The Interesting Challenges of Designing for Humans in Space

Sandra Häuplik-Meusburger [1], **Brand Griffin** [2]

[1] *TU Wien / space-craft Architektur*
Vienna, Austria

[2] *Genesis Engineering Solutions*

Abstract

Extra-terrestrial living and working environments are characterized by significant challenges in logistics, environmental demands, engineering, social and psychological issues, to name a few. Everything is limited: physical volume, air, water, power, and medicine ... everything, even people, and therefore all is treated as valuable resource. This situation is complicated by the end product being the result of balancing many competing interests. The relationship between humans, space, and technology is forced, as well as a dynamic process. Although mathematical models for complex systems exist, long-term effects are hard to predict, and even more so to calculate. Even if we had technological solutions for all hazards and threats, there would still be the question of how these subsystems work together, how they are perceived, and if they are accepted by the inhabitants. Habitability design is vital to the success of future space exploration. Research into the dynamic system of 'living together in an isolated and extreme environment for a long time' does not lead to a single common solution. Instead, designers are left trying to translate differing first-person astronaut accounts into a solution bound by the constraints of physics, schedule, and cost. The early days of human spaceflight were all about discovery. Trying to replace conjecture with experience and fact. For example, the Moon was thought to have meters of soft dust that would swallow landing spacecraft. We have built on the successes and failures, but some achievements have also been forgotten. Today, we use these lessons to create effective designs for 'living together in the isolated and extreme environment (ICE)' of space. Following are descriptions of historical and newer examples of possible solutions that show what can be achieved when the demanding constraints of space inspire creative solutions for combining human needs with technological possibilities.

Keywords

Space architecture, space history, habitability design, critical design challenges, design consequences, in-situ-resources,design innovation, creativity

DOI

https://doi.org/10.7480/spool.2021.2.5267

Introduction

From a technical and engineering point of view, one of the critical characteristics for human space operations and mission success is the dependency on the habitat, its technological capabilities as well as its provision of relevant resources for life-support. To sustain life, humans need oxygen at a minimum of 12.2 Kilopascal pressure. The Earth's atmosphere at sea level is 21 percent oxygen at 101.3 KPa. Space is a vacuum, the Moon is in a vacuum, and the Martian atmosphere unbreathable carbon dioxide at less than 1 percent of Earth atmospheric pressure. Therefore, all space habitats need to be constructed as pressure vessels. There is simply no human mission without (a lot of) technical subsystems.

With respect to upcoming and future human space missions, it will be important to build functional, supportive, persistent long-term infrastructure that extend the characteristics of survival shelters to become places that support all kinds of human activities. Integration of habitability in relation to human activity needs is key when mission length increases. As stated by Frances Mount (Mount 2002, p. 87): "*The impact of a poorly designed switch or lack of stowage area is different for a mission of six months compared to a mission of one week*."

At first sight, today's space habitats seem old-fashioned and not suitable for future space exploration. However, we should not forget the efforts that have been put into the design process. Designing a space station takes a long time and lot of people are involved. From the first idea to the actual realization, more ideas are discarded than advanced. It is a process of high creativity and also a process of selection. According to Kitmacher "*More than hundred different space stations were conceptualized [...] before the ISS became operational"* (Kitmacher, 2002 p.2) Fig. 1 and 2 show early concepts of Space Station Freedom, which was announced in 1984, slimmed down, and eventually realised as today's International Space Station (ISS).

FIGURE 1 Early space station concept by Boeing in 1984. At that stage, it was required to have two ways to exit each module. The modules would be linked in a loop configuration. (Illustration by Paul Hudson)

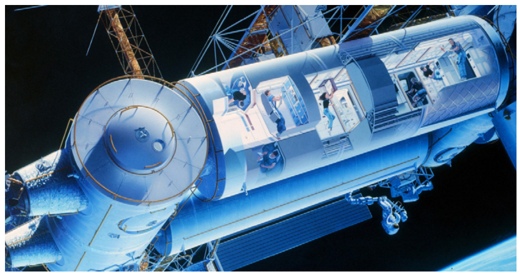

FIGURE 2 Concept of Space Station Freedom in the mid-1990s. That concept still included a habitation module that did not fly. (Illustration by Paul Hudson Design Boeing)

Over the years of designing and evaluating for today's International Space Station, a lot of features that would improve habitability were not included. The diameter of the modules was constrained to the Shuttle cargo bay. Yet, the ISS is the largest and most-advanced off-Earth architecture that has been built and it has been permanently inhabited for the last 20 years.

Human space exploration is as much a story of scientific discovery as one of optimizing humans and their newly created environments. Using selected historical examples, the authors will show what can be achieved when the demanding constraints of space inspire creative solutions for combining human needs with technological possibilities.

How to fit it in – Mass, Volume, Form

"*Early spacecraft had been designed to be operated, not lived in*" (Compton and Benson 1983, p. 130). There is this famous saying that Mercury astronauts[1] did not climb into the spacecraft, *they put it on* (Img 3). The Mercury spacecraft was a 3.3m (10.8 ft.) tall, 1.85m (6 ft.) wide cone-shaped craft made for one astronaut. Spacecraft design remains primarily functional, and weight and size are among the major criteria for spacecraft design. Those restrictions also influenced criteria for astronaut selection, in that the astronauts also had a 'height limit' 1.82m (5ft. 11 in.) as a function of the spacecraft design (Burgess, 2011). It was at that time that the term 'tin can' as a synonym for the spacecraft and 'man in a (tin) can' as a synonym for an astronaut or cosmonaut were born.

FIGURE 3 Mercury 7 astronauts examine their 'couches'. Each astronaut's couch was moulded to fit his body to help withstand the G-loads of the launch.1959 (NASA)

FIGURE 4 Saturn V rocket launch, 1969 (NASA)

FIGURE 5 The space shuttle Discovery with its payload bay doors open. A module is resting inside the payload bay. (NASA)

Consequences of the Transportation System

A space station in orbit or a habitat on the Moon or Mars is to a large extent a product of the launch system. The habitat size, mass, and very often the geometry depend upon the launch vehicle used. In terms of engineering and economic issues, there is a severe limitation on mass and volume. The Apollo flight system was made for only one flight and to land on the lunar surface, with only the command module returning to the surface of the Earth. The biggest portion of the available space within the Apollo spacecraft (Fig. 4) was occupied by enabling subsystems (structure, life support systems, propulsion systems, power systems, etc.).

