all three factors need to be taken into account during the design.

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As we have seen, the size of inflatable structures is severely limited by the thin external atmosphere, i.e. the lack of external air pressure, and the tensile strength of the materials known today. It is possible to improve the tensile strength of inflatable membranes to some extent by using special high-tensile strength ropes, but the size limit is still in the region of 5–10 m in diameter. With such a size limit, the spherical shape allows for only a relatively small interior volume. Contrary to this, the cylindrical shape sets the size in only two directions: in the longitudinal direction of the cylinder, in principle, there is no limitation to the size. In other words, instead of a spherical shape, the elongated tubular shape, which can even be closed in on itself in the form of a ring, allows much larger living spaces to be created.

In this way, the spaces to be formed can be created using three main shapes or any combination of them. Adjoining spheres, cylindrical tubes and toroidal ring shapes can be used to create interiors of varying sizes and shapes. Concentric rings or parallel tubes can even be used to create very large habitable spaces on other celestial bodies.

Due to the restrictions on the diameter, there are only three main shapes that can be useful in the design process – all buildings should be created by any combination of these. Spheres, cylindrical tubes and toroidal ring shapes should be fitted together to create interiors of varying sizes and shapes. For increasing the size, concentric rings or parallel tubes can be used, thus creating very large habitable spaces on other celestial bodies.

A key advantage of inflatable structures over traditional metal structures is their large size, despite their lightness. Considering the same weight, the inflatable structure can be an order of magnitude larger than the structure made of metal. If, for example, we have to build a structure with a mass limit of 10 tonnes, this structure, when built of metal, would be no larger than a space station module, even with relatively thin walls: it could be around 4–5 metres in diameter and 6–8 metres long. In case of inflatable structures, the diameter is also limited to about 5 metres, but for linear tubes, the length can be up to 100–150 metres. The floor area of such an inflatable structure can reach 600–700 m^2 without exceeding the mass limit of 10 tonnes.

However, there is a serious disadvantage of inflatable structures compared to traditional metal structures: they offer much less protection against the external hazards mentioned above. In low Earth orbit, this poorer protection is still a relatively acceptable compromise, since the Earth's magnetic field already provides significant protection against most of the radiation. While against the impact of micrometeorites – as in the case of Bigelow Aerospace's inflatable module – a multi-layer cover based on Kevlar fabric protects the interior.

However, for deep space applications beyond low Earth orbit, we need to provide much more effective protection for the inflatable structure itself, and for the inhabitants or even the plants grown inside. To provide the same level of radiation protection inside as we are used to on the Earth's surface, we need to protect the structure with a layer of several metres thick dense material. In terms of radiation protection, the thickness of the Earth's atmosphere is equivalent to about a 10 metres thick layer of water or a 3–4 metres thick layer of rock.

Of course, it is possible to make a compromise and use a thinner radiation protection layer to reduce the difficulties and costs of construction – thereby accepting the risks associated with higher radiation exposure and shortening the service time for astronauts. Since the radiations from the Sun and mainly the effect of the relatively low-energy solar wind are eliminated by a layer of material even only half a meter thick, and the danger caused by micrometeorites is also eliminated, the radiation protection layer is no thicker than half a meter in case of most inflatable structures. The radiation exposure in such a building is much higher than it would be on the surface of the Earth, but even such limited protection still allows a quite long service time of 1 to 2 years for the personnel.

There are already numerous plans on how to build the first outposts on the Moon or Mars. All the designs using inflatable structures agree that only the inflatable structure is transported from Earth to the celestial body in question, and the protective layer against radiation and micrometeorites is built around the inflatable structure in situ, with the help of locally available materials.

There are special designs that would use unconventional materials to form the radiation shielding layer around the inflatable module. In case of Mars, for example, some designs would use local water ice to build a protective layer. Of course, such solutions can only work if the temperature at the building site is constantly below freezing. Below –20 °C to be precise, because above such temperatures ice can melt due to an increase in pressure, whereas in the case of the lower layers of the ice building, the weight of the upper layers can create this pressure increase. In other words, such an ice dome can survive for long only in very cold climates, even on Mars.

