INFLATABLE HABITATION FOR THE LUNAR BASE

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Inflatable structures have a number of advantages over rigid modules in providing habitation at a lunar base. Some of these advantages are packaging efficiency, convenience of expansion, flexibility, and psychological benefit to the inhabitants. The relatively small, rigid cylinders fitted to the payload compartment of a launch vehicle are not as efficient volumetrically as a collapsible structure that fits into the same space when packaged, but when deployed is much larger. Pressurized volume is a valuable resource. By providing that resource efficiently, in large units, labor intensive external expansion (such as adding additional modules to the existing base) can be minimized. The expansive interior in an inflatable would facilitate rearrangement of the interior to suit the evolving needs of the base. This large, continuous volume would also relieve claustrophobia, enhancing habitability and improving morale. The purpose of this paper is to explore some of the aspects of inflatable habitat design, including structural, architectural, and environmental considerations. As a specific case, the conceptual design of an inflatable lunar habitat, developed for the Lunar Base Systems Study at the Johnson Space Center, will be described.

INTRODUCTION

As NASA plans future missions involving long-term human presence on the Moon, we must strive to provide a safe, productive working environment, while at the same time minimizing the cost of transporting the lunar base elements. Inflatable structures, also known as expandable or pneumatic structures, have great potential for achieving both of these goals.

An inflatable is a flexible pressure vessel that may be folded compactly for transport and then deployed to its full size on delivery. It offers the twin advantages of a large operational volume and a small transportation volume.

HISTORY

The use of inflatable structures in space goes back to the beginning of the space program itself. In the early sixties, the Echo satellite program sent enormous mylar balloons into orbit for communications experiments. Packaged, the Echos fit into a 1-m-diameter sphere, but when deployed they were 30 m in diameter and were easily visible in the night sky.

During the Apollo program, work was done on a number of inflatable manned space systems by the Goodyear Aerospace Corporation through NASA's Langley Research Center. The studies included materials testing and selection and the construction of inflatable prototypes. The configurations studied included a collapsible lunar shelter to be carried on the Apollo LEM to extend mission durations; a space station module, of which a full-scale prototype was built and pressurized to 5 psig; and a collapsible airlock (*Tynan et al.,* 1971). Though all these projects showed promise, insufficient funding was available to pursue the concepts beyond the prototype stage.

Meanwhile, fabric structures were finding new applications on Earth as well. In 1962, a West German architect, Frei Otto, published *Tensile Structures,* a landmark text describing the attributes and design considerations of pneumatic and air-supported structures (*Otto,* 1962). Interest in these structures grew due to their light weight and low cost, and the availability of increasingly stronger, more durable materials. Very large spaces could now be spanned at a fraction of the cost of rigid structure. The World Exposition of 1970, in Osaka, Japan, marked a watershed in the history of tensile structures. Many of the pavilions were pneumatic or air supported. The U.S. pavilion was covered with an enormous fabric roof made from a material derived from the Apollo spacesuits. This pavilion was the model for many domed stadiums and arenas erected throughout the country during the seventies and eighties.

Inflatable habitation for use in space merges the civil technology of large tensile structures with the aerospace technology of pressurized vessels. There is a sound experience base from which to launch an aggressive inflatable structures program.

ADVANTAGES

Transportation

Space habitation design is severely constrained by the dimensions of the launch vehicle payload bay. The high cost of space transportation drives the subsystem designer to utilize every cubic centimeter available. The result of this process is often a highly efficient, extraordinarily expensive, unique piece of hardware. If this volume constraint could be relaxed, allowing greater use of off-the-shelf technology, the result might very well be cheaper manned space systems.

Cost savings could be realized in launch operations as well by allowing a more flexible manifest with fewer vehicle-dependent payloads. The largest single element of a space station or lunar base is the habitation. If this element could be separated into its basic components, the options for launching it would expand considerably. It might be launched on a large vehicle, if one were available, or on a series of smaller vehicles. This flexibility in launch operations can be attained by launching the pressure vessel separately from the habitat components, and integrating them in place. This approach requires that the pressure vessel be collapsible, so that it may be packaged efficiently (a rigid vessel occupies the same space whether it is empty or full). A fabric structure is the simplest way to make a collapsible pressure vessel.

Some advantage may be claimed for the rigid module because it carries its air with it. The air required to pressurize the inflatable habitat must be supplied separately, requiring space on a launch vehicle. However, transport of air will be part of the routine logistics system for a lunar base. It will be supplied to the base continuously to make up for losses (chiefly through the airlocks, which lose 10% of their air by volume each time they are used). There must also be an emergency repressurization supply on hand at all times. An efficient system for the transport of volatiles to the lunar base will be required, perhaps employing cryogenic technology to transport them as liquids. (The development of such a system is particularly likely if the transportation system uses cryogenic fuels.) The advantage to the program of getting the first load of air "free" inside a habitation module will therefore be minimal.

