CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

LOW EARTH ORBIT BUSINESS CENTER

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by

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PREFACE

The Low Earth Orbit Business Center (LEOBC) was initially conceived as a modular structure to be launched aboard the Space Shuttle, it evolved to its present configuration as a result of research, discussions and the desire to increase the efficiency of space utilization.

Although the idea of placing space stations into Earth orbit is not new, as is discussed in the first chapter, and the configuration offers nothing new, LEOBC is unique in its application. Previous concepts and current justification cited for space stations were and are based on scientific need. LEOBC, on the other hand, is proposed as a speculative project. It is to be placed in low Earth orbit for the same reason a developer builds a shopping mall or a warehouse on property which appears to be out of the way -- speculation.

As more companies explore the possibilities of operating in space and NASA's Space Station becomes a reality, there will soon become a shortage of habitable volume in space. Most visionaries foresee space cities and lunar cities as a result of economic expansion into space. LEOBC can be a needed intermediate step in this process.

TABLE OF CONTENTS

Chapter	Page
FRONTISPIECE	iii
ACKNOWLEDGEMENTS	iv
PREFACE	v
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF SYMBOLS	xi
ABSTRACT	xiv
1. INTRODUCTION	1
2. THE NEXT STEP	11
3. INTERNAL ENVIRONMENT	19
PSEUDOGRAVITY	19
ATMOSPHERE	25
4. LOW EARTH ORBIT BUSINESS CENTER CONFIGURATION	31
5. INTERIOR DESCRIPTION AND ARRANGEMENT	47
6. LEOBC CONSTRUCTION CONSIDERATIONS	59
7. CLOSING REMARKS	81
BIBLIOGRAPHY	85
APPENDICES	
A SPACE/STATION HABITAT CONCEPTS	99
B SPACE STATION MISSIONS	102
C SHAPE EQUATIONS DEVELOPMENT	107
D SHELL THICKNESS ESTIMATES	136
E LEOBC INTERNAL MASS CALCULATIONS	145

LIST OF TABLES

Table		Page
1	Shape Description Summary	33
2	Shape Comparison Equation Summary	34
3	Key for Figures 13-23	40
4	Shape Evaluation Table	46
5	LEOBC Geometric Specifications	53
6	LEOBC Space Allocation (Torus Only)	54
7	LEOBC Structural And Floor Panel Description Summary	67
8	LEOBC Structural And Floor Panel Launch Data Summary	68
9	Revised Launch Data Summary Due To Payload Mass Considerations	73
10	Subsystem Options	73
11	Historical Listing Of Manned Satellite Concepts	99
12	Additional Manned Satellite Concepts	101
13	Skylab Missions	102
14	Missions To Salyut Stations	103

LIST OF FIGURES

Figure		Page
1	Hermann Noordung's "WOHNRAD"	33
2	Dr. W. von Braun's "Space Wheel"	4
3	Location of Lagrangian Points	5
4	Dr. Krafft Ehrlicke's "Star City"	7
5	STS Mission Duration Versus Power Use Rate	16
6	Pseudogravity Limits	20
7	Coriolis Acceleration Effects	23
8	Allowable Pseudogravity Design Envelope	24
9	Body Nitrogen Pressure For Tissues With A Half-Saturation Time of 240 Minutes For Two Pre-Breathe Air Mixtures	27
10	Sea Level Equivalent Atmosphere Composition	28
11	Impact Rates Of Meteoric Material	29
12	LEOBC Shape Candidates	38
13	Shapes' Volumes	41
14	Shapes' Habitable Volumes	41
15	Shapes' Surface Areas	41
16	Shapes' Projected Areas	41
17	Shapes' Floor Areas	43
18	Shapes' Habitable Volume/Volume	43
19	Shapes' Volume/Surface Area	43
20	Shapes' Habitable Volume/Surface Area	43
21	Shapes' Projected Area/Surface Area	44
22	Shapes' Floor Area/Volume	44
23	Shapes' Floor Area/Surface Area	44

LIST OF FIGURES (CONTINUED)

Figure		Page
24	LEOBC Top and Side Views	48
25	LEOBC Torus Cross-Section and Elevation	49
26	Typical Efficiency Floor Plan	51
27	LEOBC Efficiency Elevations	52
28	Artist's Concept of LEOBC Recreation Court	56
29	LEOBC Cross Section	57
30	Torus Structural Panels	61
31	First- and Second-Floor Floor Panels	62
32	LEOBC Hub Structural Panels	63
33	Hub Structural Panels H1 Through H6	64
34	Hub Structural Panels H7 Through H9	65
35	LEOBC Thickness for Various Pressures and Altitudes with Constant Radiation Exposure Levels	70
36	Structural Panel Mass	72
37	LEOBC Panels Per STS Launch	72
38	LEOBC Telescopic Spoke	74
39	LEOBC Design, Fabrication and Construction Schedule	77
40	Spherical Habitat Characteristics	109
41	Dumbbell, Beaded Torus Habitat Characteristics	114
42	Cylindrical Habitat Characteristics	119
43	Toroidal Habitat Characteristics	122
44	Crystal Palace Habitat Characteristics	127
45	Two-Axis-Stretched Ellipse Characteristics	130
46	Differential Element ds in x-y Plane	133
47	LEOBC Hub Pressure Resolution	139

LIST OF FIGURES (CONTINUED)