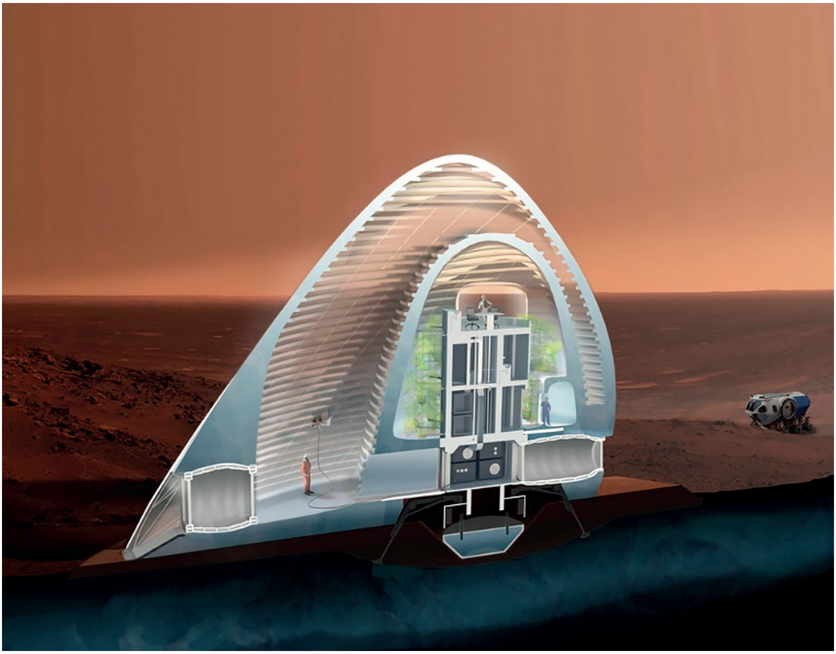

Figure 11
The 3D printed Martian ice house: inside the outer ice envelope there is also an inflatable structure
Source: www.spacexarch.com/mars-ice-house

Already for the water ice outer shell, the possible use of modern technology, the building with 3D printing has been raised. Since ice is relatively easy to melt, a 3D printer head can form an outer shell of almost any shape around the inflatable, pressure resistant part.

According to designers, 3D printing can also be a useful method for building external covers made of other materials. Local dust and rock debris that make up the lunar or Martian regolith can be the raw material for the protective wall of inflatable modules using various methods. Some methods would solve the transformation of local rock rubble into a concrete-like material with the help of additives transported from the Earth. Such additives can be special binding compounds, cement or even organic resins. Some designs even suggest that the cementing material could be available locally: on Mars, for example, gypsum (calcium sulphate) deposits may be present in accessible surface areas and this material may be suitable as a cementing material. However, if we could establish agricultural colonies on some celestial bodies, it becomes possible to produce certain plant-based organic resins, i.e. the binder material, in situ. Indeed, there are even plans to turn locally quarried debris into brick-like blocks using the threads of fungi to produce building materials.

However, lunar or Martian dust can be used to build solid walls even without binders. By heating the local dust to 1,000–1,200 °C, a ceramic-like material can be produced, which, even without additives, has sufficient strength to be used as bricks on celestial bodies with lower gravity than Earth. However, some specialists have the highest hopes for designs that plan to melt the rocky materials to create the walls. In this case, the previously mentioned 3D printing method can also be used to build the walls. The only drawback of such designs is that melting the rock requires a very large amount of energy. However, it is possible that this high energy requirement could be solved by solar energy: according to such ideas, sunlight concentrated by mirrors would directly melt the lunar or Martian rock dust into glass (Prater et al. 2018).

The question arises, of course, whether it is really necessary to build solid walls during construction on another celestial body. After all, the building of these solid walls would require considerable effort. It is not these solid rock walls that create the habitable space, but the inflatable structures and their flexible plastic walls. The solid walls would be built around the inflatable structure only for radiation protection and mechanical protection against micrometeorites. Not a surprise then, that there are designs, which would simply pile up local rock debris and dust around the inflatable structure, thus significantly simplifying the work of protecting the inflatable building and its inhabitants.