Operations and Growth

The large space available in an inflatable would facilitate rearrangement of the interior to suit the needs of the moment and would allow space for working with bulky equipment. For example, a structure to be erected outside could be put together and tested in a shirtsleeve environment before actual deployment. In this way, latent defects in the equipment could be identified before costly EVA time was wasted.

Using the same transportation, an inflatable habitation system can provide habitable volume in larger units than can a rigid system, thereby reducing the number of EVA-intensive surface construction operations as the lunar base grows. The high-volume inflatable can be "expanded" by adding more equipment and furnishings inside, as they are needed.

Habitability

The greatest advantage of large inflatable habitats may be the most difficult to quantify: habitability. Habitability is the sum total of those qualities that make an environment a pleasant place to live and a productive place to work. Studies have shown that personal space, for work and for leisure, is an important factor in the pyschological wellbeing of isolated groups (*Stuster,* 1986). The inflatable would not only provide a large volume, it would provide perceptible volume. A base built up out of rigid modules might be expanded indefinitely by adding more modules, but no single element could ever be larger than the payload bay of the launch vehicle that lifted it from earth. At no point in the lunar complex could a person perceive (or utilize) a volume larger than that of a single module. The space inside the inflatable, on the other hand, may be divided up in any way desired or left open to create large chambers.

DESIGN ISSUES FOR THE INFLATABLE LUNAR HABITAT

The design of an inflatable habitat for the Moon is influenced by a number of factors. It is influenced architecturally by the activities carried on within it, it is influenced structurally by the forces acting on it, and it is influenced by the environment in which it operates.

Architectural Design Issues

As used here, the term architectural refers to those factors that influence the volume and form of the habitat. The physical and psychological needs of humans in a confined environment must be balanced against the physical limitations of a pneumatic structure.

Volume. Habitable volume means a space to work that is pressurized, climate controlled, and protected from radiation. The amount of habitable volume needed depends on many factors: the number of crew members, what they will be doing, and how much discomfort and inconvenience they can be expected to endure. A tour at the lunar base would be the dream of a lifetime for scientists and researchers, no matter how poor the living conditions might be expected to be; but once they have been at the base for a few days, minor inconveniences may become major irritations, to the point of affecting performance. Providing flexibility in the design, so that the crew can implement their own solutions to any problems of space or interior arrangement that arise, is a primary goal in engineering the lunar habitat.

The concept of open volume is a key element in this philosophy of flexible design. There should be enough space to rearrange the interior and to expand the capabilities of the base without major exterior construction. As discussed earlier, inflatable structures are a way to provide large amounts of volume without a great impact on the transportation system.

Form. Inflatables can be made in virtually any shape, but for this study it was decided to limit consideration to those shapes not requiring reinforcing structural elements such as hoops or cables. The objective was to establish a simple baseline for comparison with more complex designs. Given this restriction, the three simplest shapes for an inflatable are the sphere, the cylinder, and the torus (Fig. 1).

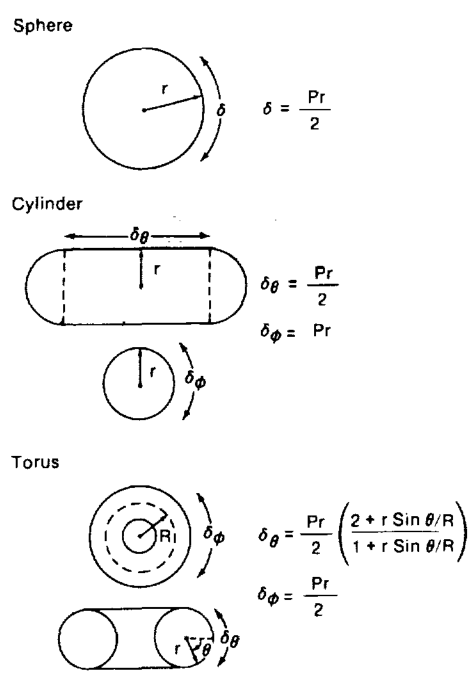

Fig. 1. Pneumatic geometries and associated stresses.

The spherical shape is the most volumetrically efficient, with the least surface area and mass for a given volume (Fig. 2). Stress is uniform throughout the membrane. The chief drawback is the architectural inefficiency of the doubly curved walls.