Figure		Page
48	LEOBC Potable Water Tank	147

LIST OF SYMBOLS

b	y - intercept of a straight line.
ds	Arc length.
F	Axial load per unit length..
FA _{s,d,md,bt,c,t,ct,cp,e}	Floor area of a sphere, dumbbell, multiple dumbbell, beaded torus, cylinder, torus, cylindrical torus, crystal palace and two-axis-stretched ellipse.
g	Gravitational acceleration; pseudogravity acceleration.
HV _{s,d,md,bt,c,t,ct,cp,e}	Habitable volume of a sphere, dumbbell, multiple dumbbell, beaded torus, cylinder, torus, cylindrical torus, crystal palace, and two-axis-stretched ellipse.
k	Time constant related to body tissue nitrogen saturation half-time.
l	Crystal palace radial hoop number.
L	Number of radial hoops in crystal palace.
m	Meters; gram-mole mass.
m _c	Slope of a curve.
m _n	Slope of a normal to curve.
M	Number of dumbbells in a beaded torus.
n	Floor number.
N	Maximum number of floors; maximum number of axial hoops in crystal palace.
Nl	Number of floors with a rotational radius greater than the shape's major radius.
P	Pressure at time t.
PA _{s,d,md,bd,c,t,ct,cp,e}	Projected area of sphere, dumbbell, multiple dumbbell, beaded torus, cylinder, torus, cylindrical torus, crystal palace, and two-axis-stretched ellipse.

LIST OF SYMBOLS (CONTINUED)

P_f	Floor design mass load.
P_i	Axial load per unit length along inner circumference.
$P_N(t)$	Body tissue nitrogen partial pressure at time t .
$P_N(0)$	Initial body tissue nitrogen partial pressure.
P_{N-mix}	Nitrogen partial pressure of pre-breathe air mixture.
P_o	Initial pressure; Axial load per unit length along outer circumference.
R	Major radius; universal gas constant.
$\bar{R}$	Average or weighted-average radius.
R_1	Radius of curvature of a meridian.
R_2	Line length of normal to curve to axis of rotation.
R_i	Inner radius.
R_n	Radius of floor n .
R_o	Outer radius.
R_γ	Habitable volume minimum radius.
$SA_{s,d,md,bd,c,t,ct,cp,e}$	Surface area of sphere, dumbbell, multiple dumbbell, beaded torus, cylinder, torus, cylindrical torus, crystal palace and two-axis-stretched ellipse.
t	Time; thickness.
T	Temperature - Degrees Kelvin.
V	Volume.

LIST OF SYMBOLS (CONTINUED)

$V_{s,d,md,bd,c,t,ct,cp,e}$	Volume of sphere, dumbbell, multiple dumbbell, beaded torus, cylinder, torus, cylindrical torus, crystal palace and two-axis stretched ellipse.
W_n	Width of floor n.
W_γ	Width at minimum radius of habitable volume.
α	Ratio of cylinder length to radius, ratio of cylindrical torus length to minor radius, ratio of two-axis-stretched ellipse offset from latitudinal axes to radius.
β	Ratio of two-axis-stretched ellipse offset from rotational axis to radius.
γ	Variation of centripetal-acceleration in habitable volume, ratio of specific heats.
δ	Ratio of two-axis-stretched ellipse semi-major radius to hub radius.
ϵ	Ratio of two axis stretched ellipse of semi-minor radius to hub radius.
η	Ratio of minor radius to major radius.
ρ	Material mass density.
σ_w	Working stress of material (ultimate stress divided by factor of safety).
Σ	Summation.
τ	Pressure decay time constant.

ABSTRACT

LOW EARTH ORBIT BUSINESS CENTER

by

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Master of Science in Engineering

The need for a business park in low earth orbit may be generated as manufacturers discover and implement the benefits of operating in space to produce cheaper and create new products. What configuration should this Low Earth Orbit Business Center have, what sort of environment should it offer and how long will it take to become operational? These questions are addressed and results presented in this paper. Comparisons are made for various gravity-oriented configurations to determine what shape is best suited for the living areas. Artificial gravity and associated problems are discussed as is atmospheric composition and pressure. An interior design for the living area is presented. The Low Earth Orbit Business Center offers

a 0.5 earth gravity environment in a toroidal structure with a standard sea level atmosphere. Inside the torus are living quarters, recreational facilities, and office and laboratory areas. A large hub provides for low-g laboratory areas, mechanical equipment and consumable stores location. Estimates based on structural panel sizing, thickness estimates and STS launch capabilities indicate that the Low Earth Orbit Business Center can be placed into orbit over a period of 20 years.

CHAPTER 1

INTRODUCTION

The concept of man living aboard an earth satellite was introduced slightly more than a century ago. Since then, various concepts have been presented in novels, short stories and scientific articles. These concepts have become increasingly larger and more complex, but, to date, only three true space habitats have been launched and utilized for extended space operations. A review of these concepts and actual space habitats is presented below.

Descriptions of man-made habitats have been around since 1865 when Edward Everett Hale wrote the Brick Moon.¹ In this short novel, several families are accidentally launched into Earth orbit inside a brick sphere. Under construction to be launched into polar orbit, it was to become a longitudinal navigation aid, similar to Polaris' aid in fixing latitude. Due to the untimely launch, its intended use was never realized. However, the families on board survived due to retention of an atmosphere. Evolution, the vogue of these times, quickly provided the residents with various and sundry plant and animal life for their long term survival needs. In this manner, the brick moon became a self-sufficient space colony. With the publication of this novelette, the seed was sown for a continuous stream of ideas regarding permanent habitation in Earth orbit aboard man-made worlds.

The next proposed habitat description appeared in Russian science fiction literature in 1895.² Written by Konstantin Tsiolkovsky, whom R. Hutton described as the founder of the science of space travel,³ this story described a space station in engineering

detail. This description was revised eight years later to include added features such as artificial gravity, solar energy and a greenhouse. This became the first serious proposal for living in space. Initial presentation may have occurred in science fiction as that may have been the only vehicle for publication of such ideas at the time.