Figure 12
Design of a 3D printed outpost planned for Mars
Note: The inflatable structure would be surrounded by walls made of a glass-like material obtained by melting local rock dust. However, such an outpost would not be self-sustaining due to the lack of large-scale agricultural production, meaning that it would imply a huge construction and maintenance cost for the builder.
Source: PRATER et al. 2018

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Research into the future methods of space architecture is currently ongoing. Today, we do not yet know exactly which methods will be the most effective on the celestial bodies we will visit in the future. However, it is almost certain that inflatable structures will play a significant role in the construction of humanity's first outposts and bases. The relatively small mass of the inflatable elements that make up the framework of these future bases can be put into orbit by relatively small launchers. We do not know of a more efficient solution:

inflatable structures enable the construction of large-scale buildings at low cost, especially if the necessary radiation protection and mechanical protection can be provided by the use of locally available materials.

Nevertheless, the protective outer layer can also be an obstacle to achieving one of our most important goals. For an outpost built on another celestial body to be self-sustaining, each member of the crew needs 0.5–0.7 kg of oxygen, 1–2 kg of food and 2–3 litres of clean drinking water per day. The simplest way to achieve this is to install large greenhouses. It has already been calculated by experts that each crew member needs at least 800 kg of living biomass in the greenhouses to produce the required amount of oxygen and food. This 800 kg of vegetal biomass needs a greenhouse with a floor area of at least 120–150 m^2: in other words, a greenhouse of this size is necessary for supporting each crew member.

Most of the designs propose hydroponic and aeroponic plant cultivation and artificial lighting. In this case, the greenhouses are filled with racks on which the plants grow vertically on several levels. The roots absorb the nutrients from the fertilizer solutions sprayed on them. In this case, the light required for photosynthesis is provided most effectively by LED lighting that emits light with only those wavelengths that are usable for plants. Of course, running such a greenhouse requires a lot of electricity. Since the energy requirement for the LED lighting of a greenhouse with a floor area of 120–150 m^2 is at least 20–30 kW, a solar panel park with an area of 120–150 m^2 – that is, approximately the same size as the greenhouse – would also need to be installed.

Due to the problem of such high energy demand, a solution that does not use artificial light for plant cultivation has also been proposed. In this case, mirrors project natural sunlight into the interior of the inflatable greenhouses. The use of mirrors is necessary as the greenhouse needs to be protected from the Sun's radiation by a protective cover – of course, the protective layer shields the greenhouse preferably from all directions, but most of all from the direction of the Sun. Fortunately, the mirrors do not transmit harmful radiation into the greenhouses, only the sunlight that is necessary for the photosynthesis of the plants.

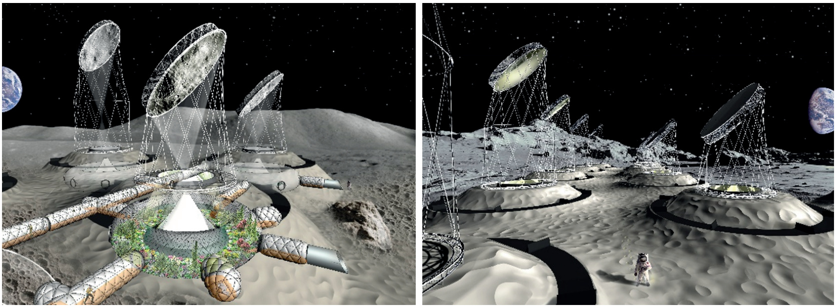

Figure 13
Plan of a lunar base consisting of inflatable elements
Note: The ring-shaped inflatable greenhouses are covered with a several meter thick layer of lunar dust. Since the Sun goes around the horizon in the lunar polar regions, we can use large, rotating mirrors to project the light into the underground greenhouses.
Source: https://pneumocell.com/pneumo-planet-moon-habitat/

One such solution is shown in *Figure 13* above. In this plan, the first outpost on the Moon would be made of inflatable elements. The ring-shaped greenhouses, the adjacent corridors and other living and working spaces are covered with a thick layer of debris, providing both radiation and mechanical protection. The whole structure is open at only a few points: above the ring-shaped greenhouses. The mirrors are placed here, which are made of stretched plastic membranes with a reflective layer and placed on lightweight towers. These mirrors continuously follow the movement of the sun and project the natural sunlight onto another, cone-shaped mirror through a funnel that leads underground. The latter mirror scatters the light in all directions, providing almost continuous illumination in the underground greenhouse (Herzig et al. 2022).