No space station module has thus far had a larger diameter than the Skylab Space Station Orbital Workshop at 6.6m (22 ft.) diameter. And this was only possible because Skylab used one of the large Saturn V launch vehicle propellant tanks for the habitat/workshop. Skylab was launched first, followed by three separately-launched Apollo spacecraft carrying three astronauts each.

To create larger space station complexes, the Soviet planners used a modular approach using successive launches to build up the Mir space station. The International Space Station is also based on this assembled-in-space, modular architecture approach. As a consequence of integrating the Space Shuttle to reduce transportation costs, the modules were reduced in size to fit the Shuttle's payload bay of 4.5m (15 ft.) (Fig. 5).

1 Project Mercury was the first human spaceflight program of the United States and ran from 1958 to 1963.

While the Mir space station used solar panels for each of the modules (Fig. 6), the ISS has a truss structure with photovoltaic infrastructure (Fig. 7). Only the first modules of the ISS, Zarya and Zvezda, were independent, using solar panels attached to the module. In contrast, the European and US modules on ISS are much like houses in a village attached to a common utility source for electrical power, heat rejection, and communications. Interestingly the word “Mir” in Russian can be translated to “village”, as well as “world” and “peace”.

FIGURE 6 Russia's Mir space station in 1989, taken from Space Shuttle STS-89 mission (NASA)

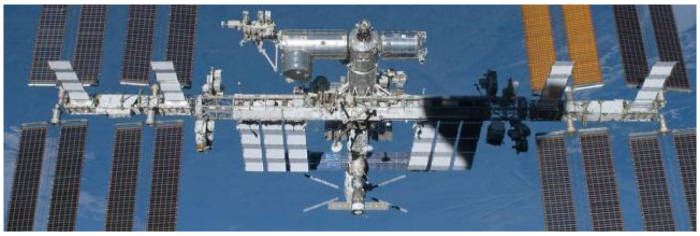

FIGURE 7 The International Space Station with its truss structure for the photovoltaic system, 2020 (NASA)

The Rover Packaged in a Wedge

The Apollo programme was announced in 1960 as a follow up to the *Mercury Project*. At the time of the announcement, the flight configurations were not yet fixed yet. It is worth remembering that, while the first lunar landing took place in 1969, work on and designing of lunar missions began much earlier, even before the first human spaceflight. It is remarkable to note that in 1952 Werner von Braun was working on a lunar lander that would take 50 people to the Moon for six weeks. His ideas captured the interest of Walt Disney and were presented in a series of TV episodes (Fig. 9). He was also the one that promoted a lunar rover for expanding the exploration distance of future astronauts. Almost 20 years later, in 1969 von Braun would watch the first manned module land on the Moon.

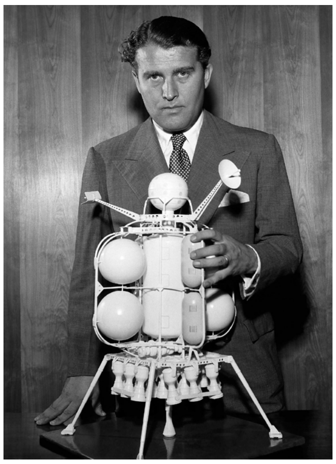

FIGURE 8 Wernher von Braun with his 1952 design of a lunar lander (Photo remastered by Dan Beaumont, original image US Information Agency)

FIGURE 9 Prototype of the Molab concept by General Motors in Hopi Buttes, AZ in 1967. It was scrapped in 1968. (U.S. Geological Survey USGS)

Along the way, there were many designs for lunar bases. Early base designs tended to be comprised of pre-integrated modules delivered from the Earth. In this way, the entire module could be fully tested before launch and immediately used on site. A disadvantage of this approach is that the weight and volume is limited to the launch vehicle payload capabilities. An innovative strategy to overcome the launch vehicle payload limitations was demonstrated by folding the lunar rover, then having it be deployed on the surface. Research into lunar surface rovers started in 1964. A variety of prototypes were designed, tested, and evaluated, as a lunar rover was intended to augment human exploration activities on the lunar surface. The MOLAB (Wright & Jaques, 2002) pressurized rover (Fig. 9) was successful in that it proved astronauts could stay in it for at least 18 days. However, it also proved that it would weigh so much that a Saturn V would have to deliver it ahead of the astronauts, which would have been too expensive. Eventually the MOLAB rover concept was dropped, and NASA gave up '*putting vehicles on the Moon*' (Riley et al., 2008). At General Motors, engineers started work on small unpressurized rovers and asked NASA HQ if there would be a possibility to include a rover. The answer was: "*If you could fit a vehicle in this triangular bay"* (in the descent stage, 1,5m (5ft) tall, wide, and deep), "*we might think about going again with a rover*" (Riley et al., 2008).

General Motors became a subcontractor of the Boeing Company and, working with NASA, delivered the Lunar Roving Vehicle that first flew folded into a small, wedge-shaped volume on Apollo 15. It was innovative because of its clever packaging and deployment as well as wheels made of wire (Fig. 10 and 11). Although astronauts had walked on the Moon, it was not clear how a rover would behave in the dust and lower gravity. The rover was powered by electric motors and designed to carry two astronauts. It was about 3m (10 ft. 2 in.) long, 1.1m (44 in.) high, with a 2.3m (7 ft. 6 in.) wheelbase. The finished lunar rover weighed only about 200kg (450 lb.), or just 34kg (75 lb.) in the Moon's gravity.