Twenty years after Tsiolkovsky revised his station concept, the first engineering concept for a space station was proposed by Hermann Oberth.⁴ In this conceptual description, Oberth presented methods for supplying artificial gravity and orbital construction techniques. In the following years, many additional proposals for space station designs were published. The most notable of these were Hermann Noordung's "Whonrad" in 1928, the first design placed on paper, and Dr. von Braun's "Space Wheel" in 1951, the most popular concept of modern times.^{5,6} These two concepts are shown in Figures 1 and 2.

The latest space habitat concepts are not mere stations, but large cities capable of supporting populations in excess of 10,000 people. These concepts have been studied by senior research workers and college students in two summer sessions sponsored by NASA.^{7&8} The proposed locations for these large cities are the L-4 and L-5 positions in the Earth-Moon system. These are two of five stable orbital locations in a two-body system first defined by the 18th century mathematician and astronomer J. L. Lagrange and are illustrated in Figure 3.⁹ The L-4 and L-5 locations are located sixty degrees fore and aft of the smaller body, along its orbital path.

Even larger structures than those studied in these summer sessions have been proposed for travel through and beyond the solar system.

Space station designed in 1929 by Hermann Noordung. K is the electric cable to an external observatory; S is the airlock; Kondensatorrohre are condenser pipes; Verdampfungsrohr are boiler pipes; Treppenschacht is a stairwell; Aufzugschacht is an elevator shaft. The design calls for power to be supplied by mirrors concentrating sunlight onto the boiler pipes. (Courtesy the Millikan Library, California Institute of Technology)

Heppenheimer, T. A. Colonies in Space. Stackpole Books, 1977

Figure 1. Hermann Noordung's "WOHNRAD"

Dr. W. von Braun. "Crossing the Last Frontier." Colliers. 22 March 1952.

Figure 2. Dr. W. von Braun's "SPACE WHEEL"

Figure 3. Location of Lagrangian Points

The latest of these was proposed by Dr. Krafft Ehricke in 1976.¹⁰ Known as Astropolis, this modular, rotating system is capable of simulating other-world environments in its various modules (Fig. 4). There is no set time for this type of system to be built, for its existence is dependent on expansion into space for economic rather than explorative reasons. This is the same driving force that led to rapid development of the North American continent in the 18th and 19th centuries.

The concepts for space habitats mentioned above, and others, are tabulated in Appendix A. Table 11 is taken from a paper by Koelle.¹¹ Table 12 was compiled by this author.^{2,7,8,10-18} Other concepts have been pursued by the National Aeronautics and Space Administration (NASA) and the Air Force but are so numerous they are not included in the listing. Suffice it to say that the stations studied by these two agencies of the U.S. Government were compatible with launch vehicles available at the time of the specific study. In general, they were not built-up structures but placed into orbit by a single launch and were capable of supporting from two to five crew members. Since the advent of the Space Transportation System (STS)*,

* The Space Transportation System consists of two solid rocket boosters, an external tank, the Space Shuttle Orbiter, and a manned maneuvering unit. The design goal is that it be capable of placing a 65,000 pound payload into circular orbit 150 nautical miles above the Earth's surface at 28.5 degrees inclination to the equator (due East launch out of Kennedy Space Center). Maximum payload volume is 15 feet in diameter by 60 feet long.¹⁹

Astropolis - Conceptual Arrangement

Dr. K. Ehricke. "A Long Range Perspective and Some Aspects of Interstellar Evolution." Journal of the British Interplanetary Society. Vol. 28, April 1975.

Figure 4. Dr. K. Ehricke's "STAR CITY"

these studies have taken on a modular, expandable theme, requiring multiple launches of the Space Shuttle Orbiter for construction capable of supporting up to 10 personnel.

Thus, since the first mention of earth orbital space habitats by Hale over 100 years ago, concepts have ranged from small 10-foot diameter cylinders to large toroidal cities more than a mile in diameter to modular, multi-g, multi-world structures capable of traveling through and beyond our solar system. Each concept had its own purpose for existence, from proving man's ability to survive and work in zero-g, to being complete environmental niches in which generations could travel through space, exploring and perhaps settling on planets in other stellar systems. In spite of these many concepts, only three true space stations have been placed in orbit: Skylab, Salyut 6 and Salyut 7.

Skylab was launched in May 1973, and housed three 3-man crews for 28, 59 and 84 days from May 1973, through February 1974.²⁰⁻²⁶ These visits are listed in Table 13 of Appendix B. However, Skylab was not designed to be a permanent station and could not be readily resupplied or reboosted to a higher orbital altitude. As a result, it was deactivated after the third crew departed and five years later, it reentered the Earth's atmosphere and was destroyed in July 1979.²⁷

Using a different approach, perhaps due to a more deliberate program for space utilization, Soviet space stations Salyut 6 and 7 were designed for resupply. Launched in September, 1977, Salyut 6 was destroyed upon return to earth on 29 July 1982, although its manned activities ended in 1981.²⁸⁻⁷⁸ During its nearly five years in service, 15 of the 17 crews sent to Salyut 6 successfully docked with

and occupied it for periods up to 185 days. In addition, 12 Progress tankers were periodically sent to the station with fresh supplies of consumables. A second station, Salyut 7, was launched April 19, 1982. As with Salyut 6, various crews and resupply missions have been made to Salyut 7.⁷⁹⁻¹¹⁸ The latest occupants were launched on February 8, 1984 and returned October 2, 1984.¹¹⁷ For a complete list of flights to the Skylab and Salyut stations, please refer to Table 14 in Appendix B.

