Modular Inflatable Space Habitats

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ABSTRACT

In space we find an extreem vacuum. Human beings need an atmosphere to survive. This makes inflatables most apt for use in human space flight. Savings in weight and packaging volume are perfect for getting them off ground. With the development of TransHab, NASA made a big step forward in proofing the technology-readiness of using inflatables for human space habitat. Protection of micro-meteorites and radiation proofed to be even better than in the aluminium ISS Module. The shape of TransHab was based on a toroid. The sphere is the natural shape of a flexible skin with an inside pressure and naturally combining maximum volume with minimum surface (insulation/protection etc). It is astonishing why this very efficient shape has not been used more often for space applications. This paper will investigate on a concept level the possibilities of a sphere for use in microgravity and planetary habitats. Possibilities for habitats for 1-2 person, 6 persons and up to sixty and more, all using the same basic standard modules and morphology. Even a whole self-sufficient space station with artificial gravity where the big structure resembles - like in a fractal system - the smallest unit will be proposed.

INTRODUCTION

Inflatable structures have always been a obvious alternative for space structures, since they combine stability with a high volume/weight ratio. Any habitat in space and on low atmosphere celestial bodies will be pressure vessels by virtue of having to provide an internal pressure preferably around 100 kPa. The use of a flexible membrane instead of a rigid metallic skin offers the important possibilities to create volumes which go beyond the dimensions of the cargo bay of the space shuttle or other transportation systems.

While early concepts for space stations were based on inflatables, it was not until recently, when NASA seriously considered and developed an inflatable Habitat Module for ISS: The TransHab. Only Spacesuits – the minimum kind of an inflatable short term space habitat – have been continuously developed and used since the 1960's and delivered a lot of the technology background to develop TransHab[1]. Especially recent development in material technology makes it interesting to consider inflatable habitats for future missions. Advanced flexible polymers and high strength fibres such as Kevlar, Vectran, and Spectra, have enabled the fabrication of very low mass structures that are deployable from a densely packed state.

SHORT SURVEY ON INFLATABLE HABITAT DESIGNS FOR SPACE

The following concepts for inflatable habitats should be pointed out:

1. Goodyear Space Station
2. Mercury Mark II
3. Livermore Habitat Module
4. TransHab
5. Mars/Moon Habitat/Laboratory
6. Bigelow Space Station

„Throughout the 1960s and early 1970s, NASA and industry teams were at work developing inflatable space structures ranging from space suits to habitats. These development programs included the manufacture and test of several large scale prototypes. While space suit development continued at a strong pace from the early days of manned space exploration to today, the development activities in inflatable habitats was not as rigorously pursued. Inflatable habitat structures were included in various studies conducted by NASA and Aerospace prime contractors through the 1980s and 1990s, such as the Space Exploration Initiative (SEI), but it was only recently that development activities which included the fabrication and test of prototype units has recommenced."[1]

