4th Space Renaissance International Congress 2026

Technical and Scientific Engineering Aspects of Living in Free Space

Werner Grandl (archigran@gmx.at), Adriano V. Autino, Alberto Cavallo

Abstract

The human body is adapted to the gravity and the biosphere of our home planet, Earth. The lack of gravity in outer space and on the surface of celestial bodies smaller than Earth causes a lot of dangers to human health, like bone demineralization, muscle atrophy, and orthostatic intolerance. Despite future human outposts on the Moon and Mars, we have to think about creating artificial environments in free space for human settlers of the future, providing simulated gravity, also called "Artificial Gravity". Since the beginning of the Space Age there have been various attempts to design space stations and even big spherical and cylindrical colonies to simulate terrestrial gravity by rotation and to provide a liveable environment for humans in space. The bigger the radius of the rotating habitat, the better the conditions for humans. At large radii, the Coriolis acceleration, which may disturb the vestibular sense, can be neglected. A crucial problem to be solved by engineers will be the construction of the joint between rotating and non-rotating parts of a space station. We demonstrate the function of a magnetic liquid rotary seal by using a so-called "ferrofluid". We discuss the feasibility of big rotating space habitats like the "Stanford Torus" and G.K. O´Neill´s "Islands in Space" in the scope of the industrialization of cis-lunar space. We will have to face various challenges, like the production of building material on a large scale from lunar and asteroid sources, and to provide huge masses of air and water for a closed water and waste cycle in a given habitat. We will have to solve the problem of cosmic rays and solar flares by the construction of multi-layer walls to protect humans and the entire artificial biospheres of space habitats. Last but not least, we have to define the role of Artificial Intelligence and robotics as key tools for humans in space.

1. **Artificial Gravity** (simulated gravity) **in rotating space habitats**

The lack of gravity in outer space and on the surface of celestial bodies smaller than Earth causes serious dangers to human health. If we design rotating space stations and space habitats to simulate gravity by centripetal force, we have to keep in mind the Coriolis acceleration, which can disturb the vestibular sense when the radius is small and the rotation rate is high. Figures 1a,1b show the ratio between radii and rotation rates and an assumed "comfort box".

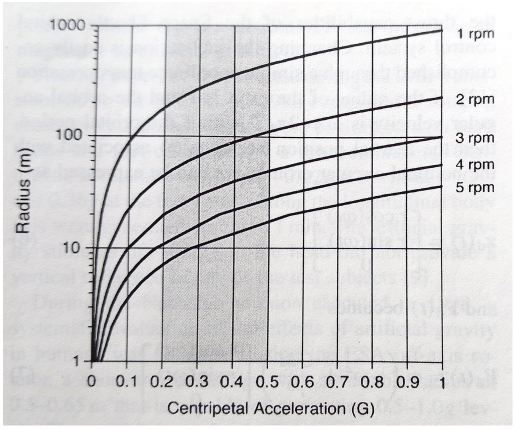

Fig.1a Radius of rotation and rotation rate (A. Bukley et al. 2007)

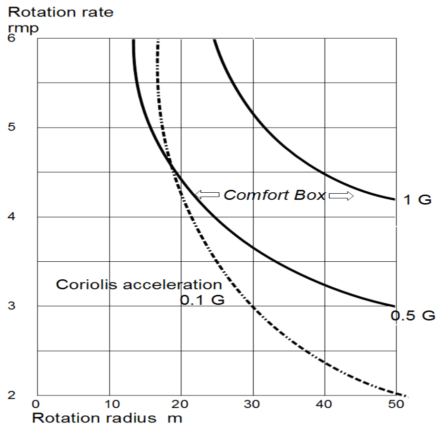

Fig.1b "Comfort box" (J.v. Puttkamer 1987)

We can conclude that there may be a “minimum” rotation radius of about 30 meters and a “maximum” rotation rate of about 4.5 rounds per minute (rpm) to create comfortable conditions. There is a clear need for an initial rotating orbital station to test various rotation rates and their influence on the human body, like the “Island Zero” concept by J. Stone (Fig. 2). To reduce costs a “minimum” rotating orbital station with four rotating modules is depicted in Fig. 3.