The next step in mankind's move into space is the placement of permanent, continuously occupied stations in Earth orbit. The USSR plans to accomplish this by using their 1960's design of a Saturn class vehicle. The USSR station will be carried into orbit by a single launch and be capable of supporting 12 cosmonauts. It will be used to aid Soviet military activities and continue the work begun on both Salyuts.^{63,119} A different approach is planned by the United States NASA. In 1980, NASA's plans called for the construction of a Space Operations Center (SOC)¹²⁰⁻¹²³ from several modules placed in orbit by the Space Transportation System. No longer called the SOC, it is now known as Space Station. NASA's Space Station will be used for logistical support of on-orbit activities such as commercial material processing operations, satellite servicing and repair, sortie support for manned geosynchronous flights, as a staging point for assembly of satellites or planetary probes that cannot be orbited by a single STS launch, materials processing and various scientific experiments. These support tasks are similar to those performed by the Old West Cavalry Forts for early settlers in North America.

For all the concepts proposed for space habitation in the past century, only three have become a reality. The next step, which is currently in the concept definition phase and should be on-orbit by 1992, is NASA's Space Station. The Soviet Union also has plans for stations larger than the Salyuts currently in use. The next generation space habitats appear to be those presented by NASA's special study groups. These are a giant step from what is currently in the planning stages. The Low Earth Orbit Business Center (LEOBC) is a proposed commercial space station which can fill the gap between the current generation of space stations and the space cities of the next century as seen by O'Neill and others.

CHAPTER 2

THE NEXT STEP

Operational limitations of current space hardware and the means of support for commercial operations in space are discussed to illustrate why there is a need for something more than the Space Transportation System and the upcoming space station and how a commercial site in space may be financed.

Following the plans of the United States NASA and visions of Gerard O'Neill, Krafft Ehricke and others, the evolutionary expansion into space leads from the Space Transportation System to logistical support centers in low Earth orbit followed by lunar mining communities and cities in the L-5 location of the Earth-Moon system. Beyond that, a modular rotating structure, known as Astropolis, is seen traveling about the solar system and interstellar space. It is difficult to visualize a sudden step from small 8-12 man stations in low Earth orbit to cities on the Moon and at L-5 with tens of thousands of inhabitants without any intermediate steps. LEOBC is proposed as one of these intermediate steps.

Current space programs are funded by federal tax dollars appropriated by Congress. However, lunar and space cities, as envisioned by Ehricke and O'Neill, are expected to be paid for by profits generated from commercial space activities. Whether or not this happens will only be answered in time.

Incentives to develop space could follow a path similar to that used to develop the North American frontier and the satellite communications industry. The biggest problem in settling the West was inadequate transportation. This was overcome with large land grants

along rights-of-way to companies that built the railroads, thus lowering the financial burden of construction. Satellite communications was an undeveloped technology in the early 1960's when Comsat was established by the U.S. Congress to provide research dollars and industry regulation needed to develop satellite communications and ensure a return on investment. Today, companies are beginning to build communication satellites on a venture basis and are selling transponders, rather than leasing them under government regulation.¹²⁴ This opens up the market to supply and demand price setting, rather than controlled income fixed by government regulations.

To open other markets in space, it may be necessary for NASA to provide incentives of lower transportation or research funding as was done for the railroads and satellite communications industries. Then, once profitability is proven, each endeavor can compete in free markets. Placing a facility on orbit such as LEOBC could be an incentive needed to spur space development.

In 1981, the chairman of American Institute of Aeronautics and Astronautics' Space Processing Committee, R. A. Weiss, was asked by this author about the prospects of material processing in space. His response indicated that private sources were finding the high development cost and long lead time necessary for return on investment to be major deterrents to investment in space processing. As a result, he indicated that it may be necessary for NASA to place the needed facilities in space for early phases of space commercialization. This position is echoed in a paper presented by Waltz at the 1981 AIAA Annual Meeting showing the need for funding and

promotion of material processing in space.¹²⁵ Eventually, as "market pull" exceeds "technology push", more private money should become available and government support can be decreased or eliminated.

NASA realizes the need to aid initial steps toward exploitation of space and is offering joint endeavor agreements (JEA) with companies wishing to explore possibilities of operating in space.¹²⁶ With a JEA, the principal investigator develops a proof-of-concept experiment and NASA provides several free launches aboard the Space Shuttle Orbiter.

McDonnell Douglas and Johnson & Johnson have signed such an agreement and are developing hardware for electrophoretic separation of biological materials. This process plays a key role in drug purification for medical research. To date, the process, which was flown on STS-4, STS-6, STS-7, STS-8, and STS mission 41D (STS-14), has shown dramatic improvements in electrophoretic separation efficiency. Four to seven hundred percent improvement in the separation rate has been reported by McDonnell Douglas.¹²⁷⁻¹³²

In addition to the McDonnell Douglas and Johnson & Johnson team, in a recent study for NASA, Booz, Allen and Hamilton surveyed 60 companies concerning possibilities in space industrialization.¹³³ Of these, 10 were identified as possible JEA signers within the next 12 months, some of which may result in STS flight activity and thirty-five are still actively examining commercial applications of space. In addition, 17 investment firms have expressed a desire to finance such activities.

In order to fully realize the benefits of operating in space, it is necessary to overcome the basic limitations inherent in the Space

Transportation System, and possibly, the Space Station. One of the key reasons for transferring a process to earth orbit is use of benefits derived from being in a microacceleration environment, commonly called zero-g. However, with the Space Shuttle Orbiter, flight duration is now limited to less than two weeks. Current studies are under way which will extend this to 30 days or longer. By adding Space Station to NASA's inventory, mission time can be extended to the maximum allowable time defined by operational or medical limits.