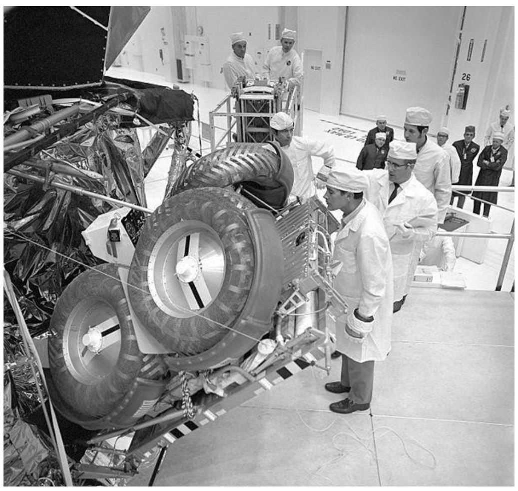

FIGURE 10 Apollo 16 Commander John Young and Lunar Module Pilot Charles M. Duke, inspect the Lunar Roving Vehicle during a deployment test in the Manned Spacecraft Operations Building at the Kennedy Space Center. November 1971. (NASA)

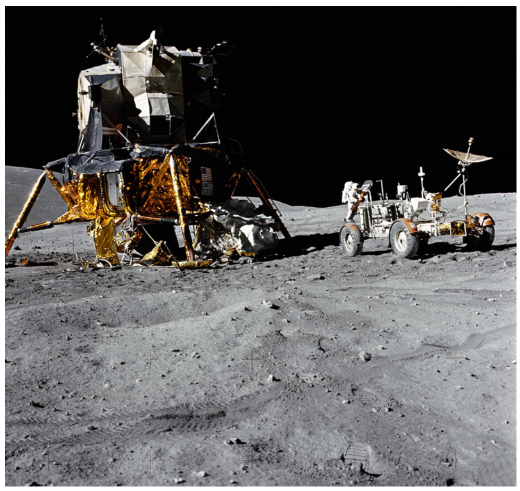

FIGURE 11 Image of the Lunar Module 'Orion', as photographed by astronaut Charles M. Duke during the first Apollo extravehicular activity. The lunar rover is visible in front of the triangular bay that hosted the folded rover. (NASA)

Expandable Structures

Looking for on-orbit volumes larger than the launch vehicle diameter, engineers and designers explored expandable structures. One innovative concept proposed as early as the 1960s was an inflatable wheelshaped space station with a dimeter of 50m (162.5 ft.) (Fig. 12). In 1965, the Soviets equipped the manned spacecraft Voskhod 3KD with an inflatable airlock (Fig. 13) that enabled Alexei Leonov to conduct the worlds' first EVA (Haeuplik-Meusburger and Ozdemir, 2012). Between 1997 and 2000, NASA developed the 'TransHab', an inflatable long duration habitat with a central core. Initially it was conceived as crew quarters for the ISS and later as a transit habitat to be used for Mars missions. It would expand to 8.2 m (26.7 ft.) diameter. The architects involved were Constance Adams and Kriss Kennedy.

FIGURE 12 This 1961 prototype of an inflatable space station concept with a solar power system collector was 7.3 m (24 feet) in diameter with an internal fabric bulkhead that could be separately pressurized in an emergency. (NASA)

FIGURE 13 The Volga airlock and Berkut spacesuit. Memorial Museum of Cosmonautics, Moscow, 1999. (Photo: Kucharek, Wikimedia)

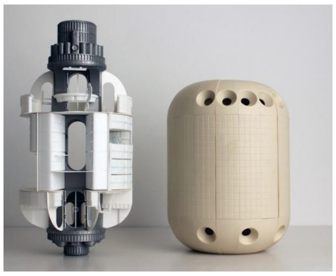

FIGURE 14 Design for a Space Station in Low Earth Orbit. Diploma project at the TU Vienna by Matas Ivan (models and image: Matas Ivan, HB2, TU Wien)

Although the TransHab concept (Fig. 18) was discarded, it was highly successful insofar as it led to the development of the inflatable architecture by Bigelow Aerospace for a future space hotel, with NASA licensing the technology. Since 2016, the Bigelow Expandable Module (BEAM), which is a prototype for a future deployable space habitat, has been attached to the ISS as a temporary experimental module. The main purpose was to test its durability, but due to its engineering and performance assessment, it was decided to keep it in place until 2028. Today, it serves as a storage module. Fig. 14 shows a design for an inflatable research station based upon the Bigelow technology. The use of inflatables is currently the only way of producing larger volumes in LEO.

Grappling with the Environment

The extra-terrestrial environment is lethal to humans. Humans can only survive within a protective pressurized habitat. The outer space and planetary environments on the Moon and Mars are zero to low pressure environments; therefore, these habitats need to be constructed as pressure vessels. To protect humans and equipment from radiation and micro-meteorites, additional protection layers and technologies have to be applied. Habitats must be thermo-regulated (active and passive) in order to maintain an even and comfortable internal temperature, to name but a few of the requirements.

Nowadays the space environment is well-understood and most of the technology is available to build a habitable extra-terrestrial environment. Threats like micrometeoroids, debris, and solar particle radiation events are unpredictable, but there are already solutions available to mitigate these hazards, at least close to Earth. The challenge is creating efficient and reliable spacecraft for long-term human transportation and exploration.

Hazardous effects of Micrometeoroids and Space Debris

We tend to think of space as empty and, for the most part, that is true. In fact, when we encounter something in space, it is usually not good. Micrometeoroids are not present on Earth[2] and represent a major threat to spacecraft and space suited astronauts. Without protection, these fast-traveling bits of rock can penetrate the pressurized skin of habitable modules and space suits.

Similar to Earth architecture, the most effective approach for protection from different forces and environmental influences is layering. The space suit, as the smallest possible protective skin, is a good example. A space suit is a highly compact technological system for sustaining human activities in space (Fig. 15), composed of multiple layers, depending upon its purpose (Fig. 16). The American Extravehicular Mobility Unit (EMU) has 14 layers and a mass of about 145 kg (319 lb.). It consists of an upper and a lower torso and is fabricated at ILC Dover with modular components. In contrast, the Russian Orlan and Chinese Feitian suits are semi-rigid one-piece suits with a rear hatch entry.

