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TORUS OR DOME: WHICH MAKES THE BETTER MARTIAN HOME

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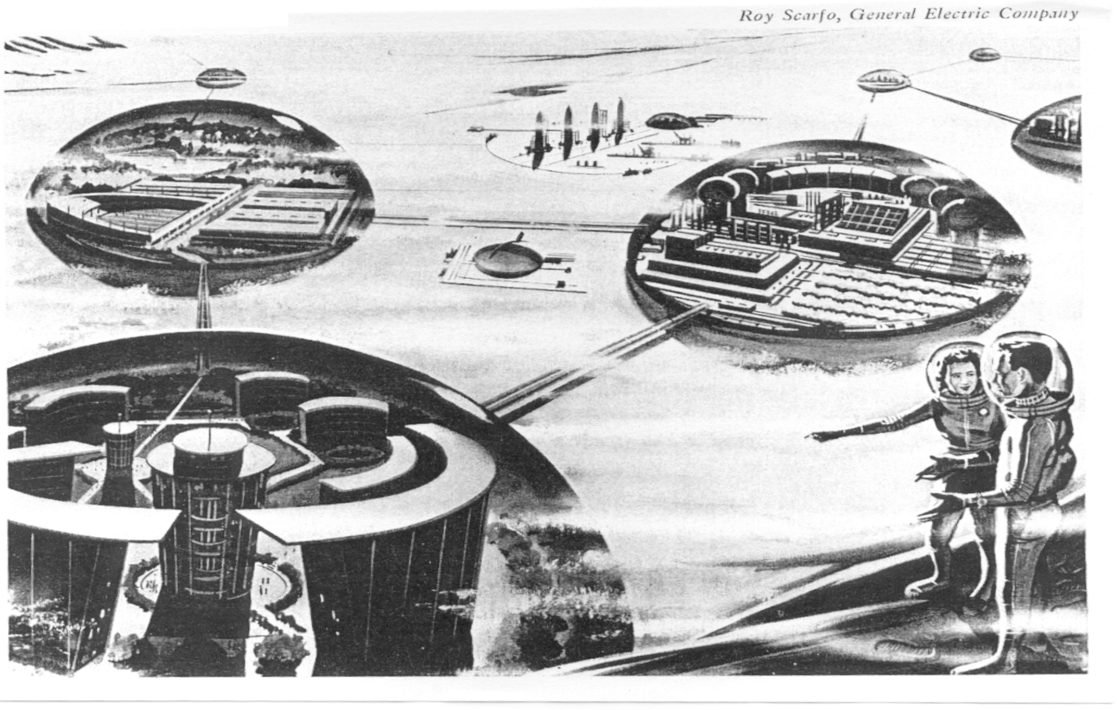
ABSTRACT

Many traditional above ground Martian colony designs have used dome structures, usually constructed from a flexible spherical membrane and inflated, to enclose the buildings of the colony. This paper will compare inflated spherical structures to inflated toroidal structures from the standpoint of internal volume, surface area, stresses, material requirements, stability, radiation shielding and safety.

I. SPACE ARCHITECTURE AS IMAGINED

In Figure 1 we see an example of how space colonies were envisioned to look. This picture, from *Islands In Space The Challenge of the Planetoids* [1] published in 1964, is indicative of the role domes have been imagined to play in sheltering humans on alien worlds.



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And members of the Independence Chapter of The Mars Society

Figure 1

Note the huge size of these domes. They must be several kilometers in diameter and several hundred meters high. Note also the separation of residential, industrial and recreational spaces. Pictures such as this have inspired a generation of hopeful space colonists. Unfortunately, they do not represent a realistic future for Mars for reasons to be discussed shortly.

II. DESIGN CRITERIA FOR A MARS HABITAT

We can divide the important considerations for a successful design into three main areas:

- Environmental
- Habitability
- Construction

	EARTH	**MARS**
Diameter	**12756 km**	**6794 km**
Surface Area (Land only)	**1.49 x 10^8 km^2**	**1.44 x 10^8 km^2**
Gravity, m/s^2 (Earth g)	**9.91 (1 g)**	**3.73 (1/3 g)**
Round-trip travel time	**–**	**12 months**
Temperatures Range C, F	**-89 to 58 C** **-128 to 136 F**	**-143 to 17 C** **-225 to 63 F**
Mean Surface Temperature C	**15 C**	**-56 C**
Pressure	**1 atm**	**0.0055 atm**
Atmosphere Composition	**78% N_2, 21% O_2**	**95% CO_2, 3% N_2**
Winds	**60 m/s**	**40 m/s (see note)**
Insolation	**1370 W/m^2**	**589 W/m^2**
Radiation GCR & SPE/yr	**2.5 m Sv**	**127 to 218 m Sv**
Seismic Activity	**Yes**	**?**
Communications lag (one way)	**–**	**3 – 23 minutes**
Length of Day/Sol	**24 h**	**24 h 37 m**
Time to orbit around Sun	**1 Earth year**	**1.88 Earth years**
Axial Tilt (Obliquity)	**23.45 ^{o}**	**25.19 ^{o}**

Note: The lower density of the Martian atmosphere (1% of Earth's) means that the wind loading on Mars for a given wind velocity corresponds to an Earth wind velocity roughly 10 times smaller and a wind loading 100 times smaller.Figure 2

Environmental Considerations

Let us consider the effect these various environmental factors have when designing a surface habitat. Figure 2 gives some comparisons between the environment of Mars and Earth. In Figure 3 the pictures of the Earth, Moon, and Mars give their relative diameters.