Major developments in the early 1960s happened at NASA Langley Research Center (LaRC). Together with the rubber company Goodyear a 7,3m (24 ft) diameter mock-up of an inflatable space station concept was built in 1961.(Fig.1) In the Mercury Mark I Program studies for a 1-man space station based on the Mercury capsules were performed. Also Goodyear made their own proposals (Fig.2).
For the Gemini space station inflatable air locks were considered and tested, but the program was stopped due to a shift in research emphasis. Nevertheless, inflatable airlocks have been used in space: The first spacewalk by Alexi Leonov in 1965 was from an cylindrical inflatable airlock. In 1963 an inflatable extension was proposed by Schnitzer in the Apollo X program[2]. The Apollo program, though, was based on hard aluminium shells and this technology became prevailing in the built hardware. Experience and know-how in this technology naturally grew.
From that point inflatable habitats were mainly considered for far away planetary exploration concepts like the NASA Inflatable Habitat Concept for a Lunar Base, which was proposed as part of the Space Exploration Initiative in 1989. In the same year the Lawrence Livermore National Laboratory studied the feasibility of inflatable modules to be used in a future space station or possibly integrated in the space station Freedom, which was already moving into hardware fabrication phase. Cylindrical and toroidal shapes were investigated in this study. With 5m in diameter and approximately 17m long, the dimensions of the deployed modules were hardly bigger than the Shuttle's cargo bay (Fig.3). But, they offered an interesting outlook on major weight, take-off volume and thus cost savings. Nevertheless, the International Space Station was completely planned on rigid aluminium modules and inflatable space habitats had to wait for another decade.
It was indeed the outlook to go beyond Earth orbit and the more and more realistic mission plans for a manned Mars mission, which led to the development of the TransHab Module by NASA. TransHab was less driven by cost reduction, but by the outlook for long-duration spaceflight. Lessons learned in space human factors showed, that for long duration missions like the transition to Mars for a crew of six astronauts, more volume and space is needed. It is worth noting, that this demand is human factor driven and that two space architects were in the 22 people team, which developed TransHab[3]. TransHab deploys to approximately 7,6m diameter in space and is organized around a central hard core, which contains the crew quarters, which are radiation shielded by water tanks. Three floors are built in after deployment. Unlike the Livermore concept TransHab extends well over the shuttle cargo bay diameter and still fits to the existing ISS modules. Unfortunately due to political and economic changes the program was stopped, after a series of promising hardware tests. (Fig.4)
A proposal to add an inflatable laboratory has been made in the NASA Mars Reference Mission (Fig.5) after the development of TransHab. Interestingly, it was not only weight savings, which led to that, but again habitability issues: “This volume augmentation for a sufficient level of pressurized living volume is critical for crew health maintenance. A TransHab-derived inflatable structure would provide such augmentation.“[4]
The growing demand of private people to enjoy space, led to many publicity-attracting concepts for space stations. Currently a team around American millionaire Bigelow is working on a design for a ‘tourist’ space station, which is using technology realised in the ISS. Also three TransHab-like inflatable modules can be seen on the concept design. There are also proposals to use TransHab as a Tourist module on ISS [5]. The space flight of millionaire Dennis Tito showed that there is a growing potential for that market, leaving it open, if resources are used intelligently.
Most of these habitats are based on a cylindrical and toroidal shape, which provides an efficiently usable space.

