N90-24999

A PRELIMINARY DESIGN OF INTERIOR STRUCTURE AND FOUNDATION OF AN INFLATABLE LUNAR HABITAT

Final Report

NASA/ASEE Summer Faculty Fellowship Program -1989

Johnson Space Center

Prepared by: Paul K. Yin, Ph.D.,P.E.

Academic Rank: Assistant Professor

University and Department: Texas A&M University @ Galveston
Department of Marine Engineering
P.O.Box 1675
Galveston, Texas 77553-1675

NASA/JSC

Directorate: Engineering

Division: Advanced Programs Office

Branch: Systems Definition

JSC Colleague: Clarence Bell, Ph.D.

Date Submitted: August 18, 1989

Contract Number: NGT 44-001-800

ABSTRACT

A preliminary structural design and analysis of an inflatable habitat for installation on the moon has been completed. This work was an extension of a concept conceived in the Advanced Programs Office of the Johnson Space Center. The concept takes the shape of a sphere with a diameter of approximately 16 meters. The interior framing provides five floor levels and is enclosed by a spherical air-tight membrane holding an interior pressure of 14.7 psi (101.4kpa). The spherical habitat is to be erected on the lunar surface with the lower one third below grade and the upper two thirds covered with a layer of lunar regolith for thermal insulation and shielding against radiation and meteoroids.

The total dead weight (earth weight) of the structural aluminum, which is of vital interest for the costly space transportation, is presented. This structural dead weight represents a preliminary estimate without including structural details.

The design results in two versions, one supports the weight of the radiation shielding in case of deflation of the fabric enclosure and the other assumes that the radiation shielding is self supporting.

To gain some indication of the amount of structural materials needed if the identical habitat were installed on Mars and Earth three additional design versions were generated where the only difference is in gravity. These additional design versions are highly academic since the difference will be much more than in gravity alone. The lateral loading due to dust storms on Mars and wind loads on Earth are some examples.

The designs under the lunar gravity are realistic. They may not be adequate for final material procurement and fabrication however as the connection details, among other reasons, may effect the sizes of the structural members.

All the computer input data, plots of the computer model, and output results are kept with the Advanced Programs Office of the JSC. For more information on these data please contact Mike Roberts at (713)483-0123. The author can be reached at (409)740-4473 for further interpretations.

INTRODUCTION

The human presence and the development of a permanent base on the moon is envisioned as the next stepping stone to Mars and toward long term space exploration[1]. Options for human habitation on the moon have been conceived and studied recently by NASA. One of the options, which appears promising, is an inflatable spherical habitat. This concept is seriously explored by the Advanced Programs Office of the Johnson Space Center[2]. With the basic concept and various design requirements reasonably defined, a realistic design of the interior structure and the exterior foundation is needed for further development of this concept.

With the design of the regolith shielding yet to be developed, two design versions were generated with one supporting the shielding and the other assuming that the shielding is self supporting.

The interior framing and the exterior support structure, all of high-strength structural aluminum 2219, have been modeled using IDEAS/FRAME, a structural analysis computer program developed by the Structural Dynamics Research Corporation (SDRC)[3]. Since the membrane enclosure does not carry any vertical load under the lunar gravity the flexible membrane is not included in the stiffness model.

Under the expected live loads on each of the five floors and the dead weight of the structure (with the lunar gravity properly accounted), all the load carrying members have been sized to their minimum sizes satisfying the Specification for the Design, Fabrication and Erection of Structural Steel for Buildings published by the American Institute of Steel Construction (AISC)[4] except the foundation mat which provides a factor of safety of 4 against the yield strength of the aluminum and the ultimate bearing capacity of the lunar soil[5,6].

To provide some indication of the impact on the structural dead weight if the identical habitat were installed on Mars or on Earth three additional design versions were generated, two under Martian gravity and one under Earth gravity.

DESCRIPTION OF THE CONCEPT

Since the interior of the habitat must provide a replica of the earth's atmosphere at approximately sea level the most efficient shape would be that of a sphere from both the view points of the interior space and the membrane stress in the wall of the enclosure due to the inside pressure of 1 atm[2].

To accommodate a crew of 12 and various other architectural requirements[7] the diameter of the habitat was selected to be 16 meters which provides enough total vertical distance for five floor levels. While the inside air pressure will be contained by a spherical flexible enclosure, the five floors will be provided by some structural framing.