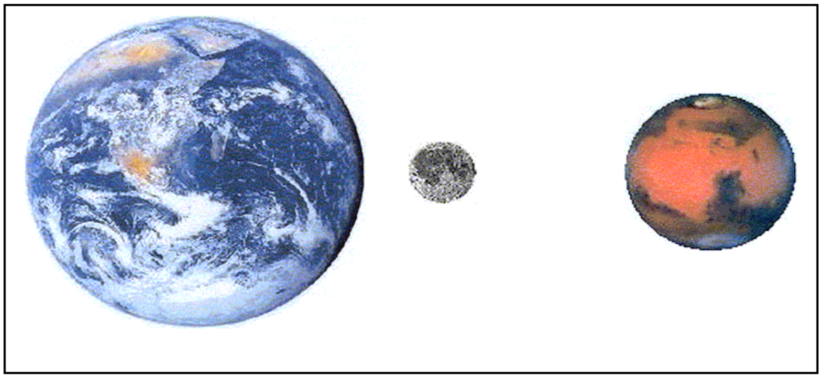


Figure 3
The relative diameters of the Earth, Moon, and Mars

The lower gravity of Mars must be considered to be an overall benefit allowing for easier transport of building materials, and erection of structures, with a lessening of the innate dead loads.

The low Martian atmospheric pressure dictates that for all inhabited structures the internal pressure loads exceed the static or live loads and therefore dictate the overall engineering of the structure. This inevitably leads to designs that serve well as pressure vessels, e.g. spheres, and spherically end capped cylinders.

The intense radiation environment of Mars rules out many materials that deteriorate in a harsh ultraviolet, Galactic Cosmic Ray (GCR) and Solar Proton Event (SPE) radiation environment. It also means that a sufficient thickness of the chosen materials be used to shield the inhabited space from dangerous levels of radiation. For inflated structures the application of shield material to the outside of the structure has the benefit of countering the internal pressure. Townsend and Wilson [2] have shown that a covering of around 20 g/cm^2 of Martian regolith provides sufficient GCR and SPE shielding.

The extreme cold of Mars dictates materials that do not become brittle at the low temperatures and remain dimensionally stable across the large range of temperature.

Mars is a world of strong winds with a light touch. Wind loading is not a design consideration; the internal/external pressure differential is by far the most important structural loading concern. Of more concern, is the abrasive nature of Martian dust and the effect this may have on rotating machinery, e.g., air lock door mechanisms.

When dealing with inflated structures, which is the focus of this paper, the planet's surface texture, is an important consideration. The Viking and Pathfinder probes have both revealed a world with a very rocky surface. To avoid puncture it appears that some site preparation, consisting of removing large sharp rocks, may be necessary before inflating any large structure on Mars.

Habitability Considerations

By habitability considerations are meant those factors that affect the psychology and physical well being of the inhabitants.

People are territorial and require a space of their own. In order to maintain social order it is essential that people be able to have dominance over some territory of their own. Factors that are important include the size of spaces; spatial variety, which is essential to our sense of freedom; views, which make spaces feel larger and provide a depth of field; natural light and fresh air, which counter depression and the illnesses associated with "sick building syndrome." Volume, and lots of it, is what is needed. Current estimates are that people need the following minimum number of square feet of space per use per person: Private space – 250, Work – 100, Recreation - 150, Assembly – 50 [3]. In addition we can expect that a Martian habitat will require additional space for food production and life support as well as common space, e.g., corridors and stairs. We must also consider that ceiling height and door heights may need to be higher in a low g environment. Inflatable habitats appear to have the edge in providing the largest, undivided interior volumes per unit mass of structure (excluding shielding).

The interior environment of the habitat can be severely degraded by a bad choice of materials. Out gassing of dangerous or noxious chemicals, or the production of secondary radiation are two critical factors when choosing materials.

Construction Considerations

The final consideration is construction requirements. Here I list a few construction constraints, some originally identified for the Moon, but of relevance to Mars as well [4]. These apply either to a structure imported from Earth or developed locally:

- Minimize need for heavy equipment (probably not available, and excavation and grading are difficult because of lack of traction)
- Minimize need for power
- Avoid hydraulic systems because out gassing can contaminate surroundings and because the near vacuum is hard on seals
- Design with as few field joints as possible
- Each component must be designed to be handled by one or at most two astronauts
- Components must be compatible with astronaut's gloved hands
- EVA time is limited
- Easy to integrate life support, power and lighting systems, and other architectural elements such as, floors, walls, airlocks, windows, etc.

In addition inflatable structures have certain material requirements:

- High strength - need to be able to withstand a pressure differential of probably a maximum of 15 psi
- Durable
- Easily folded
- Low Cost
- Low Mass
- Do not change properties or age excessively in the Martian atmosphere
- Withstand radiation without causing secondary radiation
- No off-gassing to interior
- Withstand Micrometeoroids (rip stop, easy to patch)

III. REVIEW OF SPACE INFLATABLES

Uses

Until the advent of the TransHab project inflatable habitats had not gone much beyond the paper design stage, however, inflatables have a long history in space dating back to some of the earliest space projects. Some of the uses of inflatables include:

Atmospheric studies - Upper Atmosphere Density Obtained from Falling Sphere Drag Measurements - Dec 1962

Antennas - Echo I - 1960, Echo II – 1964; Project Big Shot (the first phase in the NASA program leading to a global communication system using rigidized inflatable spheres equidistant and in orbit around the Earth) – 1961; Design and Investigation of Low Frequency Space Antennas - Jan 1964; Inflatable Antenna Experiment on STS-77 - 1996

Solar Collectors - Deployment and Rigidization Test of a Large Inflatable Solar Collector - 1967

Propellant Bladders - RCA MPU Bladder Development program Apr-Jul 1963

Trusses/Tunnels/Hangers/Solar arrays, etc. - Vacuum Deployment Tests on an Expandable Crew Transfer Tunnel - 1966; Inflatable Torus Solar Array Technology (ITSAT) Program - 1991

Decelerators - Investigation of an Attached Inflatable Decelerator System For Drag Augmentation of the Voyager Entry Capsule at Supersonic Speeds – 1968; Deployment and Performance Characteristics of Attached Inflatable Decelerators With Mechanically Deployed Inlets at Mach Numbers from 2.6 to 4.5. – 1972; Pathfinder 1997

Habitats - TransHab module for attachment to the International Space Station

Decoy – Inflatable decoys have been used in ICBM tests. Details on these projects remain mostly classified. One of the major manufacturers of space inflatables is L'Garde Inc. of Tustin, CA, which has been making decoys since 1971.