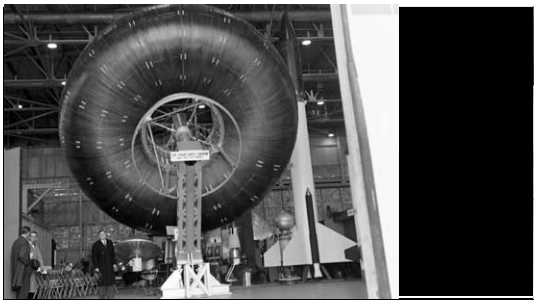


Fig.1 NASA Langley 1961

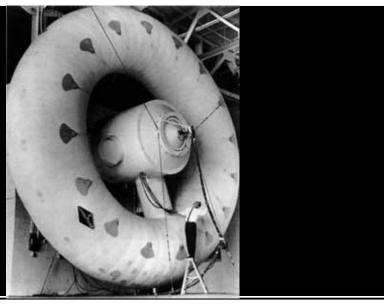


Fig.2 Goodyear 1961


Fig.3 Livermore 1989

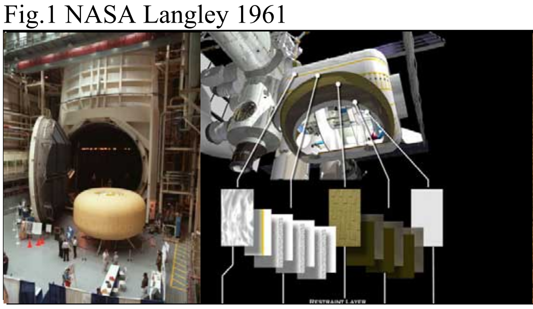


Fig.4 NASA TransHab

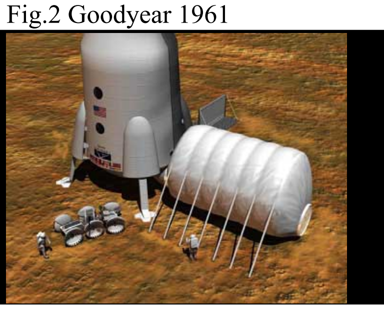


Fig.5 NASA Mars Ref Mission

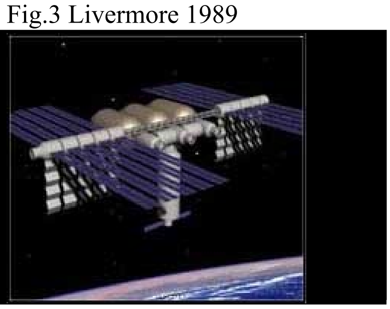


Fig.6 Bigelow Space Station

THE SPHERE AS TERRESTRIAL BUILDING FORM

The sphere has the most efficient volume to surface ratio. This is quite academic and the sphere never succeeded to become a relevant typology for terrestrial habitats. This is due to the effects of gravity on a unpressurized sphere and the difficulty to make efficient use of the curved geometry for small scale functions like housing or offices. Nevertheless the structurally most efficient shape for over 2000 year has been the dome – half a sphere. The Roman Pantheon in Rome, built A.D. 123, spans over 43m with a minimum thickness on top of 60cm, still stands today. It was unsurpassed for over 1300 years. The Haghia Sophia dome from the 6th century, which spanned the largest column-free area, was unsurpassed up to the 1920s!

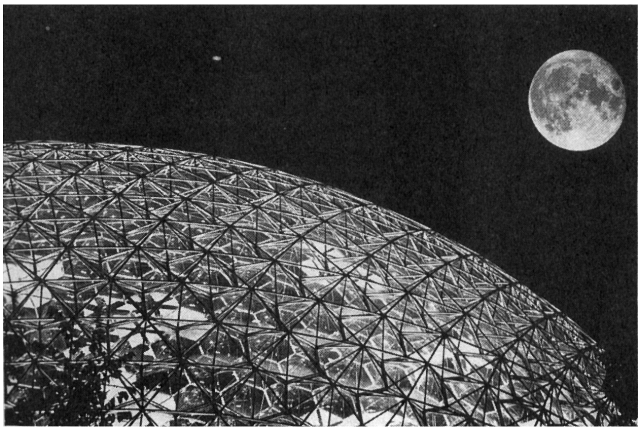


Fig.7 Fuller Expo Montreal dome at night

In the 20th century with new construction methods and materials the dome stayed to be a very efficient structure for wide spans. A draw back in terrestrial use is that the heatable volume becomes larger and stays in a paradoxical contradiction to the positive volume/surface ratio of a sphere. Buckminster Fuller developed geodesic domes, which allowed an efficient and extreme low weight construction of a sphere covered with plexiglass. Fuller also followed the train of thought, that when geodesic spheres get big enough, they eventually would float in the air: "By enlarging the sphere to nearly one kilometre in diameter, Fuller believed that the ratio of structural weight to enclosed air volume would become negligible and the warming effect of the sun upon the enclosed air would be sufficient to allow the sphere to rise like a cloud."[6] Fuller, who became an expert in domes (over 300'000 geodesic domes have been built under his patent), explains the advantages like this:
"All domes share certain advantages, whether or not they are geodesic. Their compound-curved shape is inherently strong, giving a self-supporting clear span with no columns. Domes are resource and energy-efficient because, of all possible shapes, a sphere contains the most volume with the least surface. This holds true for domal slices of a sphere as well. The minimal surface presents the least area through which to gain or lose heat…When you double the exterior dimensions of a dome the skin area rises by a factor of four while the volume rises by a factor of eight...Larger domes are more efficient because less percent of the contained air is near of touching the skin where most heat loss or gain occurs. Doubling the size of a dome doubles its thermal efficiency…The favourable surface-to-volume ratio is not the only reason for a dome's remarkable thermal performance; interior and exterior aerodynamics play a part, to0…A dome's heat loss is further reduced by the concave interior…Moreover, like an enormous, down-pointing headlight, a dome reflects and concentrates interior radiant heat that would otherwise escape through the skin." [7] The near spherical domes, as presented at the World Expos in Montreal 1967 and Osaka 1970, though were not often repeated. A main problem under the influence of gravity is, that to build small-scale functional spaces on several levels, a separate structure has to be built inside, compromising the structural efficiency of the dome and leaving it as a mere climatic skin.