FIGURE 15 The Apollo 11 A7L spacesuit as worn by Neil Armstrong. (NASA)

FIGURE 16 Cutaway view of the first extravehicular spacesuit from the Gemini missions in 1965, showing the many layers. (NASA)

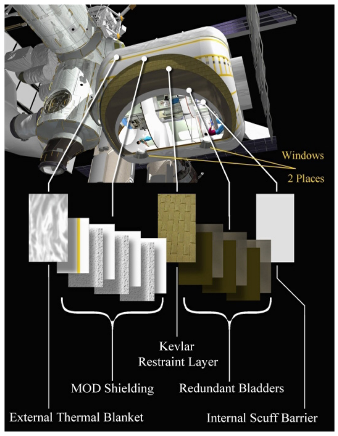

FIGURE 17 The Transhab module consisted of multiple layers: external thermal blanket, micrometeoroid and orbital debris (MOD) shielding, Kevlar restraint layer with three bladders of Combitherm, and an internal fireproof protective Nomex layer. (NASA)

The ISS modules also have layers of aluminium and Kevlar covering the pressurized module. In low Earth orbit there is the additional threat of debris from launch vehicles and other spacecraft. Image 17 shows a cut-away view of the Transhab module exemplarily representing the many layers of inflatable modules (Fig. 14). Transhab micrometeorite protection used twenty-four layers and was about one foot (0.3m) thick. The layers were used to break up particles of space debris and tiny meteorites that may hit the shell with a speed seven times as fast as a bullet. The outer layers protect multiple inner bladders, made of a material that holds in the module's air.

2 Meteoroids that enter the Earth's atmosphere are called meteorites and most burn up before hitting the surface.

Making most out of the resources you have

Once you are off Earth, **all you have is what you bring** (which is highly restricted) **or what you can take advantage of** that is already there. One of the biggest issues for an extra-terrestrial habitat is its protection from solar radiation, in particular solar particle events. Galactic cosmic rays (GCRs) are ever present and virtually impossible to stop. On Earth, we are protected from hazardous radiation by the Earth's magnetic field and the atmosphere. Beyond low Earth orbit, radiation exposure can result in short term health risks and an increased probability of cancer or heart disease in the long term.

In August 1972, between the Apollo 16 and Apollo 17 missions to the Moon, the sun released powerful solar flares. It is believed that if this had occurred during one of these missions, the astronauts would have died. (NASA [SpaceWeather], 2020) Today, radiation protection remains a major concern for human missions to the Moon and, in particular for the long travel time required for Mars missions.

The challenge lies in finding the right protection with respect to mass and volume constraints. On Earth, nuclear power plants are screened by massive physical barriers. For space travel, a different approach has to be found. For solar protons, molecular hydrogen (H2) offers the most effective radiation protection. There is no easy design solution for using gaseous hydrogen, so the most manageable compromise is to use the hydrogen component in water or plastics to provide protection. For some Mars mission studies, the idea was to minimize the total mass by using the water content in strategically stored food to provide an added measure of protection. Of course, after the food was eaten, the water would need to be replaced.

FIGURE 18 Cutaway of the Transhab Module. The inner core is protected by a so-called radiation shield water tank. (NASA)

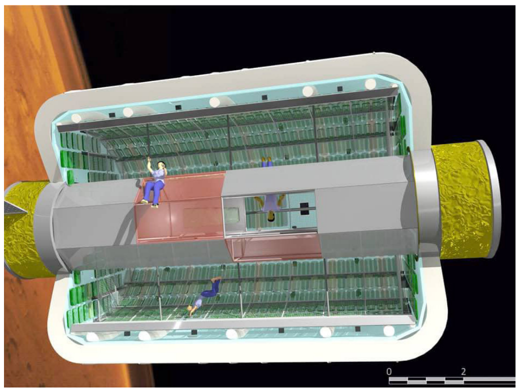

FIGURE 19 Longitudinal Section through a Bigelow 330 (TransHab type) space habitat, showing Water Walls Air Revitalization Bags installed around the inside perimeter and end walls of the inflatable pressure vessel. The water walls design concept includes algae and filters, which would replace solid waste and wastewater to be recycled for repeated human use. As published in Cohen et al. (2012) (NASA)

Recently, this approach was integrated into a radiation shielding concept in combination with the on-board life support and waste processing systems (Fig.19). The layout suggested for the use of the Water Walls Architecture uses radiation shielding wrapped around the whole module (Flynn et al. 2019). This is probably because it is not possible to predict solar flares on space transfer missions to Mars. Surrounding the entire habitat with water is a heavy solution. An alternative is the concept of a dedicated shelter. This shelter would be a protected location where the astronauts would retreat for the duration of the solar event. The logical place for the shelter is an area where the astronauts spend the most time. Typically, the astronauts will each spend 8 hours a day in their crew quarters, so shielding this area would provide a very effective, mass-sensitive solution (Fig. 18).

Other passive approaches to shielding available to astronauts on the surface of the Moon include in-situ resources. For example, using the lunar soil (regolith) has been proposed for shielding habitats. Several architectural approaches exist, including piling up regolith sand or bags filled with regolith, or recently, 3D printing or sintering structures with regolith (Fig. 20). Concepts of active shielding, based on the Earth's magnetic shielding, encompass electrostatic shielding, magnetic shielding, and plasma shielding. All require significant electrical power, so they are not appropriate for early missions.

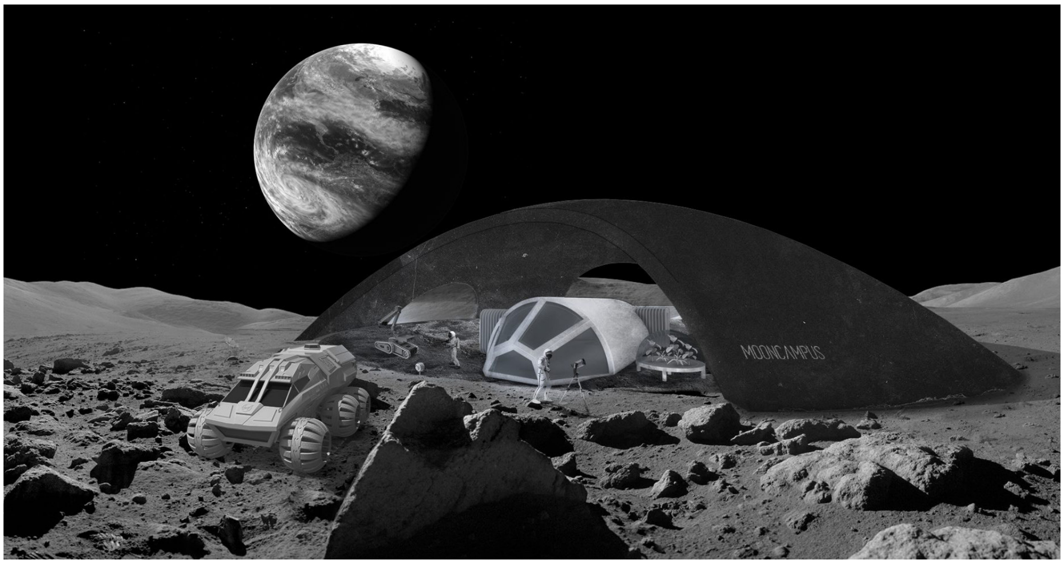

FIGURE 20 Concept of a training campus for scientists on the Moon, featuring a semi-protected area for outside lunar operations. Student project Moon Campus. (MoonVillage Design studio, HB2, TU Wien, by B. Dogan, J. Oblitcova)