Technology

The materials used in inflatable technology depend a lot upon the end use of the structure. Early on, aluminized polyester, e.g., Mylar, was used for the Echo communications satellites. Later on, resins that harden in the space environment, such as developed for a project to create an inflatable self-rigidizing space shelter and solar collector from honeycomb sandwich in 1963-1964, were created. Inflation for these types of structures was only required to achieve the final shape, after which the material would harden to maintain the shape even if the initial, low pressure, inflation gas escaped. This includes technologies such as plasticizers that boil off, and reactions that result in the final cross-linking in a matrix resin of a fiber reinforced composite.

For habitats such as TransHab, laminated materials are being considered. The primary concerns being resistance to micrometeorite penetration, and retention of the internal pressure.

There was even a metal bellows concept developed by Tracor, Inc in 1992 [5] that combined traditional aerospace design with inflatable concepts. The pneumatically erected habitat was constructed like a bellows with the skin made of very flexible and thin (.0007") titanium foil attached to rigid stringers.

Other technological advances include dual wall construction [6]. A dual wall structure achieves its final shape by inflating the space between to membranes or walls, rather than the interior space. The two major designs are pile fabric, called "Airmat" by Goodyear and "Rigidair" by Air Inflatable Products Corporation and "Wing tab" or I-Beam rib. In pile fabric many threads, in basically a drop stitch method, connect the membranes where the thread lengths are controlled to maintain a predetermined distance between the membranes. Wing tab fabric incorporates attachment flanges for the web as integrally woven portions of the membrane material. Wing tab fabric looks like a large air mattress with I-Beam webs holding the two membranes parallel. The stresses are evenly distributed and wing tab construction allows shaping of the structure into compound curves.

Inflatable Habitats - Advantages

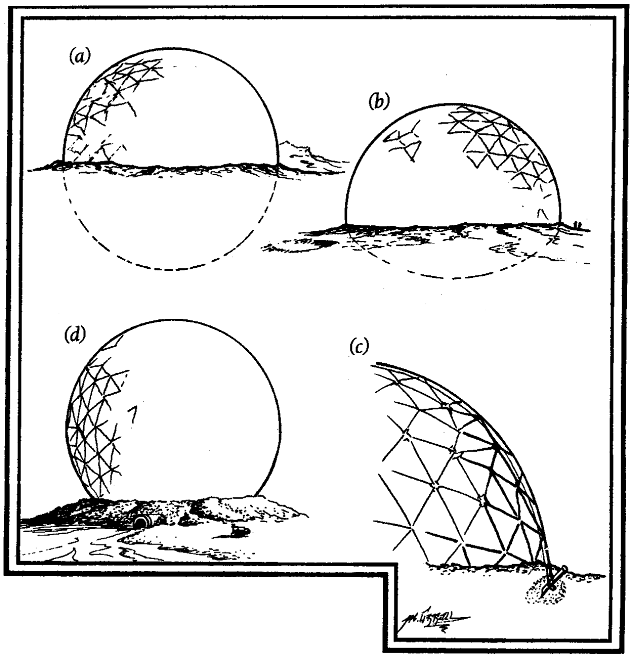
- More volume per pound: 30 – 50% lighter than Hard Aluminum structures
- Greater flexibility of interior arrangement
- Large, continuous volume
- Automated deployment/ Simple assembly
- Lower cost?
- Structural dead loads and occupancy live loads are negligible
- May better handle thermal stresses caused by temperature changes

Inflatable Habitats - Disadvantages

- Credibility: Unproven technology
- Cost: Requires longer lead time to develop, little manufacturing infrastructure exists
- Complexity: Need to resolve issues of durability, manufacture, deployment, maintainability and repair

IV. SPHERE/DOME DESIGNS

Case For Mars Designs



(a) Dome from half buried sphere.
(b) Dome with lower half with twice the radius of curvature as the upper half.
(c) Anchored tent dome.
(d) Sphere held in place by berm with interior suspended decking.