THE USE OF SPHERES IN SPACE

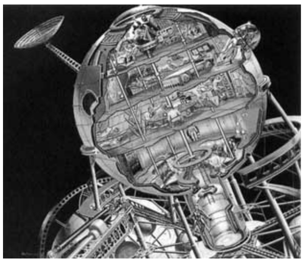
In space, the fact that we deal with high inside pressure and low levels of gravity, the sphere could be used to its full advantages. Thus, it is astonishing, why there have not been more considerations of using the sphere in space architecture. A further highly valuable advantage for spaceflight – the optimum shielding geometry against radiation in free space – has been pointed out by. Marc Cohen from NASA AMES Research Center: "A sphere has the minimum ratio of surface area to volume of any solid, the area = $4\pi r^2$. For a spherical habitat 7m in diameter, the surface area is $154m^2$. For a shielding of 30 $grams/cm^2$, one square meter of surface has a mass of 300kg. The total spherical area of $154m^2$ will require a shield mass of about 46,000kg, not including attachment hardware. It is necessary to launch this entire shielding mass into Low Earth Orbit, either from the Earth or from the Moon. This omnidirectional shielding may be solid, as in formed aluminum gore panels or liquid, as in water to pump into interior perimeter tanks. [8]
It is probably due to the fact of construction possibilities and the difficulties of controlling small volumes safely, before even considering large pressurized volumes, that spheres in space have not been used very often. There are a few exceptions though.
As early as in 1952 Collier's famous space series depicted the Interior of a lunar spaceship passenger sphere, based on a mission design by Wernher von Braun and his colleagues.[9] This sphere of about 11m diameter, was organized in 5 floor levels, which contained all living functions, Life Support and flight control systems. The passenger sphere was independently on top of the actual rocket systems – a very similar concept used today for the transfer spacecraft to

Mars. (Fig. 8) The drawing indicates, that this sphere was probably an inflated rubber sphere and after inflation cladded with small-scale aluminium panels for meteorite protection and radiation shielding as in Werhner von Braun's famous 'Collier Space Station'.[10]

ECHO 1, a 30,5m (100ft) diameter inflatable communications satellite, was developed and flown to space by the NASA Langley Research Center and constructed by General Mills of Minneapolis, Minnesota in 1959 (Fig.9). Forty thousand pounds of air was required to inflate the sphere on the ground, while in orbit it only required several pounds of gas to keep it inflated. Echo was a passive communications satellite, which reflected radio and radar signals as a limited communications relay. With a weight of 150 pounds, the satellite was inflated in space. To keep the sphere inflated in spite of meteorite punctures and skin permeability, a make-up gas system using evaporating liquid or crystals of a subliming solid were incorporated inside the satellite [11]. Although not a habitat, ECHO I and II, were extreme lightweight large volume structures flown in space more than 40 years ago.

In the classic film of spaceflight "2001: A Space Odyssey" based on a novel by Arthur C. Clarke and directed by Stanley Kubrick the Aries IB spacecraft served as a shuttle from the 2001 space station to the moon. It is a sphere with an estimated diameter of 16m. It's crew consisted of a pilot, a co-pilot, two stewardesses and some twenty passengers.[7] Fig. 10 shows Aries IB with its landing legs retracted. Main boosters were at the bottom, with four small steering rockets equally distributed around the equator of the sphere. The passenger deck and windows were on the top half.