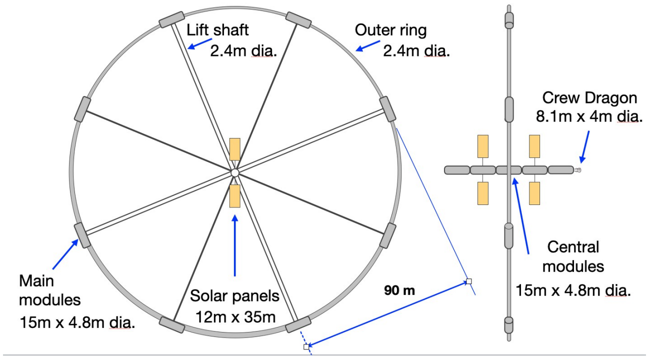

Fig. 2 “Island Zero” design by Jerry Stone

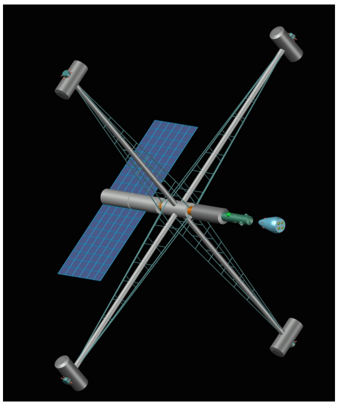

Fig. 3 “small” rotating orbital station by W. Grandl

1.1. Roto-joint: connecting rotating and non-rotating elements by magnetic liquid rotary seals

Rotating space stations and habitats will have some non-rotating parts, like a central hub, a docking harbour for spaceships, and solar panel arrays. It will be a crucial challenge for engineers to design a roto-joint between rotating and non-rotating parts of a station without loss of air. A possible solution could be a magnetic liquid rotary seal. This kind of sealing operates nearly without maintenance and with low leakage even in a vacuum by using a “ferrofluid”, an oil-based liquid with iron filings, which is kept in place magnetically between a rotor and a stator in a labyrinth seal (Figure 4)

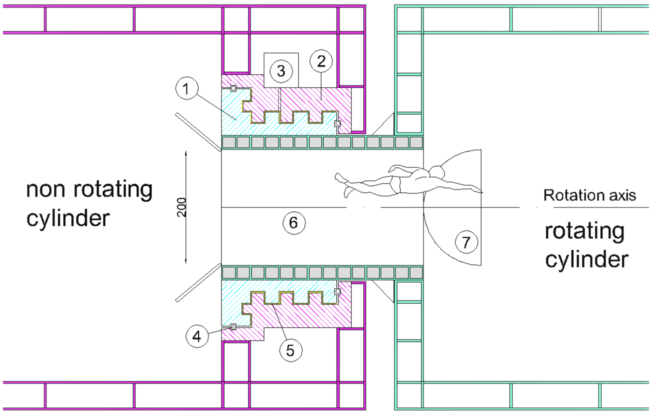

Fig. 4 The Roto-Joint: (1) rotor, (2) stator, (3) auxiliary ferrofluid tank, (4) ball bearings, (5) seal gap with ferrofluid, (6) air lock, (7) fire door (© W. Grandl)

2. Construction technologies for rotating habitats

2.1. Modules from Earth

There is a clear need for an initial rotating orbital station to study several levels of gravity simulation and their influence on human health and comfort. The first rotating space station in Low

Earth Orbit (LEO) at an altitude of 450 to 500 km will be built of modules, nodes, and some structural framework. All parts will be lifted into space either by (reusable) rocket launchers like SpaceX or by HOTOL (Horizontal Take Off and Landing) spaceplanes.

One can use either inflatables or rigid modules of aluminium (combined with carbon fibres and similar materials). Inside the Van Allen belt, the station is naturally protected from solar flares.