Getting in and out – dust free

During the Apollo missions, astronauts used a small hatchway to get in and out. Before getting out, astronauts had to put on their suits. Then they vented the air out of the lander cabin and started their Extra-Vehicular Activity (EVA). After their outside activities, astronauts were covered with dust, which can be seen on many images from the Apollo missions (Images 21 and 22).

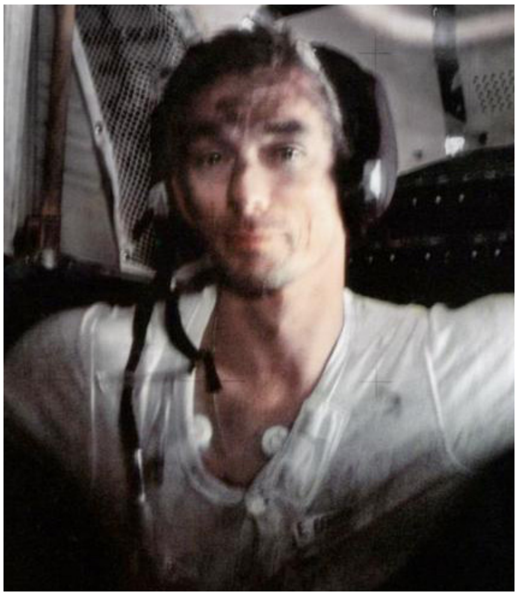

FIGURE 21 Gene Cernan covered in lunar dust (NASA)

FIGURE 22 Apollo 17 astronaut Harrison Schmitt, taking samples on the Moon. His suit is covered in lunar dust. (NASA, photo taken by Eugene Cernan)

Lunar dust is not like Earth dust. It is very abrasive because it was formed by meteoroid impacts resulting in shards of rock that have not been rounded-off by wind or water erosion. It can be toxic when breathed, clings to the suit, and gets into joints causing difficulty putting on gloves and helmet. Future explorers will also face the same problems that the Apollo astronauts had with dust. Lunar dust became a major problem not only inside the Lunar Module, but also inside the Command and Service Module, because the fine dust floated in microgravity and was too fine for the cleaning system (NASA [Debriefing A12], 1969; NASA [Dust Management], 2006). The filter system was possible upgraded for the Apollo 17 mission; Harrison Schmitt reported that most of the dust was filtered out of the cabin atmosphere (Schmitt, 2009).

During Apollo, the astronauts went straight from the cabin to outside. On the ISS, astronauts use an airlock to transition from inside to outside for EVAs. This is a small volume (module) that minimizes air loss between two different environments while not having to vent the cabin atmosphere (Griffin, 2010). Most concepts for future exploration include an airlock function. Different kinds of airlocks exist. Typically, they are cylindrical, just big enough for two suited astronauts. However, NASA is looking at a concept that uses a space suit with a hatch-like backpack that mates to a pressurized rover. The dusty suit remains outside while the astronauts enter and exit by opening the backpack into the rover. It is called the *suitport* (Fig. 23 and 24) and it allows faster egress and ingress while conserving atmosphere with the distinct advantage of minimizing lunar dust within the cabin. Future challenges include design for maintenance and repair by astronauts. Another open issue is related to the inhabitants. The space suits are still fitted to the astronaut's size and, so far, there is no spacesuit that fits all. With repeating missions, it has to be ensured that the attached spacesuits are just right for the crew working and living in the habitat.

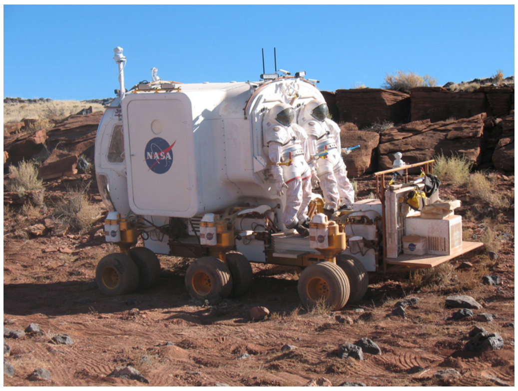

FIGURE 23 This is one prototype version for NASA's Lunar Electric Rover. This small pressurized rover is about the size of a pickup truck (with 12 wheels) and can house two astronauts for up to 14 days with sleeping and sanitary facilities. It is designed to require little or no maintenance, be able to travel thousands of miles climbing over rocks and up 40 degree slopes during its ten-year life exploring the harsh surface of the moon. Two spacesuits are attached to the rover suitlock. (NASA/Regan Geeseman)

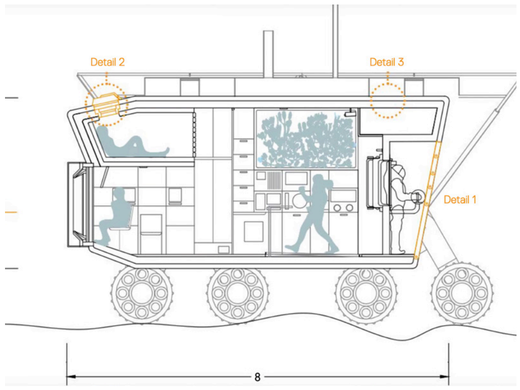

FIGURE 24 Section of a rover design with integrated suitport concept. (MoonVillage Design studio, HB2, TU Wien, by Günes Aydar, Emirhan Veyseloglu, Gözde Yilmaz)

Humans in Micro Gravity

Humans outside the Earth environment are subject to lower gravity forces. Gravity is a strong force of nature. On Earth, this force is 1G (about 9.8 m/s^2) and represents the standard against which other gravity states are measured. In comparison to Earth, Moon gravity is about 1/6 and Mars about 1/3. All life that we know has developed in 1G and going into space means being subjected to a change of gravitational forces. This change affects a wide range of human activities, like body movement, posture, and locomotion. Furthermore, there are differences in human physiology. Most dramatic is weightlessness, or zero-g, in which physiological effects include calcium loss, fluid shifts, skeletal changes, muscle mass loss, and vestibular alterations (NASA [MSIS], 1995 p. 178). Changes in spatial orientation, movement, and sensory perception are among the most important aspects to consider when planning the habitat. Furthermore, without gravity there is no convection which means hot air does not rise, and there is no "natural" settling of heavier gases. Without careful attention to air flow, it is possible for the body's heat and exhaled carbon dioxide to surround the astronaut, which can lead to life-threatening consequences for the astronaut.