A spherical space colony of the type first described in the 1920s by J. D. Bernal, was the base of Gerard K. O'Neill's scheme for his "Island One" space colony in 1975, some 500 meters in diameter (Fig.10). Rotating twice a minute this would generate an Earth-normal artificial gravity at its equator. Sunlight enters as shown by the large fuzzy ring. As an special advantage of the sphere was again pointed out the fact, that it has the smallest surface area for a given internal volume, so minimizing the amount of radiation shielding required.



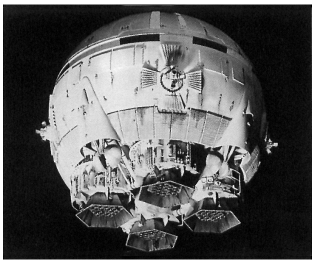


Fig 8 Lunar Passenger Sphere 1952, Fig 9 ECHO 1 Satellite, Fig 10 Aries IB, Fig 11 Bernal Sphere

The Space Shuttle Personal Rescue Enclosure (PRE) Rescue Ball is using the advantages of a sphere for a minimal short-duration single astronaut rescue sphere, actually the most minimal spacecraft of all time.[12] The rescue ball was an 86 cm diameter high-tech „beach ball" with three layers: urethane inner enclosure, Kevlar middle layer, and a white outer thermal protective cover. Crew members were to climb into the ball, assume a fetal position, and be zipped inside by a space suited crew member. They donned an oxygen mask and cradled in their arms a carbon dioxide scrubber/oxygen supply box with one hour worth of oxygen. The ball would be connected by an umbilical to the shuttle to supply air until the airlock depressurized. The crew member would then be floated over to the rescue shuttle by the suited astronaut. A tiny window was provided to prevent total sensory deprivation.

Fig.12PersonalRescueEnclosure

A CONCEPT PROPOSAL FOR SPACE HABITATS BASED ON SPHERES

The following proposals are based on simple ideas of applying inflated spheres to human spaceflight, using their advantages mentioned above. Many necessary evaluations and calculations have not been done at this stage. The proposals shall mainly provoke a discussion on the First European Workshop on Inflatable Space Structures to intensify work on inflatables for human space habitats.

For habitat or laboratory use the size of a spherical module is dependant on crew size and mission duration.[13] For larger sizes it makes sense to work with usable floor areas, also in microgravity environments, since it helps to organize the omnidirectional space. Diameters of 4m, 8m and 16m will be considered relating to crewsizes of 1-2, 6 and 12-15.

One problem to solve is the packaging of a sphere to bring it up to space. Simple model studies by the author (Fig.13) indicate that rolling up of a flexible sphere – depending on skin thickness – can be considered realistic in a ratio diameter packed to length packed (which equals approximately the spheres inflated diameter) of 1/4, approximately the proportions of the Shuttle cargo bay.

Fig. 13 Model study of unfolding a packed flexible sphere

A 4,0m diameter sphere (Fig.14 left) could be considered as a minimum functional size with a projected floor area of 9,3 m^3 and an inner volume of 33,5 m^3. This would be too small for an independent habitat use, but could be used for extensions of existing mission modules. Also a circular arrangement of racks would be inefficient with such a diameter. New storage units, which use the curved space more efficiently, would have to be introduced. In the current space station design a 4,0m sphere would not bring many advantages over the existing modules, but could be used as a test module for this technology.

A sphere of 8,0 diameter (Fig.14 middle) could already be organized using 3 floor levels like TransHab. It would provide a projected floor area of approximately 132,3 m^3 and an inner volume of 268 m^3. This would allow considering a habitat for up to 6 people for 100-day missions. In the central area crew quarters can be organized to provide maximum radiation shelter and the two side domes could provide living, working and/or sport functions. The domes would introduce the feeling of a large space for a small actual volume, which would benefit the overall habitability.