Available power in earth orbit is another concern to any who desire to manufacture products in orbit. Just as on the surface of this planet, there is a power shortage in space. The Space Shuttle Orbiter has a limited electrical power generating capacity on board at lift-off. As mission duration is extended to seven days, usable payload power drops to 50 kw-hr.¹⁹ As stay time is shortened, available power increases as shown in Figure 5. Eventually, a power extension package, in the form of a solar array, may be added to the Orbiter to increase payload usable power to as much as 25 kw continuously.¹³⁴

The McDonnell Douglas Electrophoresis Operations in Space (EOS) Program is an example of the need for additional power in space. Currently being operated in the Orbiter mid deck region, EOS operations will eventually move into the payload bay and then onto a free-flying platform. While in the payload bay, EOS will need to draw 3.5 kw during operation.¹³⁵ This limits Orbiter mission duration to a maximum of five and a half days, unless power usage rate is decreased (Fig. 5). This, however, will reduce the operational efficiency of the EOS. The solar array addition to STS hardware would

Figure 5. Payload Average Power Impact on STS Mission Duration

Space Shuttle System Summary, SSV80-1, Rockwell International, May 1980, pp. 24-85.

make long duration missions possible for power intensive activities such as EOS. Even with this Orbiter capability extension, McDonnell Douglas is pursuing permanent on-orbit operation with a free-flyer or in conjunction with Space Station.¹³⁶

The third of three important factors limited by the Space Shuttle Orbiter is usable volume. On the Orbiter, a user is limited to a maximum payload bay volume of 300 cubic meters. This cannot be increased without placing permanent structures in orbit. As of this writing, current plans for Space Station will actually provide less internal volume per module than is available in the Space Shuttle Orbiter payload bay because each module will be carried into orbit inside the payload bay. Volume per module can be increased by carrying the external tank into orbit and using it as the basic building block for a station. By using only the hydrogen tank, a habitat that is over 8 meters in diameter and 29 meters in length would be available, providing a usable volume in excess of 464 cubic meters per module. However, this approach may not be cost effective. Without using this tank and by following current plans, maximum size of any equipment utilized in an enclosed environment on orbit is limited to an envelope of less than 15 feet in diameter and 60 feet in length since each module is viewed as an isolatable volume.

Although not necessary for man's survival in space, a pseudo-gravitational environment may be extremely advantageous from a medical and human factors viewpoint. A key reason for providing an acceleration field for long periods of stay-time on orbit is to counteract mineral losses that are associated with zero-g. These losses, which can amount to as much as 0.3 - 0.4 percent per month,

remain unexplained. As shown in the 84-day Skylab mission, neither vigorous exercise nor special diet had an effect on the rate of heel bone deterioration.¹³⁷⁻¹³⁹ However, the longer flights aboard the Soviet Salyuts indicate that these mineral losses become asymptotic.

A gravitational environment may also be desirable to preclude changes in personalities during long missions. The negative impact on productivity and safety that these personality changes have had on space flights and in other confined environments has been documented by Dr. B. J. Bluth in her studies on the physiological and psychological aspects of space flight.¹⁴⁰ Weightlessness has been pointed to as a possible source of these changes.¹⁴¹

An additional advantage associated with an acceleration field is the elimination of the need for special equipment designed for zero gravity in the laboratory and living areas. Also, by living in a pseudogravity environment while on orbit, the time necessary to readjust to a one-g acceleration field upon return may be shortened or eliminated.

The major disadvantage to a gravity-oriented habitat is that it forces processes which require micro-g levels to be housed in counter-rotating or non-rotating co-orbiting facilities. This will impact either the LEOBC design or the operational logistics for these processes.

The proposed LEOBC will overcome the operational limitations associated with the STS and the upcoming Space Station. It will also provide experience in space construction and operation of rotating facilities before implementation of larger programs such as the space cities proposed by the NASA-Ames studies of 1975 and 1977.

CHAPTER 3

INTERNAL ENVIRONMENT

Prior to evaluating geometric configurations for LEOBC, parametric limits on pseudogravity and atmospheric pressure and composition will be presented. The pseudogravity limits are taken from various studies on rotation rate and radius of rotation effects on crew performance. Atmospheric pressure and composition are related to current and future space hardware, decompression sickness and equivalent sea-level composition.

PSEUDOGRAVITY

In order to create an artificial gravity for LEOBC, the structure must be rotated about its longitudinal axis at some angular velocity. Several studies and experiments have been conducted on this subject resulting in various limits that should be considered when establishing a gravity-oriented environment through rotation. These limits were established or reinforced by testing in a ground-based rotating test facility. These test were conducted by North American Rockwell Corporation, Space Division (NR/SD), in cooperation with NASA Langley Research Center to determine the effects of rotational rates, acceleration levels and radius of rotation on several test subjects.¹⁴²

Referring to Figure 6, the rotational limits suggested by these past tests and studies are plotted as a function of radius. Those combinations of rate and radius eliminated by each upper or lower boundary are covered by diagonal lines.

For design purposes, a value of one-g was set as a pseudogravity maximum and was chosen as an upper limit as it is man's natural

(a) Upper G Limit

(b) Upper Rate of Rotation Limit

(c) Upper Gravity Gradient Limit

(d) Rim Velocity Lower Limit

(e) Ratio of Coriolis Force to Local Force = 0.25

(f) Lower G Limit

Figure 6. Pseudogravity Design Limits

environment. This upper limit removes all combinations of rotation rates and radii as shown in Figure 6a.