The cylinder is somewhat more convenient architecturally than the sphere, because the walls are curved in only one direction. With a vertical orientation, one could have vertical walls rather than the arched walls in the sphere. However, for a cylinder of similar dimensions to the sphere, mass and membrane stress are higher. (The circumferential stress in the barrel of a cylinder is twice that for a sphere of the same diameter.) To reduce this, one might make the cylinder more slender and lay it on its side, but this would largely eliminate its architectural advantage over both the spherical inflatable and the rigid space station-type module.

The torus is basically a cylinder wrapped into itself, thus saving the mass penalty of endcaps. It provides a "race-track" configuration that may have safety advantages if the inflatable is compartmentalized, but it suffers from the same compound wall curvature as the sphere. If a large minor diameter is chosen (to gain the open volume that is a presumed advantage of inflatable structures), the result is similar to a sphere with a "pucker" in the middle. From the inside, there will be a column in the middle of the structure that serves no purpose. This effect could be minimized by reducing the minor diameter and making the torus more ring-like, at the expense of open volume.

Structural Design Issues

Structural design issues arise from the nature of the structure itself, relatively independent of the environment. A pneumatic structure required to be pressurized to 101 kPa imposes certain constraints on its designers, regardless of its secondary functions or its environment. Chief among these considerations are the membrane stress, the leakage rate, and the puncture resistance.

Membrane stress. A pneumatic structure is stressed primarily by its internal pressure, overshadowing external forces such as gravity. The internal pressure creates stress in the wall of the inflatable called the membrane stress, measured in N/m. It depends on both the internal pressure and the local radius of curvature. In a sphere, the membrane stress is given by

$$\text{stress} = (\text{pressure} \times \text{radius})/2$$

There are similar equations for the stress in a cylinder or torus. The wall material must be strong enough to resist this stress, yet flexible enough to fold and package efficiently.

In general, the larger the inflatable, the larger the radius of curvature, and the higher the membrane stress. To reduce the membrane stress in a very large inflatable, structural reinforcements such as cables or hoops may be added. These take up some of the stress and reduce the local radius of curvature. As noted earlier, these elements complicate the design.

Leakage. Aside from resisting the membrane stress due to the internal pressure, the structure must also be sealed against leakage. The wall material must be impermeable to air, and care must be taken in the design of hardware interfaces (such as hatches or windows) to limit potential leak paths.

Puncture resistance. An inflatable structure is no more inherently vulnerable to puncture than a rigid pressure vessel. The difference is that an inflatable, if unsupported, will collapse of its own weight when all the air is removed. The internal framework needed to support the floors, walls, and equipment inside the habitat will also support the relatively lightweight pressure envelope. (In the Johnson Space Center concept, the structure must also support the regolith shielding in the event of a loss of pressure; in fact, this potential load condition drives the design, dwarfing the normal load imposed by the interior habitation elements.)

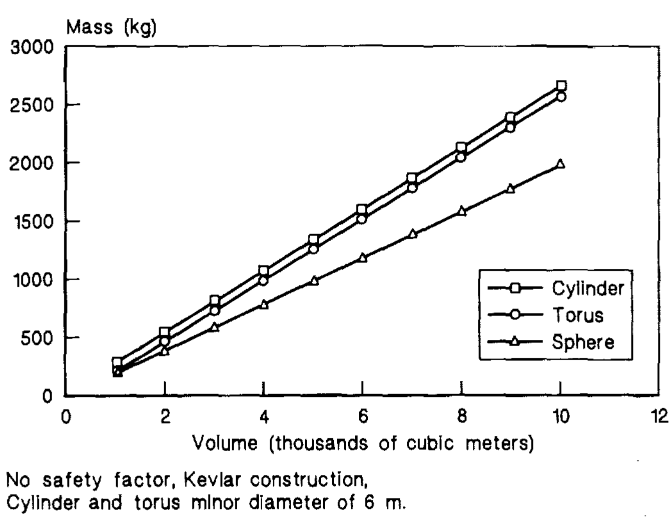

Fig. 2. Mass vs. volume for sphere, cylinder, and torus.

Environmental Design Issues

When designing a lunar habitat, the effects of the lunar environment over a long period of time must be considered. Radiation, temperature extremes, vacuum, and meteoroids all act to erode the integrity of the structure over time.

Radiation. The surface of the Moon, not protected by a thick atmosphere and strong magnetic field as is Earth, is exposed to higher levels of radiation from space. The radiation hazard comes from two sources of different character: galactic cosmic radiation ("background" radiation that permeates space at roughly constant levels) and solar energetic particle events that produce extremely high levels of radiation for short periods of time.