A further interesting consideration would be to make full use of the Space Shuttle cargo bay with its 4,5m diameter and 18m length to send an inflatable habitat into space. Based on the model studies mentioned above a sphere of 16m inner diameter with an approximately 50cm multi-layer skin like conceived for TransHab should be possible, depending on packaging possibilities and necessary hard equipment, like the connectors. Such a sphere would have to be equipped after the deployment for weight reasons, but would allow up to 970m^3 projected floor area and would have a volume of 2.144 m^3, which is double as much as the International Space Station.

Central axis in all 3 directions could form the inner circulation system and the volume could not only be organized in decks but also into quadrants. This would allow a very efficient movement in space. Though, severe problems of noise, vibration, fire emergency etc. would have to be overcome.

A standard connection in all x,y,z directions would allow adding inflatable airlocks and/or further spheres to form conglomerates.

Similar considerations for floor area can be done using spheres of these sizes for surface habitats in low atmosphere and low gravity environments. Inflatable legs can be added (Fig 15). The bigger the spheres get, the better the space can be organised. Inside pressure helps to support the structures. Additional radiation protection can be added on the top half.

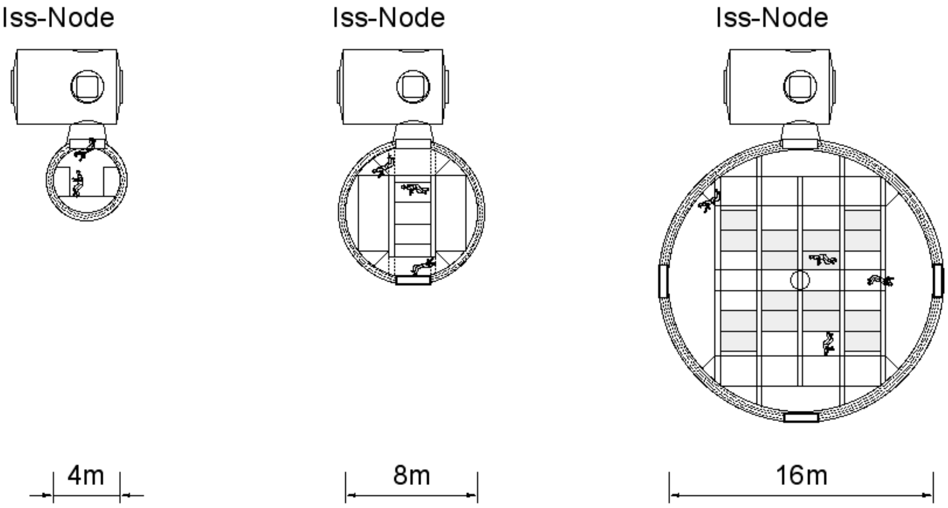


Fig. 14 Schematic sections through spherical microgravity habitats

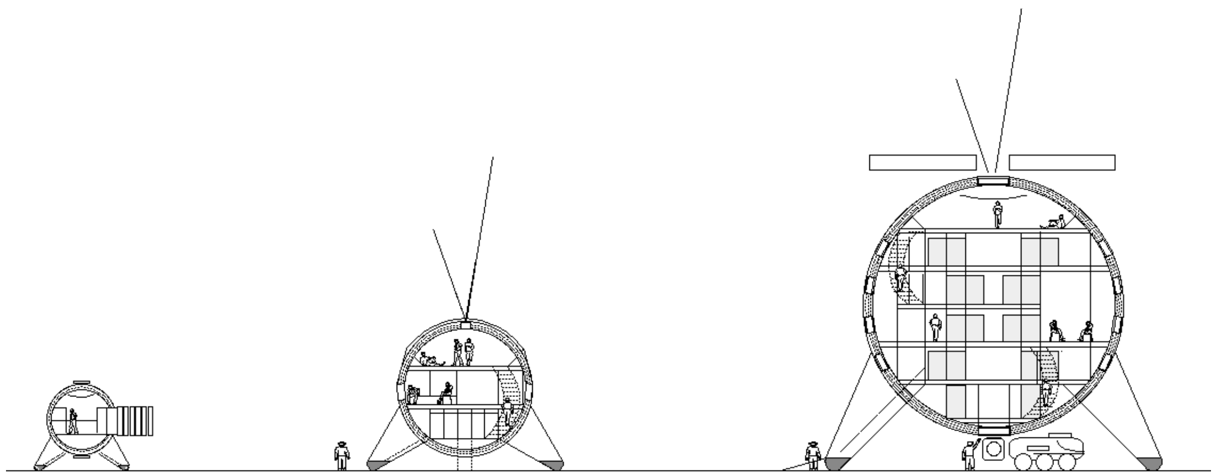


Fig. 15 Scematic sections through spherical surface habitat with 4m, 8m and 16m inner diameter

The bigger the spheres become the less structural redundancy can be achieved compared to a system based on small modules though. The development of self-healing skins will be very important. Also a good radiation protection. This maybe both achieved by integrating a liquid (water) system into to skin.

Inner diameter	Inner surface	volume	Volume/surface ratio	Projected area (h=2,15m)	Proposed crew size	Mass estimate primary structure
4m	50 m^2	33,5m^3	0,67	9,3m^2	1-2	200 kg
8m	201 m^2	268 m^3	1,33	132,3 m^2	4-6	804 kg