On Earth, we sit in chairs, lie down in beds, and get exercise just by walking. In zero-g, there is no need for chairs, astronauts sleep on the wall, and it takes special equipment to exercise. After going to the Moon, NASA created a space station using a large empty propellant tank that was outfitted as an orbital workshop. Before the Skylab mission, astronauts only knew the small, densely packed volume of a re-entry capsule. With Skylab it became evident that workstation designers have to take microgravity conditions into account. Following this experience, an analysis of positions in microgravity was conducted in 1975.

Designing for the Unknown: The Zero-G-Posture

"On Earth, gravity is holding the feet to the floor. In zero-g [an astronaut] must have restraints for that purpose." (NASA [Bull. 7], 1974 p. 2)

Skylab's long duration missions and large open volume (Fig. 25 and 29) provided the opportunity to – for the first time – document the neutral body position in space. The neutral body posture is when all muscles are in their neutral state without requiring extra effort. There is a clear difference from the neutral body position in space compared to Earth (Fig. 27). At that time, when the measurements were taken during the Skylab missions, it was believed that "*there is a definable relaxed body posture in zero-g and that the eligible flight crew population can be fitted to that posture*" (NASA [Bull.17], 1975 p. 2). Today, we know that the range between those positions varies much more and also relates to the individual astronaut. However, there are some similarities that have large consequences for the design of the whole space station interior (Griffin 1978). **The head is tilted down, the arms and legs lift up, and there is no pooling of fluids in the lower extremities.** The neutral body position in 0 gravity is called the Zero-g posture (Fig. 26).

FIGURE 25 Mission Specialist Carl Meade at the Spacelab glovebox, rack # 12. (NASA)

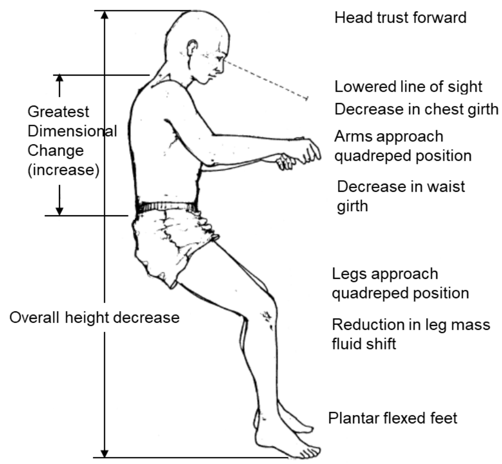

FIGURE 26 Description of the main characteristics of the zero-g posture, the neutral body position in space. (Brand Griffin)

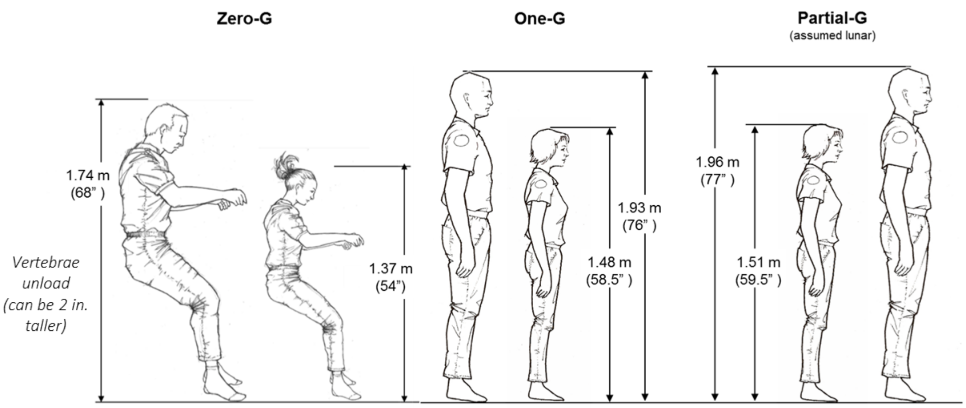

FIGURE 27 Comparison of the neutral body position depending on different gravity conditions. (Brand Griffin)

Some tasks require the use of both hands and a stable body position. In microgravity this is particularly essential, because without some type of restraint (which is the floor on Earth), an astronaut trying to tighten a screw will do the turning, not the screw. The solution for Skylab was to create a shoe with a triangular cleat on the sole which was secured to an open triangular grid (Fig. 28 and 29).

The grid proved useful for attaching equipment and tools. But as each crew became quickly familiar with motion and restraint on Skylab, the shoe was not used much. In order to operate the control panel for the Apollo Telescope Mount, one of the astronauts thought that a chair-like body restraint would be useful. Later, this, along with a fireman's pole were abandoned and considered unnecessary. (NASA [Bull.10], 1974; NASA [Bull.11], 1975)

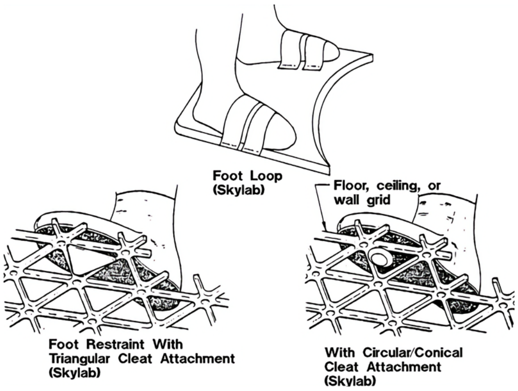

FIGURE 28 Selection of foot restraints used during the Skylab missions. (NASA)