Figure 4

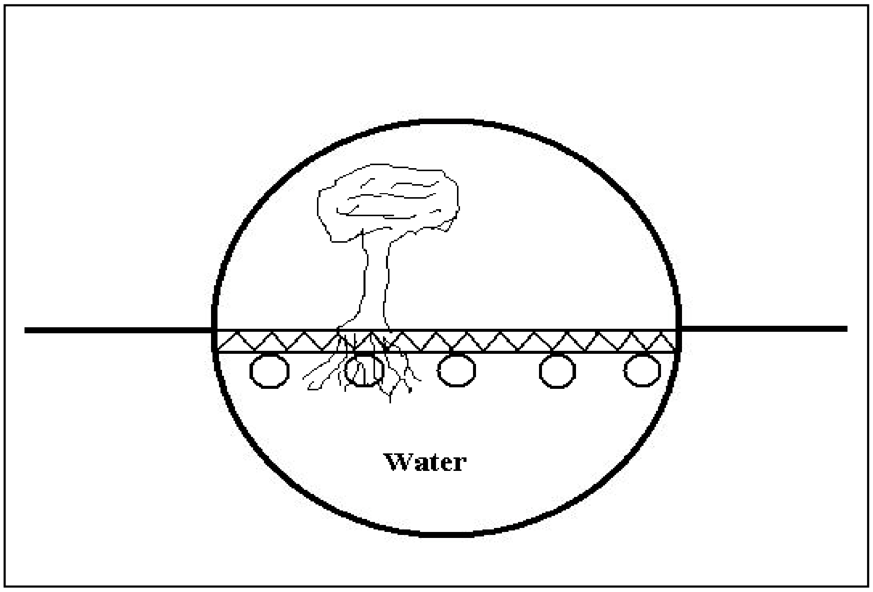
Figure 4, from *The Case For Mars* [7], illustrate the fundamental problem with a dome. The pressure in a dome acts as a force trying to tear the dome from the Martian surface. The forces acting on the circumference of a 50-meter diameter dome pressurized to 5 psi is 44 tonnes per meter! Dr. Zubrin has proposed several ways to address this. One is to create a domed space by filling a sphere half full of dirt in order to provide the inflated sphere with stability and a flat floor. Alternatively, to avoid such massive excavation (with the corresponding problem of transporting a massive quantity of regolith into the sphere) the sphere can be held stable by a berm, or the radius of curvature of the lower half may be twice that of the upper half. If a dome is to be used, then a significant amount of excavation is required in order to bury a skirt deep enough to counteract the lifting force. To provide radiation protection all these designs include an additional external unpressurized Plexiglas shield. Dr. Zubrin proposed two basic sizes: 50 and 100 meters in diameter.

AUTHOR'S PROPOSED SPHERE/DOME DESIGNS

Here are three design concepts by the author for an inflated spherical habitat.

The Chinapas Sphere

The first is based upon the idea of Chinapas, the floating gardens built by the Aztecs. In this design the flat floor of the dome is created as a floating floor, the regolith that would have had to be imported into the sphere being replaced by water, which could be inserted by a through-wall fitting and a hose. As in the Aztec Chinapas, plants are allowed to grow roots through the floating floor into the water below. Figure 5 is a sketch of such a sphere.



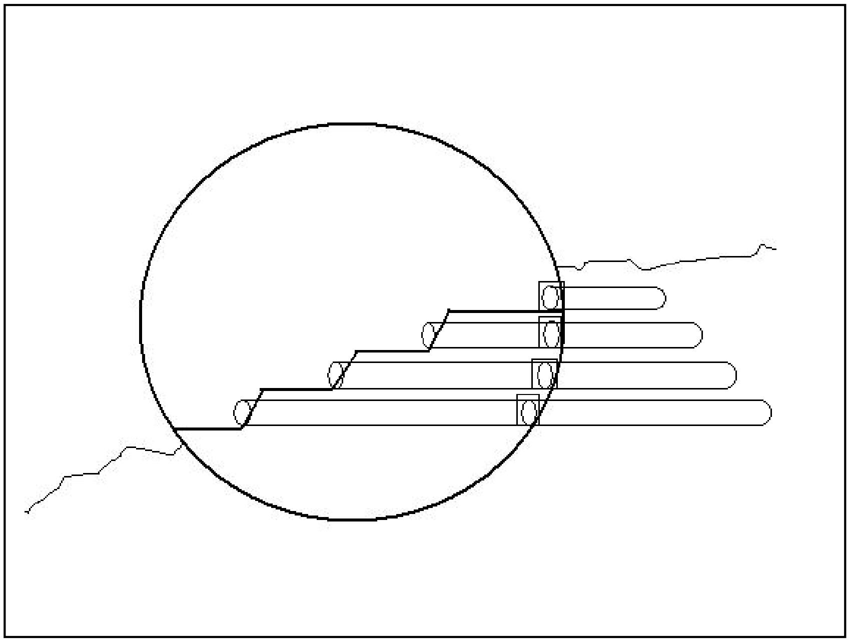
The floating floor is supported by pressurized gas tanks containing supplemental air in case of a loss of pressure. The floor is made like a woven mat, perhaps of bamboo, covered with regolith treated to act like soil. Plants can grow their roots through the floating floor to reach the nutrient rich water below. Occasionally mud must be pumped up from the bottom of the sphere to be spread on the floating floor.

Figure 5

This design is probably limited to greenhouse spheres because of the high humidity. Some form of flexible skirt must be attached at the interface of the floor and the sphere dome to minimize evaporation around the edge of the floor and to prevent the floor from tipping if excess weight is placed near the periphery. For residence-type spheres the membrane of the lower half of the sphere may be designed to be thermally conductive while the upper half is thermally insulating. Under these circumstances the water will freeze and the installed, nonfloating, floor should also be highly insulating so that the water below does not melt. Given a ready supply of water, filling a sphere by pumping in water is much simpler than importing regolith. Lacking water, liquid CO2 could be pumped in and allowed to freeze into dry ice.

Cliffside Sphere

This next design, figure 6, simplifies the excavation required for the sphere. A site is located on a crater or cliff wall where explosive charges are placed into holes drilled in a semicircular pattern. When exploded the charges cause a semicircular depression along the crater wall or cliff to be created; the material being removed is blasted into the crater or onto the land below the cliff. Some minor shaping of the depression created will need to be done before the sphere is inflated into it. Rather than a flat floor, a terraced interior is created by tunneling into the regolith at the back of the sphere at multiple levels. As the mine tailings are dumped into the sphere and bulldozed into a terrace level, additional inhabitable space is being created in the tunnels. By locating the sphere in this manner significant radiation shielding is provided by the adjacent regolith.