Many of the materials considered for use in inflatable space structures show sensitivity to radiation exposure. If a material cannot be found that has sufficient resistance to long-duration radiation exposure, then the radiation protection provided at the base should include the entire inflatable habitat. To deal with the radiation problem, it has been suggested that the habitat be covered with lunar soil or buried. This concept is as valid for inflatable structures as it is for rigid ones. The 101.4-kPa internal pressure is capable of supporting 40 m of soil on the Moon, assuming a soil density of 1.6 g per cubic centimeter. Obviously, though, some form of reinforcement should be provided in case pressure is lost and the inflatable is no longer able to support the soil load. Some precaution should also be taken against abrasion of the habitat material by the lunar soil, as vibrations from activities inside are transmitted through the envelope. A protective layer of abrasion-resistant fabric, or coating, could be employed.

Temperature and vacuum. The habitat material must be insensitive to temperature swings from 100 to 400 K (darkness to full sunlight) in vacuum. While the material will stay at room temperature and pressure during normal base operation, it may be exposed to more extreme conditions during transport and deployment, or in the event of a major malfunction in which the base is completely shut down for some period of time. In addition, the low thermal conductivity of polymers in general means that the wall material may be subjected to large thermal gradients, with room temperature (293 K) inside and 100 or 400 K outside.

Meteoroids. If the base is properly shielded from radiation, it is more than adequately shielded against micrometeoroids. Only a few centimeters of soil are required for this purpose. (Impacts large enough to penetrate several meters of soil are extremely rare.) In any case, the problem is the same for both inflatable and rigid structures.

THE INFLATABLE LUNAR HABITAT

The inflatable habitat, as currently envisioned, consists of a spherical pneumatic envelope with an interior structural cage to support the floors, walls, and equipment, and to hold up the envelope if pressure is lost (Fig. 3).

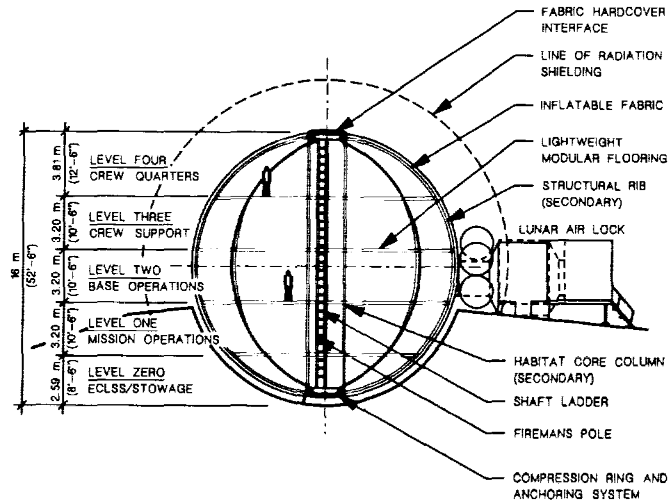

Fig. 3. Cross section of the inflatable lunar habitat.

The sphere, when inflated, will be 16 m in diameter, containing 2145 cu m of open volume. The internal pressure is assumed to be 101.4 kPa (standard sea-level atmospheric pressure on Earth). This pressure was chosen, not because it was deemed best for the lunar base (there may be advantages to operating at a lower pressure), but because it represented a maximum. The spherical shape was chosen for its simplicity and efficiency and will be compared with other shapes in trade studies to come. The contained volume was arrived at by taking the total volume of the space station, dividing by the crew of 8, then multiplying this volume/crew member by the 12 crew members anticipated for the lunar base. There are four floors in the current design, with a total of 594 sq m of floor space. (The bottom floor will be curved like a bowl and is expected to be used as a maintenance bay or storage space.) An open shaft 2 m in diameter runs from the top to the bottom for transfer of personnel and equipment from floor to floor.

The inflatable envelope will consist of a high-strength multi-ply fabric, with an impermeable inner layer and a thermal coating on the outside. The analysis done so far has concentrated on sizing the structural layer alone, assuming it to be the primary contributor to the mass per unit area of the wall material. The material selected for use in making mass projections for the envelope is Kevlar-29, a high-strength aramid fiber made by the DuPont Chemical Company. DuPont literature indicates that a broadweave fabric of Kevlar-29, with a thickness of 0.114 mm, has a breaking strength of 525 N/cm (*Dupont Co.,* 1976). Based on this material, the envelope is anticipated to mass 2200 kg, with a structural safety factor of 5. (Keeping all other parameters the same, the mass is directly proportional to the safety factor.) The thickness of the structural layer is estimated at 5 mm, giving a material volume of 4 cu m. Assuming a 10:1 ratio of packaged volume to material volume (meaning that for every cubic centimeter of material there are 9 cu cm of empty space in the package), the packaged volume of the inflatable will be 40 cu m.