Studies on the effect of rotation rates on selected individuals have shown that a limited number can adjust to rotation rates as high as 1.05 rad/sec (10 rpm).¹⁴³ However, a maximum rotational rate of 0.42 rad/sec (4 rpm) is usually quoted as an upper limit. The tests performed by NR/SD show that performance improves as induced g-levels increase from 0.1 g with a plateau achieved between 0.3 and 0.4 g's. They also showed that performance improved as rotation rates were increased from 0.31 rad/sec to 0.52 rad/sec for radii of less than 18.29 meters. Indications are that performance increases as rotation rates decrease for radii above 18.29 meters.¹⁴² To ensure adaptability by the general population, the 1975 summer study group used an upper limit of 0.105 rad/sec (1 rpm).¹⁴⁴ Since LEOBC staff will be from a select population, tolerance to rotation rates may be checked. Therefore, the limit suggested by Green, et al of 0.42 rad/sec has been established as the upper limit on rotation rates.¹⁴³ Figure 6b shows those rate-radii combinations eliminated by this limit.

For objects in a uniform gravitational field, such as earth's surface, hydrostatic force varies linearly with height. However, in a rotating structure the centripetal acceleration also varies with radius or height. As a result, hydrostatic pressure varies as the square of the height. This change in acceleration levels with height is called gravity gradient. An arbitrary upper limit on gravity gradient of 15% has been recommended.^{142,143,145} This ensures that the ratio of hydrostatic pressures of the heart and feet for a six

foot tall individual is similar on a rotating structure and the earth's surface. This sets a lower limit on the rotational radius at 12.2 meters, as seen in Figure 6c.

Side forces generated by motion in a rotating structure can inhibit locomotion if they are too great. These coriolis accelerations are cross-products of the rotational rate and the velocity of an object. Inside a rotating structure such as LEOBC, effects caused by coriolis accelerations include apparent weight change when motion is in the pro- or anti-spin direction or when motion is in a radial direction, an apparent force is generated in the pro- or anti-spin direction. This is illustrated in Figure 7.¹⁴⁶ Two different limits have been proposed to minimize effects of coriolis accelerations in the living area. One limit establishes a maximum rim velocity of 7.4 m/sec (Fig. 6d) in order to reduce the apparent weight loss or gain while moving either opposed or parallel to the direction of spin.¹⁴⁵ The second criterion suggested that side forces generated when an object moves radially be limited to 25% of an object's weight.¹⁴³ Since this is both a function of radius and velocity, a representative limit can be found by using walking speed (1.34 m/sec) as the velocity at which side forces are generated. This limit is illustrated in Figure 6e.

The final limit places a lower bound on acceptable pseudogravity acceleration levels and were established by walking tests conducted by NR/SD.¹⁴² They found that mobility, as defined by walking speed, fell drastically as induced g-levels dropped below 0.3 g's. Figure 6f depicts the radii-rotation rate combinations eliminated by this lower limit.

A - In Plane of Rotation

B - Side Effects

C - For Radial Motion

Kramer & Byers. "A Modular Concept for a Multimanned Space Station."
Proceedings of the Manned Space Station Symposium. IAS, 1960

Figure 7. Coriolis Acceleration Effects

By combining all limits discussed above and shown in Figure 6, an overall design envelope is defined for rotation rate versus radius and is shown in Figure 8. This envelope indicates that the smallest radius that should be considered for a rotating structure is 20 meters. It also shows that there is no rotational speed limit for any structure larger than 50 meters in radius except that set by the maximum desired g level. The rotational radius for LEOBC will be targeted for the mid point of rotation versus radius envelope to provide an acceleration of 16.1 ft/sec^2 .

Figure 8. LEOBC Pseudogravity Design Envelope

INTERNAL ATMOSPHERE

LEOBC's atmospheric minimum design point is driven by current STS orbiter cabin pressure, STS spacesuit pressure, baselined space station suit pressure, oxygen partial pressure in the lungs and caisson's disease or the bends.

Current Space Shuttle Orbiter cabin and spacesuit atmospheres are not conducive to immediate extravehicular activity (EVA) because of pressure and composition differences. The orbiter operates at standard sea-level pressure and composition while the EVA suit contains 100% oxygen at a pressure of 0.2925 atm (4.3 psi).^{124,147} Since decompression sickness occurs whenever the nitrogen partial pressure in the body is greater than 1.5 times the new ambient pressure and STS cabin nitrogen partial pressure is greater than twice the suit pressure, astronauts must eliminate nitrogen from their body before attempting an EVA. This imposes a time-consuming operational constraint for the purpose of removing nitrogen from the body. This can be accomplished by either prebreathing a nitrogen-poor mixture or by reducing the cabin pressure. Both of these methods have been used on STS flights. The mathematical relationship between body nitrogen pressure, initial atmospheric nitrogen partial pressure, the nitrogen content of the prebreathing air and time were described by Edel in 1968.¹⁴⁸ This relationship is given by equation 1,

$$P_N(t) = P_N(0) + [P_{N-mix} - P_N(0)][1 - e^{-kt}] \quad \text{eq. 1.}$$

where k is related to the body tissue nitrogen saturation half-time by the ratio of $0.693/t_{1/2} \text{ min}^{-1}$. Edel states that a value of 240

minutes proved safe for sea lab decompression schedules. It has been suggested, but not verified, that saturation half-times are longer for women than for men due to higher body-fat content. Typical prebreathing times for half-saturation times of 240 and 300 minutes are shown for a breathing air mixture of 25% N₂/75% oxygen and 100% oxygen in Figure 9.