After inflation, crews use pressure doors incorporated into the membrane to begin excavating tunnels into the cliff face. Beginning with the lowest level regolith is excavated and the tailings dumped into the sphere to create the first terrace. Higher terraces result in shorter tunnels since less material is required. The tunnels provide additional inhabitable space and a refuge in case of loss of sphere membrane integrity.

Figure 6

Hydrosphere

This next design, figure 7, is a variation on the Chinapas design. It utilizes the pressure differential between the exterior and interior of the dome to fill the space between the two walls of the sphere full of water. The principle being applied is that of the U-tube barometer. The interior air pressure forces the water below the floating floor through a hole in the bottom of the inner wall up into the space between the two walls. The interior air pressure also supports the weight of the water in the wall above the floor. The space between the two walls is chosen to provide the optimal radiation shielding while transmitting sunlight. A rigid wall, rather than a flexible wall may be preferable for this design. A simpler structure might consist of a dual wall rigid cylinder with a flat roof covered with regolith.

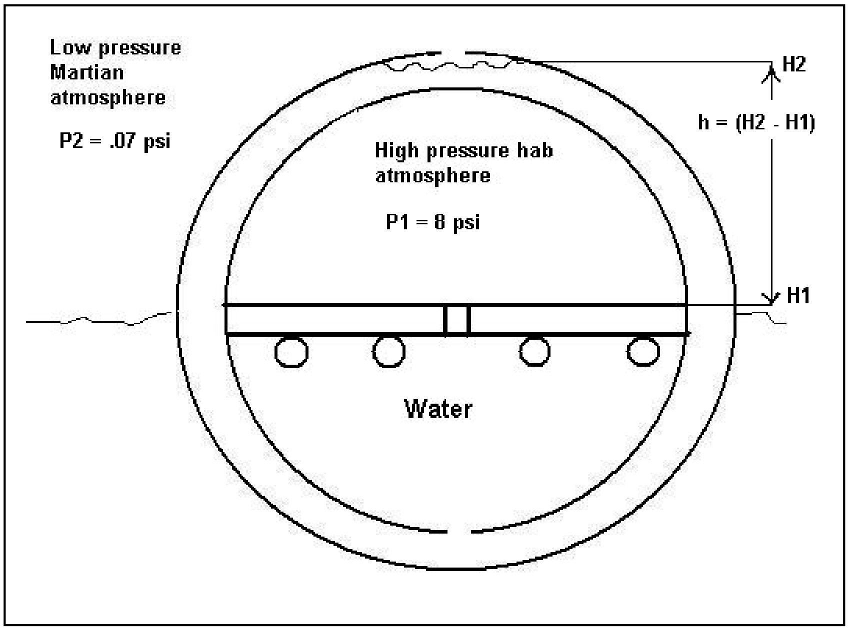


Figure 7

The pressure of the hab atmosphere pushes out in all directions including pushing on the floating floor and the water beneath it. This forces water through the hole at the bottom center of the inner membrane and into the space between the two membranes. The outer membrane has a hole at the top that puts the water into communion with the exterior, low, pressure Martian atmosphere. In order to achieve hydrostatic equilibrium the water column will rise above the floor of the sphere providing a water radiation shield.

The height, h, that water will be raised by the pressure differential can be calculated as:

$h = (H2 - H1) = (P1 - P2)/(rho*g) = p/(rho*g)$

Where: h = the height difference $H2 - H1$
P = the pressure difference $P1 - P2$
rho = the density of water = 1000 kg/m^3 (at 0 degrees Celsius)
g = the acceleration of gravity on Mars = 3.711 m/s^2

If the internal pressure is P1 = 8 psi = 55 kPa and the external pressure is P2 = .07 psi = 0.49 kPa the resulting height h is 14.7 meters!

OTHER DESIGNS

Cylindrical Fabric-Confined Soil Structures

Richard Harrison, of TRW, Inc. has proposed [8] creating fabric tubes that are filled with dirt in order to create arches, which help counteract the internal pressure, hold the inflated structure in place and provide some radiation shielding. A number of such arches can be used to confine, and in cases of loss of internal pressure, support an inflated sphere.

Note: The reader is directed to the source paper for illustrations of this concept.

Hexmars-II

Prairie View Agricultural and Mechanical College's Hexmars-II concept [9] consists of six inflated spheres partially buried. Shape charges are used to do the initial excavation. An interior telescoping core post is put in place followed by inflation of a Kevlar membrane. The crater is backfilled with regolith, the exposed upper portion of the sphere covered with rigidized foam and then covered with sandbags. This concept includes an ingenious non-penetrating connector for connecting cables to anywhere on the inside of the dome. Three floors are attached to the central core post.

Note: The reader is directed to the source paper for illustrations of this concept.

Inflatable Lunar Habitat

The inflatable lunar habitat design [10] from a joint NASA Texas A&M university study of 1989 came in two designs, both incorporate a 16-meter diameter inflated sphere, one third below grade and the upper two thirds covered with a layer of regolith for radiation and meteoroid shielding and thermal insulation. One design provided an exterior aluminum frame to support the regolith shield in case of loss of internal pressure, the other design assumes the regolith shield is self-supporting. The interior was designed to have 5 floors and accommodate a crew of 12. This study primarily looked at the mass requirements of the aluminum structural elements. A rough calculation of the effect of Mars gravity on the design was done.

Note: The reader is directed to the source paper for illustrations of this concept.

LUNAB

The LUNAB design [11] developed at the Italian Affiliate Campus for Space Architecture of the International Space University in association with the Shimizu Corp. of Tokyo and Binistar Inc, of San Francisco began with the same design requirements of the Texas A&M 1989 study but addresses the excavation question in a unique way. In this design of a self-constructing space system the 16-meter diameter sphere has a central core post containing an Archimedean screw. By some undefined method the screw is rotated and penetrates the regolith transporting material up the central core and then expelling it through a cupola at the top over the inflated sphere providing a radiation shielding coating. Some additional excavation would probably be required, but the Archimedean screw would anchor the structure and automate the covering with regolith. Five levels of floors are ingeniously folded up against the central post from which they deploy.