16m	804 m^2	2.144m^3	2,67	970 m^2	12-15, More volume can be used for fully recycables ECLSS	3216 kg
TransHab	~262 m^2	339,8m^3	1,30	136,1 m^2	6	1.039 kg

Fig. 16 comparison of different diameters for spherical inflatables

Fig. 16 shows calculations and estimates compared to TransHab data. The weight estimates are based on TransHab Technology.[14]
A 16m sphere could be the base of a concept for a 1000-day mission microgravity spacecraft as shown in Fig. 17. A tethering cable would connect the sphere to the solar panels and allow turning the whole system in a diameter of 90m, introducing a partial gravity. Added rigid aluminium modules could contain the ECLSS, thus reducing noise impact on the habitat. These modules could also serve as emergency retreats. The sphere would allow enough space for a crew of 12 to grow food. A spacecraft like this could maybe be considered for a human mission to Europa ("Europe goes to Europa")

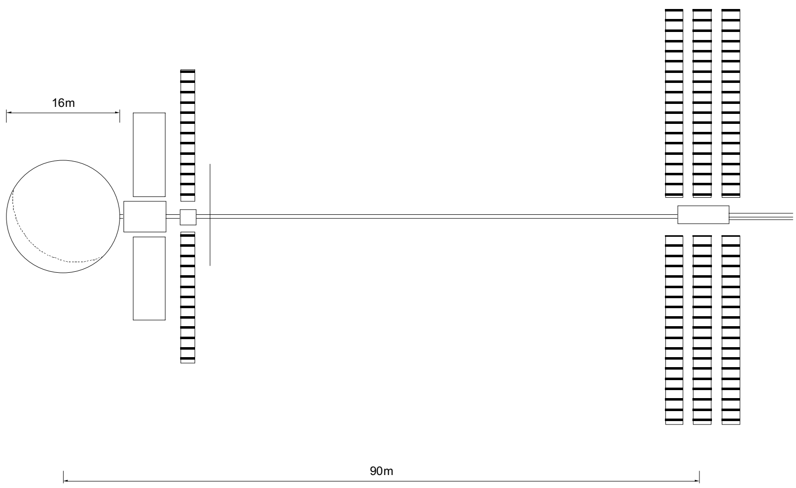


Fig. 17 Tethering spacecraft with 16m diameter inflated sphere

In a further jump in scale a sphere could be made as wide as 80m in diameter to provide at least partial artificial gravity[15]. On the inside wall of the big sphere 8m habitat spheres could be docked, allowing a high redundancy, but also small family size communities. The earth-like atmosphere could be limited to these 8m spheres. The volume of the big sphere could be pressurized much lower with a high carbondioxide concentration, still allowing plants to grow and produce oxygen. Humans would have to use oxygen masks moving in that environment and would need to go through airlocks. An optimisation between pressures and short prebreathing times would have to be found. On the inner poles of the sphere plants and animals for food supply could be grown. Main connection points to the outside would be at the poles. The inner center of the sphere could contain a further sphere with microgravity environment for laboratory or factory use. The sun directed hemisphere could be covered with solar cell film technology. A station like this could be conceived for one of the libration points between Earth and Moon. The big sphere would need to be welded in space.