In the JSC concept, the habitat is covered with 3 m of lunar regolith in the form of "sandbags" (Fig. 4). This is sufficient to attenuate even the largest recorded flare to safe levels. The regolith imposes a maximum load of 7.8 kPa on the surface of

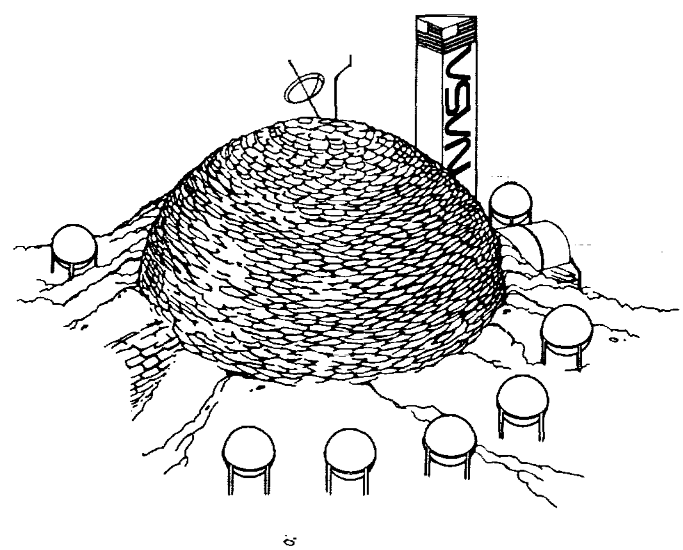

Fig. 4. The inflatable habitat "sandbagged" for radiation protection.

the habitat, easily supported by the internal pressure of 101 kPa. However, placing the regolith is very labor intensive, taking up much of the crew's time during the early missions. An alternative might be to provide a few inches of shielding to protect the habitat from galactic cosmic radiation, with a separate, smaller, "storm shelter" to protect the crew in the event of a serious solar flare. In this case, it was felt that the operational simplicity of a completely shielded base, where no special operations would be required in the event of a flare, would justify the difficult construction task. Also, the long-term effects of exposure to cosmic rays are not well understood, and it is better to err on the side of caution in safety issues.

The interior structure of the habitat will consist of curved beams running along the inside of the envelope, like lines of latitude and longitude on a globe. A combination of radial and concentric beams will support the flooring. This interior framework will support all the equipment and furnishings of the base. It will also support the regolith shielding in the event of a loss of pressure, and this load actually sizes the structure. (The interior equipment and furnishings are expected to weigh about 60 kN; the regolith weighs 1500 kN.) A rough estimate of the mass of this framework puts it at 16,300 kg, including primary structure (9000 kg), flooring (6000 kg), and walls (1300 kg).

There is a spectrum of assembly options for the internal structure, ranging from hand assembly at one end to fully automatic deployment at the other. A detailed design effort must be initiated to determine where in this spectrum the optimized configuration falls.

CONCLUSION

Inflatable habitation holds great promise for human presence on the Moon and in space. By making it possible to use smaller launch vehicles to lift lunar base infrastructure (the largest single element of which is currently projected to be the habitation), inflatables will allow greater flexibility in launch operations, while improving habitability.

The feasibility of large inflatable structures for space habitation has been demonstrated, but much work must be done to bring the concept to fruition. Materials have been developed that are strong enough for these applications (Kevlar, for example), but numerous other factors, such as temperature sensitivity and radiation resistance, must be examined. Fabrication techniques must also be refined. This can only be done through extensive laboratory testing and use of prototypes on Earth and in space.

In conclusion, a direct quote from the Langley engineers' 1971 paper, "Expandable Structures Technology for Manned Space Applications" (*Tynan et al.,* 1971), is appropriate:

> Tests on full-scale models of representative concepts show that they are sound structurally, have satisfactory deployment characteristics, and in most instances possess remarkable packaging ratios...
>
> With proper attention to the selection of materials, effects of the vacuum environment, electromagnetic radiation, and temperature extremes can be minimized...
>
> The most difficult problem faced by the expandable structures proponent, however, is getting the "breakthrough" acceptance of such a structure for a manned application to an operational flight program. Understandable prejudices against expandables for manned occupancy can only be overcome by actual use of the concept, at least on an experimental basis, in the space environment.

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