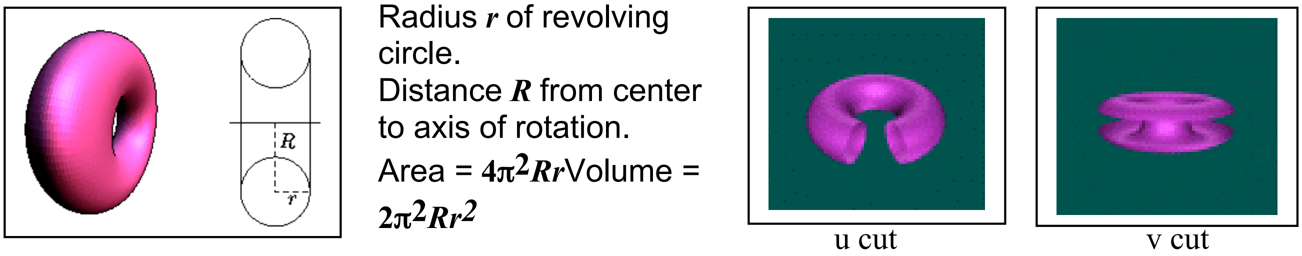
Note: The reader is directed to the source paper for illustrations of this concept.

V. THE TORUS

A torus, figure 8, is a geometrical shape familiar in everyday life as the shape of a doughnut or bagel. In fact, it was while sitting by a swimming pool and observing a beach ball and an inner tube floating by that the thought first came to the author that the inner tube (toroidal) shape might be preferable to the beach ball (spherical) shape for an inflated habitat. Geometrically the standard torus is parameterized as a surface of revolution: a circle is revolved around an axis.

The general equations for such a torus are:

$$f(u,v) = [(a+b*\cos(v)) * \cos(u) , (a+b*\cos(v))*\sin(u) , c*\sin(v)]$$



Radius r of revolving circle.
Distance R from center to axis of rotation.
Area = $4\pi^2 Rr$Volume = $2\pi^2 Rr^2$

u cut

v cut

Figure 8

The stresses (σ), Figure 9, on a torus can be calculated using the following formula [12]:

Circumferentially around the torus the stress is the same as in the surface of a sphere:

$\sigma = Pr/2$ where P is the internal pressure

For the stress around the membrane from the outside to the inner hole the stress is calculated as:

$$\sigma_\theta = (Pr/2)((2+r \sin \theta/R)/(1+ r \sin \theta/R))$$

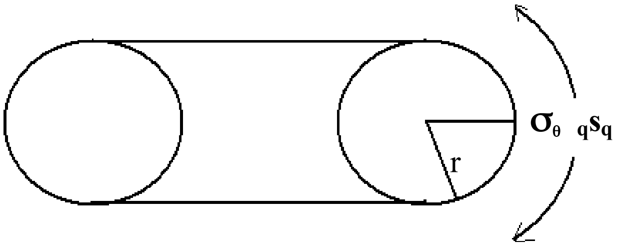


Figure 9

VI. TORUS DESIGNS

The torus shape was adopted for the 1975 Stanford University space colony design for a large space habitat for up to 10,000 people. The 1975 Summer Faculty Fellowship Program in Engineering Systems Design sponsored by NASA and the American Society for Engineering Education (ASEE), convened at Stanford University and the NASA Ames Research Center. Nineteen professors of engineering, physical science, social science, and architecture, three volunteers from academe, industry, and government, six students, a technical director, and two co-directors worked for ten weeks to design a system for the colonization of space. The technical director was Gerard K. O'Neill. Their final report appeared in 1977 as NASA Special Publication SP-413 [13]. Their prototype colony is known as "the Stanford Torus". The Stanford torus was designed as a rigid, not and inflatable, structure, however, the final report of this project represents the best, most detailed discussion of the issues facing a large space habitat with particular reference to a toroidal-shaped structure.

The torus, as a shape for an inflated habitat, appears to have been originated by Peter Kokh [14] and, independently, by Lawrence Livermore National Laboratory under a project led by Dr. Lowell Wood. ILC Dover did a follow on configuration analysis and design study for Livermore [15]. This study resulted in two toroidal designs for the development of standardized modules that could be combined to create larger stations similar to the ISS. The TransHab module, developed at the Johnson Space Center, built upon the Livermore/ILC Dover studies. TransHab was designed to provide additional livable space on the Moon, Mars, or as an attachment to the ISS.

The author's poolside epiphany resulted in roundtable design effort by members of his Mars Society Chapter that lead to the design of the Independence Torus designed to accommodate a small settlement on Mars.

The Lunar Hostel, aka Moonbagle

Peter Kokh's seminal paper discussed the concept of a lunar hostel, "an inexpensively equipped habitat with lots of elbow-room that needed only to be hooked up to the cranny-jammed expensive equipment of a docked visiting vehicle in order to function as a complete base." This concept is not limited to "hostel" use. The core could contain all the "works" needed for a full-function base.