Inflatable material can help to reduce launch weight and costs at the beginning. But after inflation, most of the interior equipment and furniture has to be brought separately from Earth. On the other hand, rigid cylindrical or spherical modules can perfectly be equipped from the very beginning. Since reusable launchers with payload capacities up to 100 metric tons (SpaceX Starship) are available, it may be easier and even cheaper to use rigid modules. In LEO the modules and other components like structural framework, trusses, etc., will be assembled preferably by robots and remote control. The present ISS will be decommissioned in the early 2030s, but it could be continuously used as a "site hut" and storage facility for astronauts to supervise the erection of a future rotating orbital station. Figure 5 shows a modular orbital station, that is built in stages, starting with the non rotating central hub and four rotating living quarter modules. Step by step additional modules can be plugged in. Finally a closed ring provides living and working areas for about 180 persons.

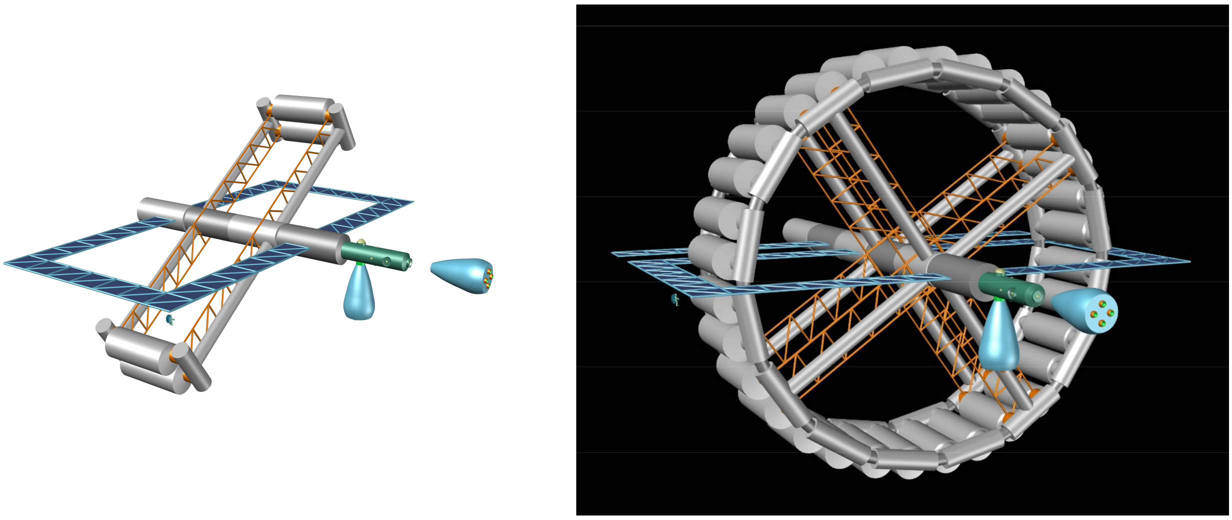

Fig. 5 AGOS Artificial Gravity Orbital Station, first stage (left), final stage (right), W. Grandl, C. Böck 2017

2.2. ISRU In Situ Resource Utilization

2.2.1. Lunar material

When building an initial human base on our Moon, it will make sense to use its natural resources. Fe, Al, Ti, Si, O, and H_2O can be extracted from regolith and processed into building material. Initially, regolith layers will cover modular stations on the lunar surface and protect them from cosmic rays. Later on the regolith will be molten and processed to fused bricks, the so-called "lunarcrete" (lunar concrete). Regolith itself does not provide a great insulation, because its substance is similar to glass. Insulation property changes when the regolith is mixed with polymers, getting a kind of almost rigid bricks, very much better for insulation purposes. Tests were made at Tales Alenia Space Torino, on request by Enrico Dini. Concepts by A. V. Autino, Marco C. Bernasconi, Enrico Dini, Prof. Valentina Colla (Scuola Superiore S.Anna diPisa). Tests were conducted by Antonietta Perino (Tales Alenia Space). https://www.santannapisa.it/en/node/45412

The bricks can be used to build spherical domes and cylindrical shelters. When a lunar industry is established, one can produce beams and trusses of steel and aluminium.