The flexible enclosure together with part of the interior framing will be so designed that it can be folded down into a canister for space transportation and field erection on the surface of the moon. The habitat is to be installed with its lower one-third below grade and its upper two-thirds covered by a one-meter layer of the lunar regolith as the thermal and radiation shielding (Fig.1).

The habitat is intended for permanent human habitation and mission operations for a duration longer than six months.

DESIGN REQUIREMENTS

In addition to the various requirements described in references [2] and [7], listed below are some specific design considerations:

- The total structural dead weight should be minimized.
- The design satisfies the Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings by the American Institute of Steel Construction (AISC)[4].
- The design provides structural redundancy to allow for load redistribution in case of damage and thus preventing catastrophic collapse until the damage is repaired.
- Interchangeabilities among structural members should be maximized for expediency of field erection and minimization of inventory of spare structural members.
- The framing configuration should be suited for space transportation and field erection.
- The habitat can be installed anywhere on the surface of the moon.

STRUCTURAL FRAMING

The interior framing is to provide 5 floor-levels with a central vertical core of open space for vertical traffic and air circulation. These are provided by the five horizontal framings and the six central columns defining the central core of the open space. To create maximum degree of interchangeability among structural members it has been decided to maintain the structure axi-symmetrical about its vertical center line and to have six identical vertical-radial planes of "frames" without diagonal bracings to provide maximum usable open spaces between levels. These six vertical frames are 60-degree apart about the vertical axis of symmetry of the entire structure. Loads are transferred from the interior structure to the exterior support structure across the air-tight membrane at the six "hard" points at the first floor level as well as at the bottom ends of the six central columns. The global torsional rigidity and the structural redundancy are provided by the secondary bracings in the planes immediately next and "parallel" to the surface of the spherical membrane.

All horizontal members are of rectangular tubulars with their strong axes horizontal and all the six vertical central columns are of hexagonal tubulars. All secondary braces are of pipe tubulars and so are the six vertical exterior support columns. All members are of commercially available sizes (Figs.1,2)[4].

STRUCTURAL MATERIALS

The same material used for the frame of the Lunar Rover, Aluminum 2219[8], is used for the design. Extensive selection of material is beyond the scope of this design exercise. Better choice of alternative material is possible, such as, Aluminum Lithium developed more recently which is 10% lighter than 2219 with comparable strength. Relevant properties of the Aluminum 2219 are[9]:

Specific weight:	.101 lb./cu.in.
Ultimate strength:	66 ksi(455,070 kpa)
Yield strength:	51 ksi(351,645 kpa)
Modulus of elasticity:	10.6x10E6 psi(73.1x10E9 kpa)