FIGURE 29 Internal arrangement of the Skylab Orbital Workshop. From left to right is the dining area, waste management, and sleeping quarters. Portable restraints are on the wall beside the sleeping quarters. The walls are all made of a triangular grid as restraints. (NASA)

On the Salyut and Mir space stations the walls were also used as storage and utility areas (Fig. 30) Today, there are many restraints, such as handholds, waist restraints, and foot restraints. Velcro is used all over the International Space Station to hold things in place (Fig. 31)

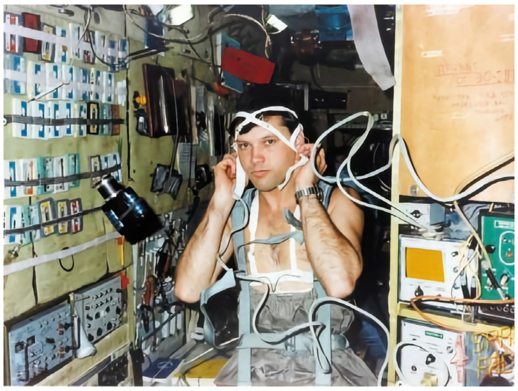

FIGURE 30 Cosmonaut Dorin Prunariu onboard the Salyut 6 space station in 1981. Rubber bands are used to hold things in place. (Courtesy: Dorin Prunariu)

FIGURE 31 Japan Aerospace Exploration Agency (JAXA) astronaut Takao Doi, STS-123 mission specialist, looks over his choices of beverages and snacks in the galley on the middeck of the Space Shuttle Endeavour while docked with the International Space Station. Note the many Velcro patches to secure all different kinds of things to the wall. (NASA)

Same, same, but different - Human Activities in Space

Weightlessness changes (almost) everything. While the feeling of weightlessness is the most unusual and most desired experience of the astronauts (see Fig. 25), as "*you can use it to make your life easier*" and "*you can use all surfaces*" (Clervoy 2009), the physical effects are a challenge for the human body. Most severe is the change in cardiovascular, bone, and hormonal physiology. The astronauts' heart rate and blood pressure decrease in space, as does the variability in heart rate and blood pressure. Astronauts' bones lose calcium and strength, their muscles lose mass. In strong contrast to Earth, where exercise is mostly seen as a leisure activity, in space it is essential for staying healthy and strong (Fig. 32).

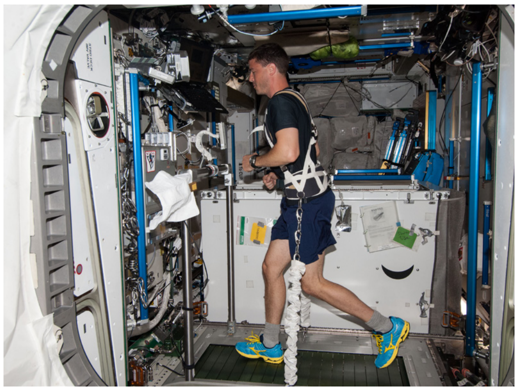

FIGURE 32 NASA astronaut Reid Wiseman, equipped with a bungee harness, exercises on the T2 treadmill. (NASA)

FIGURE 33 Canadian Space Agency astronaut Julie Payette preparing tortillas onboard the Space Shuttle Endeavour. Payette was a mission specialist on STS-127. (NASA)

Eating and drinking are also different. To prevent fluids and pieces of food from getting into electronics and equipment, the liquids are squeezed from tubes and other foods tend to have a paste-like consistency. Because there is no natural drainage in the head, the concentration of fluids affects the taste of food. It is not uncommon for astronauts to bring a spicy sauce and be inventive to liven up the dull taste (Fig. 33). With that, cleanliness and personal hygiene have been considered from early on. Most Apollo astronauts shaved during the mission. Although space stations are considered 'clean', in total three shower systems have been developed for use in microgravity, and were used during the Skylab, Salyut, and Mir missions. Opinions vary. In-space showering was considered a pleasant experience, but at the same time too time-consuming. As a compromise, in the case of Mir, the shower cabin was used as a sauna, before it was removed because it took up too much space. ISS does not have a shower; instead, the crew use wet wipes (Häuplik-Meusburger, 2011). For future long-term missions, the system of full-body cleansing will become important again.

Not all things change: Local Vertical

The first impression is that without gravity there is no need for a floor or ceiling. That is true, but our human form and Earth conditioning yearn for a reference system. Without the natural orientation of gravity, the solution is to create a local vertical that provides a common up and down across the spacecraft. This establishes the orientation for controls, displays, and labelling and is useful in face-to-face communication. We do not like looking directly into the light source; therefore, overhead lighting not only provides the preferred illumination, it is also used to imply an 'up' direction. Furthermore, because there is no natural convection of gases, it is conceivable to generate a bubble of body heat and exhaled carbon dioxide around the body. So, rather than blowing air up the nose, the accepted design creates a head-to-toe airflow reinforcing the up-down orientation. (Img 34). In the weightless environment, hands are more important than on Earth. In addition to normal tasks, astronauts use their hands for translation and stabilize themselves. Because this prevents two-handed operations, having floor-mounted foot restraints provides stability while freeing up both hands. Although zero-g seems to offer unconstrained freedom, there are good reasons to retain a floor and ceiling along with a local vertical orientation for some human activities.

The ongoing debate on windows

Nobody would question having a window in a house on Earth. In space, it's different; the inclusion of windows has been a delicate topic.

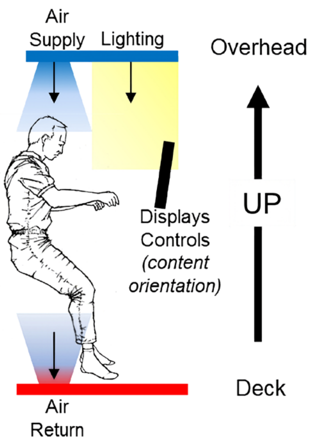

FIGURE 34 Even in zero-g there are good reasons to have a floor and ceiling with a local vertical orientation.