2.2.2. Asteroid material

After having established a factory in cis-lunar space e. g. in a Lagrange point we can process asteroid resources to produce building material, water, air, rocket fuel etc., in space. Various Near Earth Asteroids (NEAs) are passing Earth´s solar orbit frequently and contain Fe, Al, Ti, Au, Ar, C, N, H_2O, and even rare Earth elements. Big cylindrical habitats as discussed below will need a huge amount of air, water, nitrogen and carbon to create an artificial biosphere. For this purpose in the long run asteroid mining and material processing in space factories will be inevitable.

3. Shape, geometry and lighting

3.1. Toroidal structures

A torus seems to be the most feasible shape to construct an initial, large rotating habitat in space. The amount of air and water is less than in a sphere or a cylinder. An initial toroidal design was proposed by Wernher von Braun in the 1950s by using inflatable structures. The so-called "Stanford Torus" has been presented by students in 1975. It was envisioned to be built of lunar material like "lunarcrete" and was designed as a habitat for 10,000 persons.

Preferably, a toroidal habitat should be built of lightweight material (aluminium, carbon fibre, inflatable units) and covered with a shielding layer made of "lunarcrete". A problem would be to use natural sunlight without having huge glass panels, which would cause danger by cosmic rays and meteorites.

3.1.1. An advanced lighting system

To avoid huge glass panels a system based on optical fibres could be used to convey sunlight into the internal of a building while avoiding excessive heat transfer. This is achieved by using specialized filters that separate the heat-carrying infrared (IR) radiation from the visible light spectrum before the light enters the fibre optic cables. A solar collector, usually mounted outside and using sun-tracking technology and lenses (like Fresnel lenses), captures and concentrates the maximum amount of sunlight.

Filtration: At this initial focusing stage, a critical component such as a spectrally selective "hot mirror" or "cold mirror" is used. A cold mirror reflects visible light into the fibers while allowing IR radiation (heat) to pass through and dissipate externally. A hot mirror reflects the unwanted IR radiation while transmitting the desired visible light into the fibres.

Transmission: The filtered, cool, visible light is then coupled into high-purity optical fibres (often glass or quartz for high efficiency, though plastic is a lower-cost option) and transmitted through the building using total internal reflection. The flexibility of the fibres allows them to be routed through walls and ceilings, similar to electrical wiring.

Distribution: At the destination point inside the building, a diffuser is used to uniformly distribute the natural light into the room.

3.2. Spherical design, e.g. "Island One" by Gerard K. O´Neill

The *Island One* design is in fact a pressure vessel made of aluminium plates and glass panels. Only on the equator it can provide 1 g simulated gravity and the usable area for housing is limited. The air volume is much bigger than in a torus with the same diameter. The O´Neill design has glass windows all around the sphere which are exposed to meteorites and rays and may cause also thermal losses and freezing of condensed water at night (Fig.6). Maybe modern technologies based on optical fibres as discussed above might give a better result in terms of conveying the light from external panels into the internal environment, avoiding the excessive heating effect