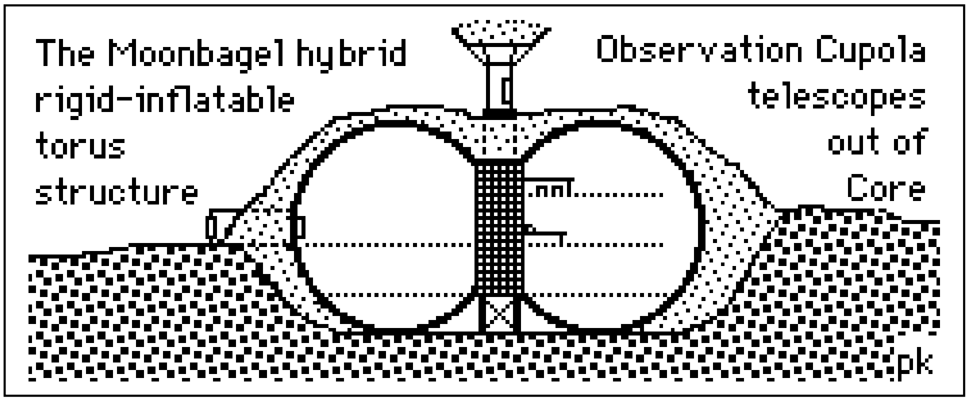


Figure 10

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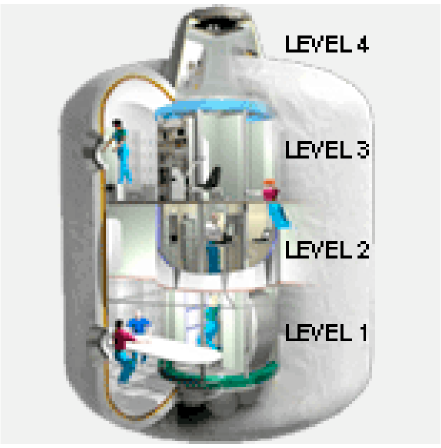
Figure 10 shows a shielded Moonbagel (the name given by David A. Dunlop) deployed in a suitably sized crater to ease placement of shielding overburden. A core module in the center contains the electronics, power, plumbing, heating/cooling, air/water recycling, communications, and galley. The hollow ribs are filled with a rigidizing foam. The torus is for sleeping, recreation, dining, exercise and other functions needing lots of space. A rigid central core extends upward through the regolith shield and provides an exit for suited EVA. A tunnel through the regolith shield provides a place for vehicles to dock.

TransHab

The concept for TransHab, figure 11, originated at NASA's Lyndon B. Johnson Space Center in 1997 as a possible design for an inflatable living quarters on future Mars-bound spacecraft.

The structure is, like the Moonbagel, a hybrid having a rigid core with an inflated toroidal outer component. TransHab's foot-thick inflatable shell has almost two dozen layers. The layers are fashioned 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. Debris protection is achieved by successive layers of Nextel, spaced between several-inches- thick layers of open cell foam, similar to foam. The Nextel and foam layers cause a particle to shatter as it hits, losing more and more of its energy as it penetrates deeper. The outer layers protect multiple inner bladders, made of a material that holds in the module's air. The shell also provides insulation from temperatures in space that can range from plus 250 degrees Fahrenheit in the Sun to minus 200 degrees in the shade. Many layers into the shell is a layer of woven Kevlar that holds the module's shape. Three bladders of Combitherm, a material used in the food-packing industry, hold the air inside. The innermost layer, forming the inside wall of the module, is Nomex cloth, a fireproof material that also protects the bladder from scuffs and scratches.



Level 4 – Pressurized tunnel

Level 3 – Crew health care

Level 2 – Mechanical room and crew quarters

Level 1 – Wardroom and galley

Weight at launch:	13.2 metric tons (29,000 lbs.)
Length at launch:	11 meters (36 feet)
Diameter at launch:	4.3 meters (14 feet)
Diameter after inflation:	8.2 meters (27 feet)
Inflated volume:	339.8 cubic meters (12,000 cu. ft.)

Figure 11
Courtesy of NASA

Independence Torus

The Independence Torus, figure 12, is the result of a design project of the Independence Chapter (Philadelphia, PA) of the Mars Society. The design assumes an R of 15 meters and an r of 10 meters for an overall diameter of 50 meters. The structure is segmented into quadrants, each of which may be isolated by interior pressure doors from the adjacent quadrants. The whole structure is protected from UV and other radiation by a Plexiglas shield supported on guy wires descending at an angle from a central mast. The Plexiglas panels can be hoisted, like sails, to the top of the tower by pulling on lines for that purpose. In the illustration two rovers are cooperating in "hoisting the shields." The shield also provides minimal micrometeorite protection as well as protection from dust. A more temperate microclimate should develop under this tent. The mast can be used as a radio tower, weather station, or even, as shown, a mooring mast for a lighter-than-air craft. While not shown in the illustration, a layer of regolith could be applied over the structure.

One quadrant, the one that would receive the most sunlight, is designed with transparent membranes and functions as a greenhouse. The greenhouse quadrant may function like an Aztec Chinapas and have a floating floor.

The crew living quarters would be divided between two separate quadrants. One quadrant would contain apartments for half the crew along with the galley space; another quadrant would contain the apartments for the other half of the crew along with the recreational space. The final quadrant contains the mechanical systems, the main air lock, working space, and storage.