NASA is studying the elimination of this operational constraint for its space station operations by baselining a 0.54 atm (8 psi.) suit pressure using a nitrogen/oxygen mixture. It is this suit pressure and the STS cabin pressure which establish the range of pressures considered for LEOBC. Composition will vary as a function of pressure to maintain a sea-level equivalent oxygen partial pressure in the lung as shown in Figure 10.¹⁴⁹

As unlikely as it may be (Figure 11), the possibility of being punctured by a meteoroid must be considered.¹⁵⁰⁻¹⁵¹ Should LEOBC's skin be punctured, there are two different decay processes that could dominate as defined by Roth.¹⁵²⁻¹⁵³ If the puncture is small enough that leakage rates are much less than the ventilation rate, internal temperature will remain constant and the process will follow the isothermal curve. However, should the hole created be large and leakage occur at a very rapid rate, or safety measures require that airtight doors be closed and ventilation shut down, then an adiabatic, isentropic pressure decay will occur.

For an isothermal decay process, pressure change is an exponential process, defined by equation 2.

$$P = P_0 e^{-t/\tau}$$

eq. 2

Figure 9. Body Tissue Nitrogen Partial Pressure Versus Time

Oxygen-pressure effects; adapted from Luft (1962).

Roth, E. M. Space Cabin Atmosphere Part IV, Engineering Tradeoffs of One-Versus Two-Gas System, A Literature Review. Scientific & Technical Information Office, 1967.

Figure 10. Sea Level Equivalent Atmosphere Composition

Johnson, R. D. & Holbrow, C., (ed). Space Settlements
A Design Study. NASA SP-143, 1977.

Figure 11. Impact Rates of Meteoric Material

where τ is the time constant, defined by equation 3.

$$\tau = \frac{V}{A_e} \left[\frac{\gamma R T_o}{m} \left(\frac{2}{\gamma-1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{-1/2} \quad \text{eq. 3}$$

Isentropic pressure decay is slightly faster and produces a pressure drop as defined by Equation 4. (τ is defined as before.)

$$P = P_o \left[1 + \left(\frac{\gamma-1}{2} \right) \frac{t}{\tau} \right]^{\frac{2\gamma}{1-\gamma}} \quad \text{eq. 4}$$

For standard atmospheric conditions, the time constant for any space station is $3.27154 \times 10^{-3} \text{ sec} - \text{cm}^2/\text{m}^3$ times the ratio of station volume to effective hole area. Thus, as stations grow in size, the impact of a meteor puncturing the skin becomes less of an immediate threat.

To prevent personnel from developing the bends due to decompression, airtight doors will be located where necessary. As pressure drops below a preset value, these doors will be automatically closed. The pressure at which this occurs will be based on final pressure, composition and desired margin to preclude the occurrence of bends.

CHAPTER 4

LOW EARTH ORBIT BUSINESS CENTER CONFIGURATION

If commercial activities in space justify a space business park, questions regarding its configuration and internal environment need to be answered.

Prior to selecting a geometric configuration for LEOBC, consideration must be given to user needs. These needs are defined by volume requirements, mass-to-orbit limitations, pseudo-gravity needs, expandability, and floor area requirements. Studies by industry and educational institutions that have proposed space station designs have included trade studies to determine the optimum configuration. The selection in these studies were driven by a particular launch vehicle, population density, ease of construction, total station mass based on radiation shielding requirements and cost. Most studies, however, were conducted for station populations less than 100 or greater than 10,000 personnel per habitat. Since LEOBC is expected to accommodate up to 200 personnel, a new look at configuration comparisons will be made.

The following definitions were used in generating the necessary equations for LEOBC candidates shape comparisons:

- Surface Area - Total area required to enclose the pressurized volume.
- Projected Area - Maximum habitable volume width multiplied by its circumference.
- Habitable Volume - The volume within a specified radial acceleration differential ($\gamma = 0.15$)
- Floor Area - Floor space which has a minimum overhead clearance of 2 meters.

The first step is to define the means of comparison. For all rotating structures, the following comparisons are basic: 1) volume, 2) habitable volume, 3) surface area, 4) projected area and 5) floor area as functions of rotational radius. In addition, six ratios of geometric parameters will be compared. These are 1) habitable volume/total volume, 2) total volume/surface area, 3) habitable volume/surface area, 4) projected area/surface area, 5) floor area/total volume, also as functions of radius. These parameters will be compared for each of the following configurations: 1) sphere, 2) cylinder, 3) dumbbell, 4) torus, 5) crystal palace and 6) a two-axis-stretched ellipse of revolution. Each smooth-curved body of revolution is defined in Table 1 and depicted in Figure 12.

It should be pointed out that all but the last configuration discussed in this paper have been previously compared.¹⁵⁴ In fact, two study groups under the same sponsorship and guidance came to two different conclusions. In 1975, the NASA-AMES study group under O'Neill developed a space city concept for 10,000 inhabitants. The torus was chosen as the best configuration over other shapes based on various comparisons. This has become known as the Stanford Torus. Subsequent to this, O'Neill developed a new configuration,¹⁵⁵ which he called the "Crystal Palace", after the London World's Fair exposition hall built in 1880.⁸ This new structure, in conjunction with a change in radiation shielding application to the Stanford Torus, became the preferred choice.