FIGURE 35 Astronaut Susan Helms views the Destiny module of the International Space Station from the Nadir window in the US Laboratory. This is a picture of that particular window from the time when no restraint was installed. (NASA)

FIGURE 36 Astronaut Chris Hadfield strums his guitar in the International Space Station's Cupola, in 2012. (NASA)

Early spacecraft had windows that were mission relevant. The discussion of including a window next to the eating area for the Skylab space station has become famous. It was argued that it was too expensive, that developing it would take too long, that it would weaken the structure, and at last it seemed not to be essential to mission success. After long discussions, the window in the wardroom was finally integrated and also appreciated by the astronauts. As a piece of side information, the astronauts could not see much out of this particular window because of the space station's orientation in relation to Earth. The Multiple Docking Adapter windows were much preferred because they were arranged in a 90-degree angle.

Nowadays, windows in space stations are flat windows integrated within a module. They usually have two interior and one outer redundant glass pane separated by a vented space. For micrometeoroid and debris protection, windows are equipped with external shutters. It has been established that looking out of the window is the favourite astronaut leisure activity. The neglect of that human activity led to a leak in the ISS in 2004. Due to a lack of appropriate handholds, the astronauts repeatedly held onto the air hose when looking out of the window (Fig. 35). This unplanned practice finally resulted in a leaky hose, through which internal air left the station (cf. Haeuplik-Meusburger, 2011).

Today, the ISS has a protruding window assembly, which is essentially a small enclosure with 6 windows and called a cupola (Fig. 36). The debate for the future even includes the discussion of what can substitute for a lack of outward-facing windows. Examples are virtual technology and the clever placement of greenhouses.

Summary Observations

Support and evidence for the need of integrating habitability can be found in every decade. In view of future and long-term missions, habitability design integration is an important aspect as it becomes even more important when mission length and crew numbers increase.

The history of space travel shows that much has been learned from a technological point of view. Life support systems, food systems, and the development of new technologies and materials are only a few examples of how much has been achieved in the last 50 years. But, when it comes to designing for living in space, there is still a lot to do. Knowledge transfer from one environment to the other, as well as from one generation to the next one can become tricky. Political and economic decisions can slow down and even freeze a whole programme, regardless of its originally innovative concept.

Despite, the focus of early spacecraft design on mission success defined by pure survivability, the examples show creative solutions for combining human needs with technology that are possible within the severe constraints of space flight. The examples also show that a lot of creative potential has not yet been used and remains to be uncovered, and that learning from the past can be part of a promising future. We have to bear in mind the difference between planning and realising projects, and that we will need the best minds from many different professions to let the dream of sustainable space travel come true.

References

Burgess, C. (2011). Selecting the Mercury seven: The search for America's first astronauts. Springer in association with Praxis Pub.

Clervoy, Jean-François. (2009). Transcript not published [Unpublished interview]. Sandra Häuplik-Meusburger. Paris, France, June 2009.

Cohen, M., Flynn, M., Levy, F., Mancinelli, R., Matossian, R., Miller, J., & Parodi, J. (2012). Water Walls Life Support Architecture: 2012 NIAC Phase 1 Final Report. https://www.nasa.gov/sites/default/files/atoms/files/niac_2012_phasei_flynn_waterwallsarchitecture_tagged.pdf

Compton, W. D., & Benson, C. D. (1983). Living and Working in Space, A History of Skylab. National Aeronautics and Space Administration.

Flynn, M. T., Cohen, M., Matossian, R. L., Gormly, S., Mancinelli, R., Miller, J., Parodi, J., & Grossi, E. (2019). Water Walls Architecture: Massively Redundant and Highly Reliable Life Support for Long Duration Exploration Missions. https://ntrs.nasa.gov/citations/20190001191

Griffin, B. N., Lewin, J. L., & Louviere, A. J. (1978). The influence of zero-G and acceleration on the human factors of spacecraft design. JSC-14581, NASA-JSC.

Griffin B. (2010). Lunar Surface Airlocks. In A.S. Howe, B. Sherwood (Eds.) Out of This World: The New Field of Space Architecture, Reston, Virginia, USA, AIAA

Griffin, B. N., Smitherman, D. V., & Howe, S. A. (2013). Internal layout for a cis-lunar habitat. In AIAA SPACE 2013 Conference and Exposition (p. 5433).

Häuplik-Meusburger, S. (2011). Architecture for Astronauts: An Activity-based Approach (Springer Praxis Books). Springer.

Haeuplik-Meusburger S. and Bishop S. (2021). Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space. Springer Nature .

Haeuplik-Meusburger, S., & Ozdemir, K. (2012). Deployable lunar habitation design. In Moon (pp. 469-502). Springer, Berlin, Heidelberg.

Kitmacher, G. H. (2002). Design of the Space Station Habitable Modules. 53rd International Astronautical Congress, Houston, Texas. IAC-02-IAA.8.2.04.pdf

Mount, F. E. (2002). Habitability: an Evaluation. In H. W. Lane, R. L. Sauer, D. L. Feeback (Eds.), Isolation: NASA Experiments in Closed-environment Living: Advanced Human Life Support Enclosed System Final Report. American Astronautical Society.

NASA [Bull.7]. (1974). Skylab Experience Bulletin No. 7: An Overview of IVA Personal Restraint Systems. Lyndon B. Johnson Space Center. JSC-09541.

NASA [Bull.10]. (1974). Skylab Experience Bulletin No. 10: Body Restraint Systems. Lyndon B. Johnson Space Center, JSC-09544.

NASA [Debriefing A12]. (1969). Apollo 12 – Technical Crew Debriefing. Manned Spacecraft Center, 1969.

NASA [Dust Management]. (2006). The Apollo Experience Lessons Learned for Constellation Lunar Dust Management. Houston, Texas, US : Sandra A. Wagner, Johnson Space Center, 2006. NASA/TP-2006-213726

NASA [MSIS]. (1995). Man-Systems Integration Standards (MSIS) (Revision B ed., Vol. 1). NASA. NASA-STD-3000.

NASA [SpaceWeather]. (2020). NASA Space Weather History. http://spaceweatherlivinghistory.org/timeline/31

Riley, C., Copp, D., & Davidson, N. (Directors). (2008-2009). Moon Machines [Documentary] Science Channel.

Schmitt, H. (2009). Transcript not published [Unpublished interview.] Sandra Haeuplik-Meusburger. Vienna, Austria, 2009.

Wright, M., Jaques B. (2002). A Brief History of the Lunar Roving Vehicle. https://www.hq.nasa.gov/alsj/MSFC-LRV.pdf