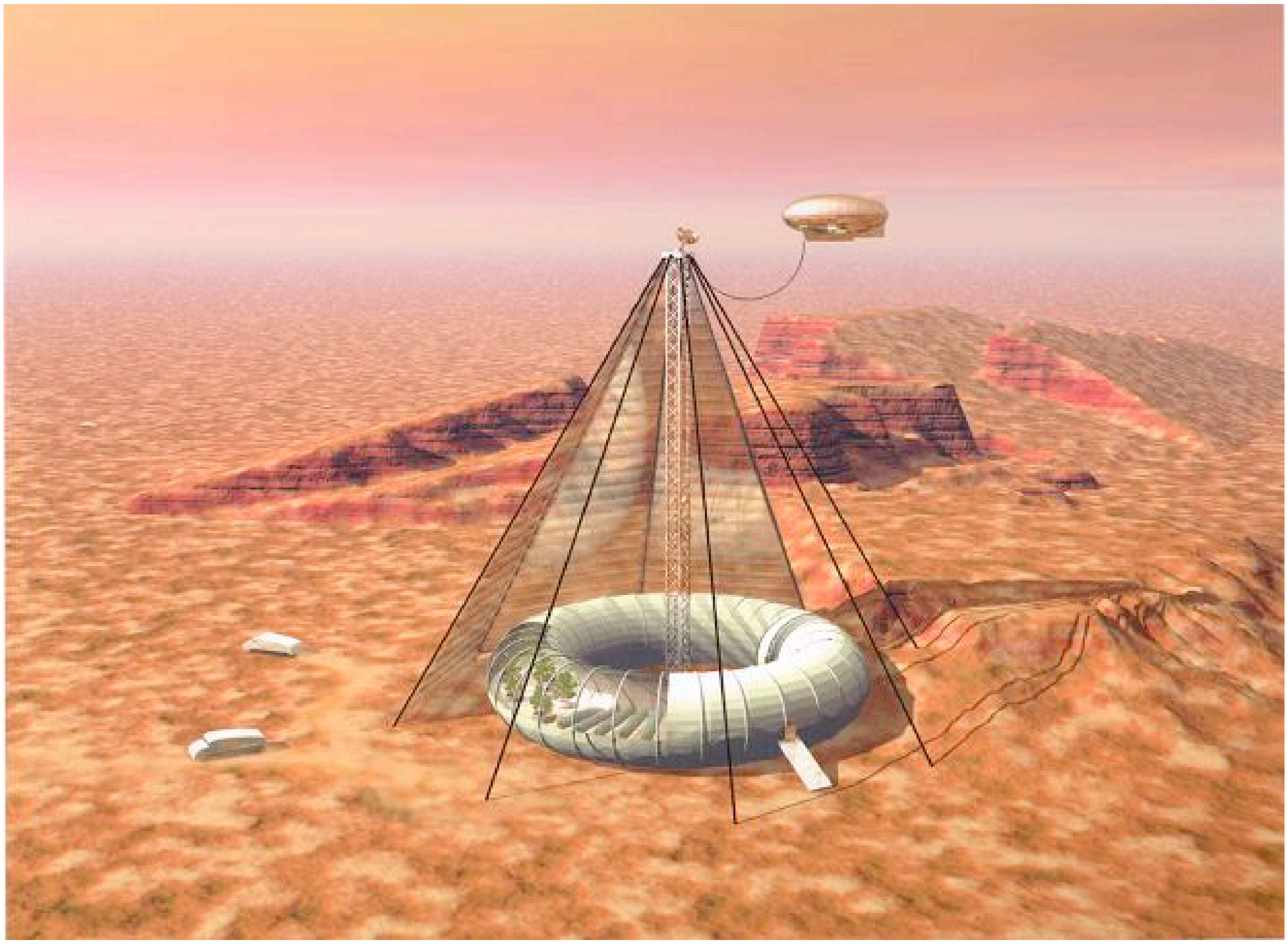


Figure 12
The Independence Torus – Rendering by Tim Bauer

VII. ADVANTAGES OF THE TORUS

The torus has a number of advantages over a sphere.

- A torus has a stable footprint (will not roll away)
- More easily segmented for safety
- Provides a natural shape for circulating the interior air
- Not as tall for its volume allowing for easier covering with regolith for radiation or other shielding
- More floor area with the maximum headroom
- Less inflation gas required for comparable floor area
- Less regolith must be imported into the structure to create the level floor

While for a given diameter a sphere has a greater volume, much of this volume is not usable unless additional floors are created.

As table 1 shows, the amount of floor area can be similar for sphere and torus of the same diameter; however, a torus may have significantly less surface area. While this reduced surface area, nearly a third in the case of the 100 meter diameter comparison in the table, translates into reduced mass, it does come at the expense of less interior volume. However, the lost volume is not usable in a large diameter sphere unless a structure is built in the sphere to create additional floors. This flooring will also add mass that will need to be imported from earth and that will require additional construction time. The breathable gas mixture that must be created to inflate a sphere is correspondingly much greater because of this additional volume.

SPHERE OR TORUS	R	r	Total Diameter	Surface Area	Volume	Floor Area	Max Ceiling Height
Sphere	25		50	7854	65450	1963	25
Torus	15	10	50	5922	29609	1884	10
Sphere	50		100	31416	523598	7854	50
Torus	35	15	100	20726	155446	6597	15
Sphere			$2*P$	$4\pi P^2$	$4/3\pi P^3$	πP^2	
Torus			$2*(P+\rho)$	$4\pi^2 P\rho$	$2\pi^2 P\rho^2$	$\pi(P+\rho)^2-\pi(P-\rho)^2$	

Table 1

Note: Floor Area is the surface area created by filling the torus or sphere half full of regolith. The sizes were chosen to correspond to the sphere sizes discussed in Zubrin's *The Case For Mars*.

VIII. CONCLUSION

While not yet as developed as the sphere (dome) from a conceptual standpoint, the torus, particularly an inflated torus with a solid core, appears to have been accepted as the preferred configuration for at least small habitats. A torus has significant advantages over a sphere, most importantly, for structures transported from Earth in the mass to floor area ratio. Significant savings are also to be had in construction time and difficulty, due to the innate stability of the torus and the significantly less inflation gas that must be used to inflate, and the regolith that must be imported into, a torus versus a sphere of similar floor area. Safety is enhanced by the relative simplicity of segmenting a torus into separate pressure compartments.

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