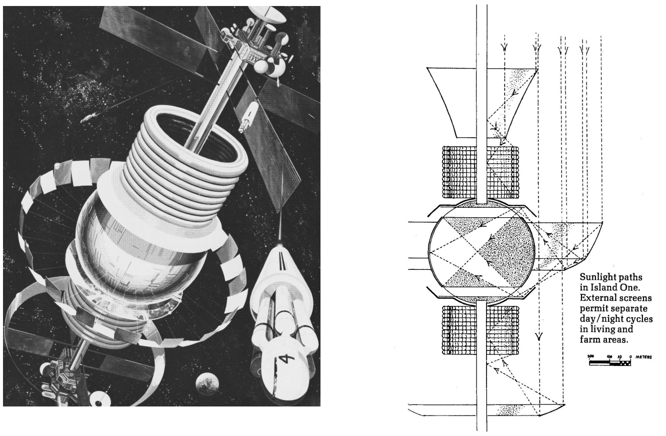

Fig. 6 "Island One" by Gerard K. O´Neill for 10,000 inhabitants, 1976

3.3. Cylindrical habitats with structural steel framework, aluminium coating and a multi-layer hull

If we build big cylinders of some hundred meters in diameter and hundreds of meters length in free outer space, the design of the primary structure is determined by the forces that act from the inner and the outer side of the cylinder. These forces are generated on the one hand by the inner loads, including air pressure, and on the other hand by the outer forces like rotation control thrusters, docking of spaceships, and possible meteorite impacts. An air evasion caused by meteorite damage must be corrected by counterforces applied by rotation control thrusters. A structural concept based purely on membranes (a pure pressure vessel like *Island One*) would make it almost impossible to correct the position of the cylinder without deformation of the hull. For this reason, a structural steel or aluminium framework is necessary to keep the entire cylinder stable in any case. A modular framework is also much easier to assemble during construction than, e. g. inflatable elements. The structural framework can be covered by an internal and an external hull, either of aluminium or made of carbon fibre. The external hull carries the shielding material (made of lunar regolith), the inner hull carries the "landscape" and the housing (Fig. 7). In most cases of meteorite impact, only the external hull will be damaged. To avoid huge air losses in case of leakage the structural cavity between outer and inner hull can be divided into sections by vertical membranes.

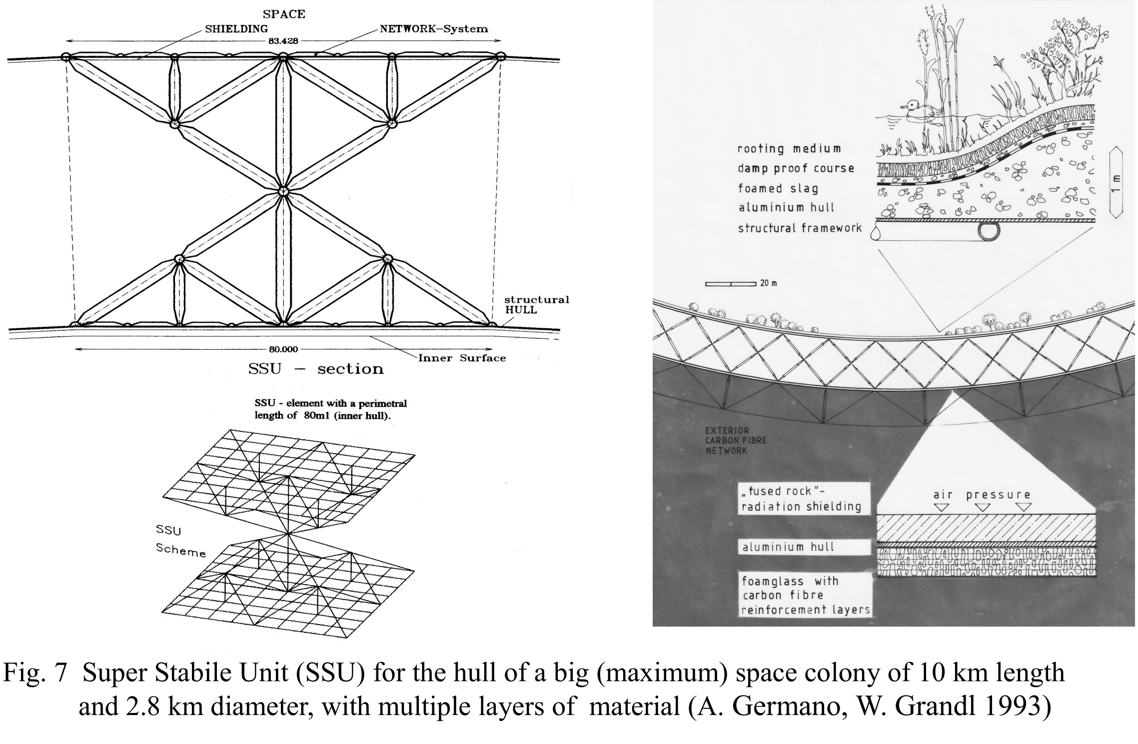

Fig. 7 Super Stabile Unit (SSU) for the hull of a big (maximum) space colony of 10 km length and 2.8 km diameter, with multiple layers of material (A. Germano, W. Grandl 1993)

4. Shielding against cosmic rays, solar flares, and meteorites

Cosmic rays are, e.g., heavy nuclei constantly coming from deep space. Solar flares frequently occur and are dangerous to human health. According to Jesco von Puttkamer (1987), the annual dose equivalent can be reduced by layers of dense material. Every 1g/cm2 shielding material reduces the annual dose by about 3.4 rem. The raw material for shielding can be lunar regolith, which is processed to “fused rock” bricks (Table 1).