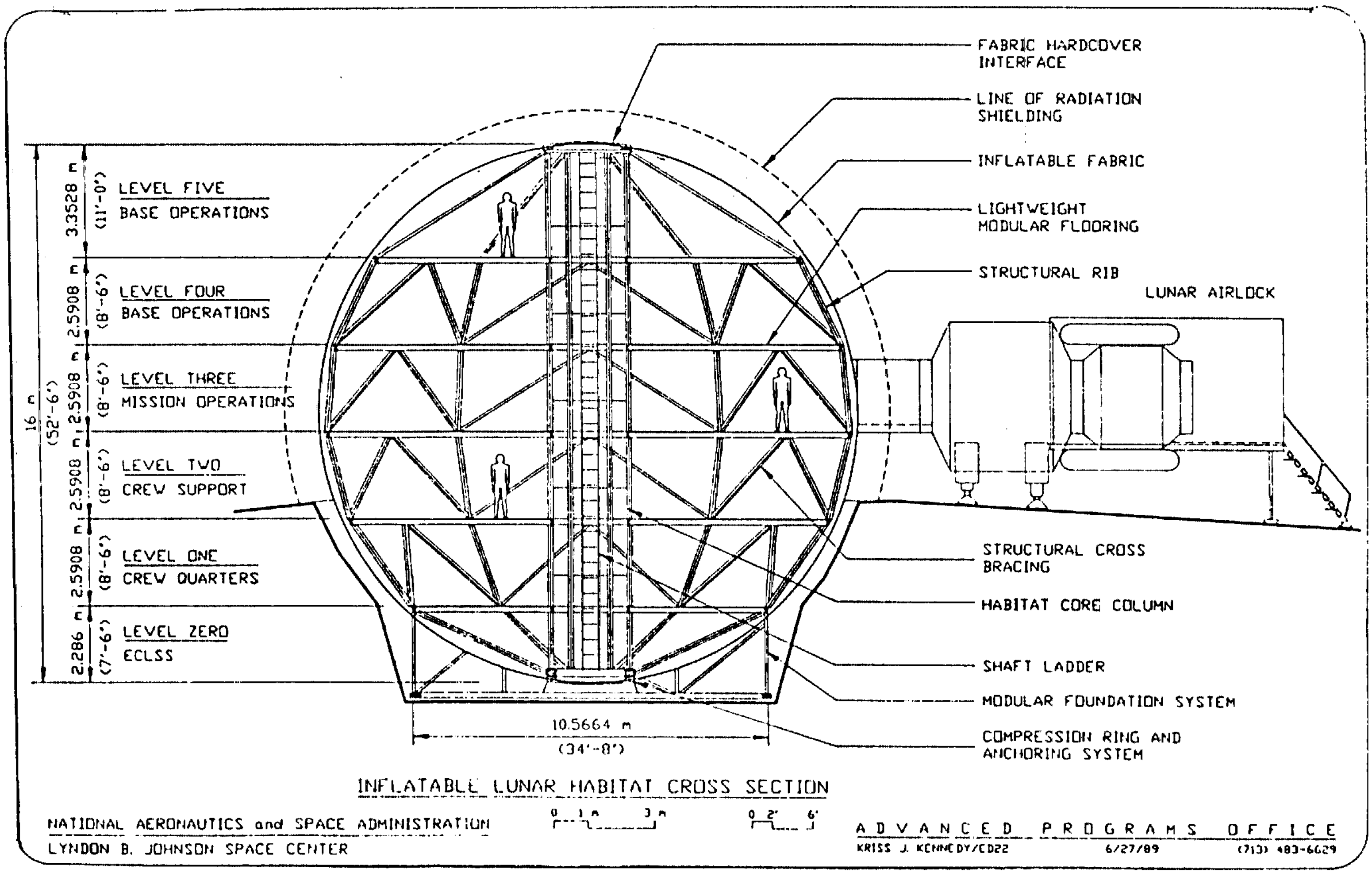

Fig. 1 - Typical Elevation

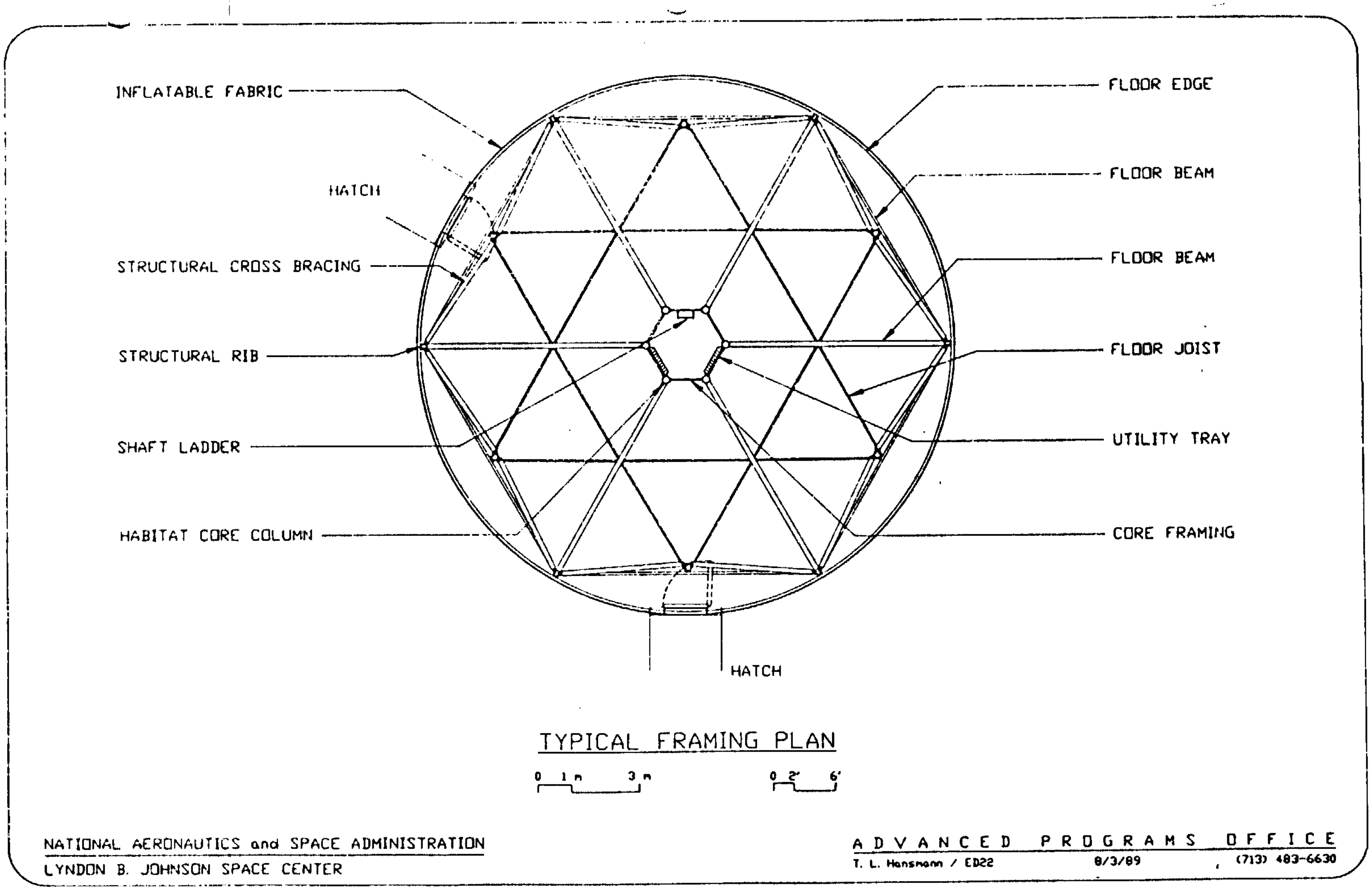

Fig. 2 - Typical Framing Plan

DESIGN LIVE LOADS

The design live loads are the best estimate of the expected area loadings due to the weight of various equipment, furnitures, people, etc[7]. Since the live loads were realistic estimates and area specific, no additional carry-down factors were applied for the structural analysis and design. The design live loads are given in Table 1.

Table 1.- DESIGN LIVE LOADS.

floor	earth psf	total earth lbs	total lunar lbs	total lunar kn
1st	50- 60	55,500	9,250	41
2nd	40-125	170,100	28,350	126
3rd	60-125	187,700	31,283	139
4th	60-125	194,800	32,467	144
5th	50-100	136,000	22,667	101
all		744,100	124,017	552
roof	Regolith shielding:		77,344	344

RESULTS

Results are presented first of the mat foundation, then followed by the bill of materials for the case where the weight of the radiation shielding is not supported by the interior structure, and thirdly of the comparisons among all design cases.

The Mat Foundation

The design of the mat foundation is summarized below:

- Factor of safety: 4 against soil ultimate bearing capacity and 4 against yield strength of the mat
- Total foundation reaction: 128,000 lbs. (569 kn)
- Total bearing area: 10,000 sq.in. (6.452 sq.m)
- Total dead weight of the mat: 1,310 earth lbs. (594 kg)
- Depth below grade: 16.4 ft (5 m)
- Lunar surface soil properties:
  Apparent density[5]: 100 lb/cu.ft (1,600 kg/cu.m)
  Ultimate bearing capacity[6]:76 psi (524 kpa)

Bill of Materials

Table 2 summarizes the total amount of material for each size and shape of all the structural members. All hexagonal tubulars are represented by pipe tubulars of equivalent strength and weight.

TABLE 2.- BILL OF MATERIALS.

section	width in.	height in.	wall th. in.	total wt. earth lb.	t. mass kg.
rect. tubular	2	3	.1875	2,426.0	1,100.2
" "	2	4	.1875	534.5	242.4
" "	2	5	.2500	1,479.0	670.7
" "	3	5	.3125	1,307.3	592.9
pipe "	3.5(o.dia.)		.2160	3,093.0	1,402.7
pipe "	4.5(o.dia.)		.2250	494.8	224.4
all sections total(interior & suppt.)				9,335.0	4,233.6

Additional Cases

The comparisons among all different design cases are given in Table 3.