Since these large mirrors project very intense light into the inflatable greenhouse – up to 50–100 kW of radiative power, depending on the mirror's surface area – the greenhouses would quickly overheat without cooling. Therefore, a cooling system should be installed in each greenhouse, with cooling radiators that radiate the excess heat to space. These horizontal black cooling panels can be seen around the debris mound covering the greenhouse.

Another similar solution plans to start growing crops on Mars, which is vital for self-sufficiency, as we have seen before. In the Moon's polar regions, the Sun goes very low along the horizon, which is well utilised by the mirror that revolves around its axis and reflects the light into the ring-shaped greenhouse underneath. However, on the equatorial regions of Mars, it is better to think in terms of linear greenhouses with side mirrors to reflect the light of the Sun high above in the sky (Benaroya 2018).

Unfortunately, Mars has a very thin atmosphere – only about 1% as dense as that of Earth – so it offers little protection against cosmic radiation or micrometeorites. Therefore, also on Mars, we have to cover the inflatable structures with some kind of protective layer. The structure shown in *Figures 14–16* are protected from above by the debris piled on top of the inflatable structure. The plastic inflatable sidewalls are protected by mounds of debris that run along the length of the greenhouse. These mounds are also used to hold the stretched mirror foils, which reflect the sunlight into the greenhouse.

The weight of the debris layer is of course much smaller than the uplifting force that pushes the ceiling up, due to the internal air pressure. The Martian gravity is only a third of that on Earth, so even a 4 metres thick layer of debris weighs only 20 kN – equal to the weight of 2 tons on Earth – per square meter on the roof. The internal pressure, on the other hand, even with the previously mentioned 0.5 bar pressure and high oxygen concentration air, pushes the ceiling upwards with a force of 50 kN per square meter. This means that even in case of an accident and sudden decompression, it takes a considerably long time until the building starts to collapse. The crew has to leave the compartment due to the decreasing pressure and the resulting breathing difficulties, not because of the collapse of the roof. Collapsing only begins when 70% of the air has already escaped. Until then, the building is safely standing and does not hinder evacuation.

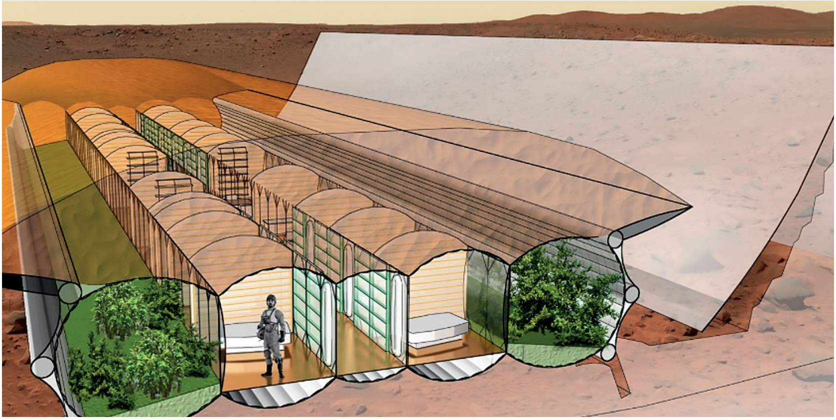

Figure 14

The building structure of a Martian settlement

Note: The basic element of a Martian settlement could be a long, inflatable greenhouse that produces the necessary oxygen and food for the crew. This design uses natural sunlight, and side mirrors to project the light into the greenhouses, the top of which is covered with Martian rock debris as a protective layer.

Source: https://marshabitat.space/

Figure 15

Image of the Martian settlement, consisting of greenhouses and residential parts similar to the one in Figure 14

Source: https://marshabitat.space/

Figure 16
Interior view of an inflatable habitation unit at the above Mars base
Note: The internal structure of the building is fixed by inflatable dividing walls and ropes. The inflatable walls are complemented by a floor of lightweight plastic elements, shelves and furniture.
Source: https://marshabitat.space/

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