TABLE 1

Radiation type	annual equivalent dose, unshielded	“fused rock” shielding	annual equivalent dose, with shielding
cosmic rays	50 rem	0.12 m	0 rem
solar flare	1000 rem	3.00 m	0 rem

A possible solution to reduce the amount of shielding material would be to apply 0.12 m dense shielding to the outer hull of a sphere or cylinder and to build an external flat “solar flare shielding” with a 3 m thick regolith layer, which is constantly floating between the sun and the colony.

4.1. lunar concrete (“lunarcrete”), regolith bricks

“Fused rock” or “lunarcrete” would be made of lunar regolith by a high pressure melting and cooling process . Different from usual concrete on Earth no water is necessary. Structures of regolith “lunarcrete” bricks can carry high pressure loads but are insufficient to tension forces. Tension loads can only be carried by steel or aluminium tubes or trusses and carbon fibre elements. Regolith bricks can be used to build domes and arcs on the Moon as well as a shielding layer for habitats in free space.

4.2. multiple layers

Multi-layer walls and hulls can provide several advantages. The structural hull of a big space colony may consist of the layers as shown in Fig. 8 :

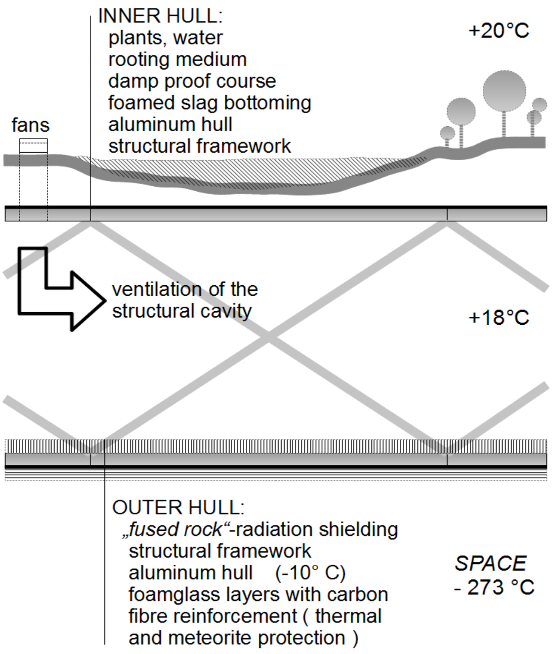

Fig. 8 Section of the structural hull of a cylindrical space habitat

The outside foamglass layer acts as a thermal insulation to keep the temperature of the structural framework between +18° and -10° C. Furthermore, this layer stops micrometorites softly to protect the aluminium hull from being constantly penetrated.

4.3 Alternative shielding technologies

For small entities like spaceships and stations in lunar orbit or in the Lagrange points one can use water as a very effective shielding. An artificial mushroom structure in a spacing between two aluminium platings may contain a certain mass of water. Maybe some electric heating must be provided to avoid freezing of the water layer. An advanced future technology would be "electromagnetic shielding" by creating a magnetic shielding system to mitigate the influx of cosmic rays and solar flares. This kind of technology deserves further research but may be available within the next decades.