TABLE 3.- TOTAL DEAD WEIGHT OF STR. ALUM. FOR ALL CASES.

	Moon	Mars	Earth
No rad. shielding, earth lbs.	9,335	11,620	28,625
kg.	4,234	5,270	12,982
Sppt. rad. shielding, earth lbs.	10,490	14,660	N/A
kg.	4,757	6,649	N/A
Gravitational constant, in/sec.sq.	64.33	146.4567	386.000
m/sec.sq.	1.62	3.6882	9.721

CONCLUDING REMARKS

Using Aluminum 2219 for the structural framing subject to a set of estimated live loads under the lunar gravity, the total structural dead weight is 9,335 earth pounds equivalent to a mass of 4,234 kg. This total amount of structural material includes both the framing inside the 16-meter diameter air-tight enclosure and the exterior support framing with the mat foundation. The structure is analyzed and designed to the Specification for the Design, Fabrication, and Erection of Steels for Buildings by the American Institute of Steel Construction (AISC) [4] except the mat foundation which provides a factor of safety of 4 against yielding of the aluminum or the lunar soil at the depth of 5 meters. The structure may be considered as a "fully stressed design" using the most efficient structural shapes in author's judgement. The total structural dead weight is increased to 10,490 earth pounds or 4,757 kg if the structure was to support a one-meter thick radiation shielding of lunar regolith.

Keeping all the design parameters the same except the gravity, the total structural material is increased by 24.5% under the Martian gravity and 206.6% under the Earth gravity. These results indicate merely the trend of increase in structural dead weight under the influence of gravity knowing that lateral loads, which are absent on the moon but present on both Mars and Earth, are not accounted.

All the summaries in weight may vary as a result of structural details, packaging for shipping, and necessary adjustments for field erection.

In view of the costly space transportation the design can and should be further optimized by way of, for example, using materials lighter than Aluminum 2219 with comparable relevant properties (such as Alum. Lithium), more suitable design specification other the that of AISC, more precise live loads, subgrade modulus for the design of foundation, and finally, a computer program for automatic design optimization.

Being situated remotely on the moon, on-site repairability of structural damage for unforeseeable reasons must be ensured by providing structural redundancy. Question on adequate degree of this redundancy can be answered rationally by performing the so-called collapse analysis. The result is a probability assessment of catastrophic collapse of the structure and its comparison with a certain maximum allowable level.

ACKNOWLEDGMENT

The author owes many thanks to his NASA Colleague, team mates, and all others in the Advanced Programs Office and in JSC in general for their valuable help in various ways.

REFERENCES

1. Davidson, W.L.,and Stump, W.R., "Lunar Stepping-Stones to a Manned Mars Exploration Scenario," Symposium on Lunar Bases & Space Activities in the 21st Century," Paper No. LBS-88-195, 1988.

2. Roberts, M.L., "Inflatable Habitation for the Lunar Base," Symposium on Lunar Bases & Space Activities in the 21st Century, Paper No. LBS-88-266, 1988.

3. Structural Dynamics Research Corporation (SDRC), User's Guide, I-DEAS, Frame.Engineering Analysis, Vol. 1, Level 4, 1988.

4. American Institute of Steel Construction, Inc., Manual of Steel Construction, 8th Edition, 1980.

5. Mitchell, J.K. et.al., "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction," Proceedings of the Third Lunar Science Conference, Vol. 3, pp 3235-3253, The M.I.T. Press, 1972.

6. Vesic, A.S., "Bearing Capacity of Shallow Foundations," Foundation Engineering Handbook, Van Nostrand Reinhold Co, 1975.

7. Kennedy, K.J., "Interior Design of the Lunar Outpost," submitted to the 2nd International Conference on Engineering, Construction, and Operations in Space, 1990.

8. Morea, S.F., "The Lunar Roving Vehicle - A Historical Perspective," Symposium on Lunar Bases & Space Activities in the 21st Century, Paper No. LBS-88-203, 1988.

9. Joseph T. Ryerson & Son, Inc., Ryerson Data Book -Steel, Aluminum, and Special Metals, 1971.