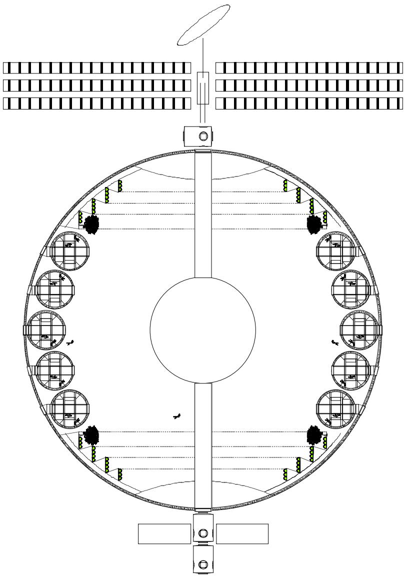


Fig. 18 Concept drawing of an 80m inflated space station

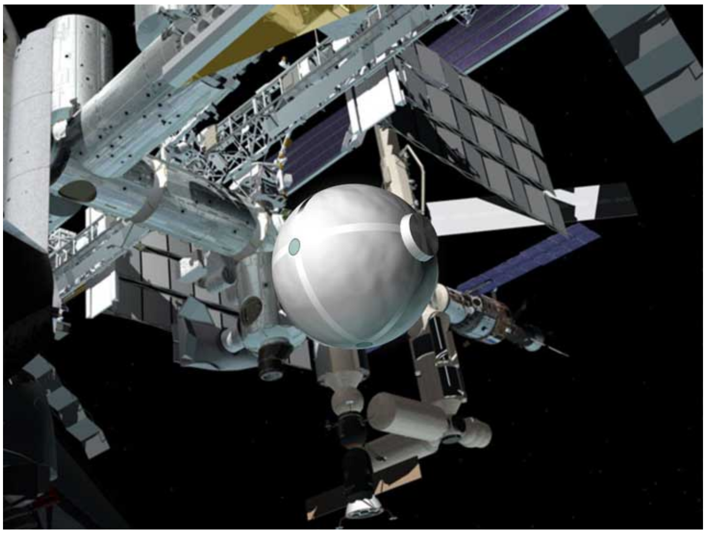


Fig. 19 Photomontage of an inflated sphere at ISS

CONCLUSION

This simple and short study shows, that we are probably just at the beginning of new ideas for inflatables habitats, maybe also for terrestrial use. New technologies, materials, rip-stop weaving methods and self-healing skins give prospects worth enough studying inflatables and their shapes more extensively. Inflatables open new perspectives of bringing volume into space, but a main problem stays: bringing mass into space. The here shown concept of a 16m sphere may not be used as a habitat, but could also provide the necessary volume for food production and recycling systems for the ISS in a first step. As important for longer missions as more volume.

Fig. 20 Inflated sphere on spacecraft

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[3] The Architects were Constance Adams and Kriss Kennedy. Constance Adams writes in a unpublished contribution to Macmillan: "TransHab was first conceived in 1997, by a team of engineers and architects at the Johnson Space Center. In June of that year, a small group put forward the idea of developing an inflatable space habitation module that was capable of supporting crew needs on a long transit journey. In October the Space Human Factors group was asked to perform a habitability evaluation of the vehicle and to recommend a dimension for the pressure-shell. This evaluation based its findings on lessons learned from earlier US and Russian missions regarding psychological, social, operational and anthropometric issues associated with human spaceflight."

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