5. **Artificial biospheres and climate simulation**

Building huge rotating spherical or cylindrical habitats in space means also creating an artificial biosphere with a stable climate, a closed water and waste cycle, and the simulation of day and night. To balance the energy budget, the thermal conductivity of the hull determines the incoming radiation quantity (and vice versa). To generate a moderate climate -similar to Sweden or Canada- we need at least a radiation intensity of 300 to 400 W/m2h at noon. Calculations have shown that the thermal conductivity of the outer hull has to be at least 0.45 W/m2K (A. Germano, W. Grandl 1993). For big colonies with their huge air volumes, it does not make sense to install a separate air conditioning system with external heat radiators. The outer hull of a big colony is actually the radiator, and the structural cavity between the outer and inner hull acts as a heat exchanger (Fig. 8).
Unlike Gerard K. O´Neill, we should avoid huge glass windows, because they would be exposed to radiation, meteorites, and large temperature amplitudes, which would lead to condensation and freezing of air moisture. A proper method of illumination would be to focus the sunlight by a system of parabolic mirrors and beam it through a central window into the cylinder. A central distribution cone with mirror facets enlightens the habitat. By using shutter elements at the window we can simulate day and night cycles (Fig. 9 and Fig. 10). The window must be cooled during daytime and heated during the simulated night. The fluid cooling and heating medium can be used for an electrical power station. The solar flare shielding could be equipped with photovoltaic panels to generate electric power, which can be beamed to the colony by laser devices or microwaves.

6. Locations for rotating space habitats

The favourite locations for space factories and space habitats are the Lagrange Points of the Earth-Moon system. There are five points where there is an equilibrium of gravity forces between Earth and Moon. Two of them, L4 and L5, are extraordinarily stable because they are building a triangle with Earth and Moon. Later on, habitats could also be located in Earth´s solar orbit, either preceding or following Earth in constant distances.
Each habitat in free space will have rotation control and manoeuvre thrusters to stay in its spatial position. The free floating parabolic mirror plant and the solar flare shielding must also be constantly positioned between the sun and the habitat by manoeuvre thrusters. Artificial Intelligence will help to control and supervise these manoeuvres.

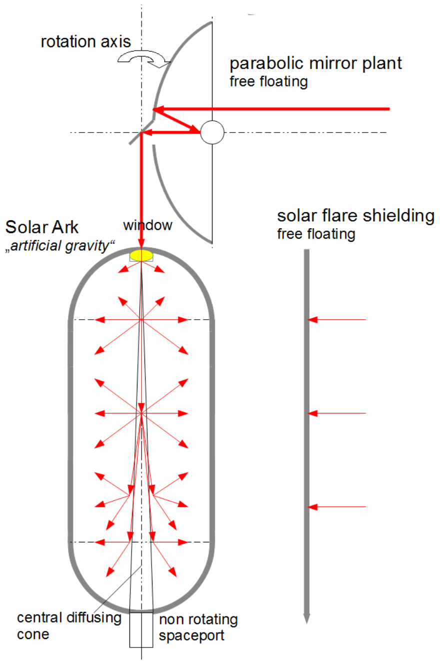

Fig. 9 Section Solar Ark habitat (schematic)

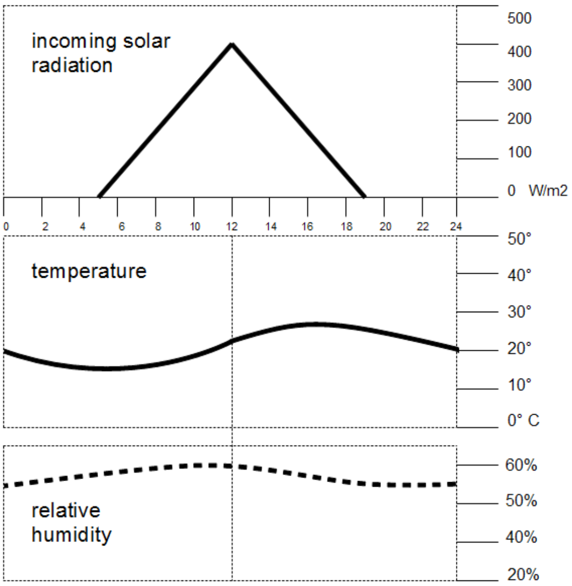

Fig. 10 daily temperature curve and humidity

7. **Energy supply**

7.1. Solar energy

In the so called "habitable zone" (approximately the space between Earth and Mars) proper solar energy is available for 24 hours. The space closer to the sun offers much more solar energy, but building space stations e.g. in Venus orbit would be dangerous because of overheating and solar flares of high density. In Earth orbit the permanent solar influx is about 1353 W/m2. By using solar arrays within the Earth-Moon system, including the Lagrange points, we can calculate about 12,264 kWh/m2 per year.
If we take as an example a solar power array of 1000 m2 we would have a thermal solar influx of about 12.26 GWh/year. Given a power conversion factor of 25% for conversion of thermal energy into electric energy we can calculate approx. 3 GWh/year for a 1000 m2 solar array, sufficient for initial manufacturing and material processing in space.
For the enlightening of human habitats about 300 – 400 W/m2 at noon would be enough – similar to Canada or Sweden.

7.2. Nuclear energy

On the Moon we have different conditions. The lunar day and the lunar night are each one about 14 terrestrial days. Therefore it will be convenient to use small nuclear reactors during the lunar night to supply lunar outposts with electric power. Also space stations in lunar orbit could carry a small nuclear battery for backup and emergency functions. Future spacecrafts for travel to Mars and beyond will also be equipped with a nuclear power source.

An advanced technology will be nuclear fusion. The isotope helium-3 is rare on Earth but abundant on the Moon and can be used as a fuel for nuclear fusion. Helium-3 and deuterium fuse to helium-4 plus protons (Bussard 2002). When nuclear fusion is available until the end of the century, it will also solve energy problems on Earth and contribute to prohibit further global warming.

8. Artificial Intelligence (AI) and robots as tools

The rise of AI, robotics and nanotechnology during the last decades is ambiguous. The use of AI may create a new order of human society, new forms of economy, agriculture and industrial production. The worst case may be total takeover of civilization by AI and the decline of humanity.
On the other hand AI and robotics offer a great variety of utilization, on Earth and especially in outer space. In space technology, such as building human outposts in space, mining of the Moon and the asteroids, material processing and industrial production in space, AI and robotics will be necessary and finally inevitable. When using AI humans have to be aware of its dangers as well as of its advantages. We have to keep in mind that AI is just simulating intelligence and consciousness by using the input it gets from humans. A so called human-AI interface by implanting electronic devices into the human brain would perhaps endanger the autonomy of humans as individuals. There has always to be a clear hierarchy with humans on top of the pyramid and AI and robots as their tools.

9. Conclusion

Engineering, mining, industrial production and building outposts in space will be a crucial challenge during the centuries to come. The technologies described in this paper cover just a few aspects of the huge enterprise to establish human civilization in outer space. Much research has to be done in the future to improve technology and engineering for this giant leap of mankind. Some production technologies are easier to perform in free space or on the Moon than on Earth because of low gravity, others are more complicated if water and oxygen are necessary. Indeed we can find and utilize in space all elements and raw materials we need to create an advanced civilization in space. In the coming centuries some hundred thousands of people could settle in cis-lunar space and constitute a new society beyond planet Earth. Industrial facilities in Earth orbit, on the Moon and in the Lagrange points will produce the material for building large habitats and products for the increasing population on Earth and in space. In the long run the resources of the entire Solar System will be utilized for the benefit of all humankind.

References:

Bukley A. et al., Generating artificial gravity onboard the Space Shuttle,
Acta Astronautica 60 (2007) 472-478

Bussard R W, An advanced Fusion Energy System for Outer-Planet Space Propulsion,
Space Technology and Applications International Forum 608 (2002)

Germano A, Grandl W, Astropolis – Space Colonization in the 21st Century,
11th SSI Princeton Conference "Space Manufacturing 9, The High Frontier,
Accession, Development and Utilization" (1993), p. 252-268

Grandl W, Autino V A, Böck C, Artificial Gravity Orbital Station (AGOS)- the simulation of gravity
in a rotating space station, IAC-23, B3,3,1,x75535, 74th IAC, Baku, Azerbaijan, 2023

O´Neill G K, The High Frontier-Human Colonies in Space 1976

Puttkamer J.v., Der Mensch im Weltraum – eine Notwendigkeit, Umschau-Verlag (1987) p.163