Table 2 lists the equations used to compare the various shapes of Figure 12. Full development and explanation of each equation is presented in Appendix C. By reviewing the graphical presentation, it

TABLE 1. SHAPE DESCRIPTION SUMMARY

Sphere	<ol style="list-style-type: none"> 1) A shell of radius R 2) Curve A revolved about x-axis 3) Most efficient structure for given pressure and volume
Cylinder	<ol style="list-style-type: none"> 1) Shell of radius R and length αR with hemispherical endcaps 2) Curve B revolved about x-axis 3) Offers more "land area" for given radius than sphere
Dumbbell	<ol style="list-style-type: none"> 1) Two spheres of radius R separated by distance $2R - \gamma R$ 2) Curve C and D revolved about x-axis 3) Most efficient structure for given pressure and volume plus rotational radius independent of structural radius
Torus	<ol style="list-style-type: none"> 1) Circular or cylindrical cross section of radius R and length $2R(1 + \alpha)$ 2) Curve E or F revolved about z-axis 3) Rotational radius independent of structural radius
Crystal Palace	<ol style="list-style-type: none"> 1) Series of semi-circular shells of radius R and R/2 joined together to allow expansion along axis of rotation 2) Curve G revolved about z-axis 3) Choice of 1977 NASA Ames study session
Ellipse	<ol style="list-style-type: none"> 1) Volume of revolution of ellipse quadrant offset from x- and z-axis 2) Curve H revolved about z-axis 3) Proposed LEOBC Hub design
Legend	<ol style="list-style-type: none"> 1) Description 2) Curve from Figure 4 3) Reason for inclusion

TABLE 2. SHAPE EQUATIONS

I. SPHERE

Volume: $V_s = \frac{4}{3} \pi R^3$

Habitable Volume: $HV_s = \frac{4}{3} \pi R^3 (2y - y^2)^{3/2}$

Surface Area: $SA_s = 4\pi R^2$

Projected Area: $PA_s = 4\pi R^2 (1-y)(2y - y^2)^{1/2}$

Floor Area: $FA_s = 4\pi \sum_{n=1}^N [R - 3n + 2][R(6n - 4) - (3n - 2)^2]^{1/2}$

II. DUMBBELL

Volume: $V_d = \frac{8}{3} \pi \eta^3 R^3$

Habitable Volume: $HV_d = \frac{8}{3} \pi \eta^3 R^3$

Surface Area: $SA_d = 8\pi \eta^2 R^2$

Projected Area: $PA_d = 2\pi \eta^2 R^2$

Floor Area: $FA_d = 2\pi \left\{ \sum_{n=1}^{N_1} [\eta R(6n - 4) - (3n - 2)^2] + \sum_{n=N_1+1}^N [6\eta n R - 9n^2] \right\}$

* Equations for multiple dumbbell stations are the same as those presented for the dumbbell except the multiplier M is added, which represents the number of dumbbells in the station.

+ For the beaded torus M is defined as: $M = \text{int} \left[\frac{\pi}{2 \sin^{-1} \eta} \right]$

TABLE 2. SHAPE EQUATIONS (CONTINUED)

III. CYLINDER

Volume: $V_c = \frac{4}{3} \pi R^3 \left(1 + \frac{3\alpha}{4}\right)$

Habitable Volume: $HV_c = \frac{4}{3} \pi R^3 \left[(2\gamma - \gamma^2)^{3/2} + \frac{3\alpha}{4} (2\gamma - \gamma^2) \right]$

Surface Area: $SA_c = 4\pi R^2 \left(1 + \frac{\alpha}{2}\right)$

Projected Area: $PA_c = 4\pi R^2 (1 - \gamma) \left[(2\gamma - \gamma^2)^{1/2} + \frac{\alpha}{2} \right]$

Floor Area: $FA_c = 4\pi \sum_{n=1}^N (R - 3n + 2) \left\{ \left[R(6n - 4) - (3n - 2)^2 \right]^{1/2} + \frac{R\alpha}{2} \right\}$

IV. TORUS (CIRCULAR CROSS-SECTION)

Volume: $V_t = 2\pi^2 \eta^2 R^3$

Habitable Volume: $HV_t = 2\pi^2 \eta^2 R^3$

Surface Area: $SA_t = 4\pi^2 \eta R^2$

Projected Area: $PA_t = 4\pi \eta R^2$

Floor Area: $FA_t = 4\pi \left\{ \sum_{n=1}^{N1} \left[R(1 + \eta) - 3n + 2 \right] \left[R(6n - 4) - (3n - 2)^2 \right]^{1/2} + \sum_{n=N1+1}^N \left[R(1 + \eta) - 3n + 2 \right] \left[4\eta n R - 9n^2 \right]^{1/2} \right\}$

TABLE 2. SHAPE EQUATIONS (CONTINUED)

V. TORUS (CYLINDRICAL CROSS-SECTION)

$$\text{Volume: } V_{ct} = 2\pi^2\eta^2 R^3 \left[1 + \frac{2\alpha}{\pi\eta} \right]$$

$$\text{Habitable Volume: } HV_{ct} = 2\pi^2\eta^2 R^3 \left[1 + \frac{2\alpha}{\pi\eta} \right]$$

$$\text{Surface Area: } SA_{ct} = 4\pi^2\eta R^2 \left[1 + \frac{\alpha}{\eta} \right]$$

$$\text{Projected Area: } PA_{ct} = 4\pi\eta R^2 \left[1 + \frac{\alpha}{2\eta} \right]$$

$$\begin{aligned} \text{Floor Area: } FA_{ct} = & 4\pi \left\{ \sum_{n=1}^{N1} [R(1+\eta) - 3n + 2] * \right. \\ & \left. \left[[R(6n-4) - (3n-2)^2] + \alpha R \right] + \sum_{n=N1+1}^N [R(1+\eta) - 3n + 2] [(6nR - 9\eta^2)^{1/2} + \alpha R] \right\} \end{aligned}$$

VI. CRYSTAL PALACE

$$\text{Volume: } V_{cp} = \pi^2\eta^2 NR^3 (2 + 3\eta L) \left(1 + \frac{2}{\pi} + \frac{1}{N} \right)$$

$$\text{Habitable Volume: } HV_{cp} = \pi^2\eta^2 NR^3 (2 + 3\eta L) \left(1 + \frac{2}{\pi} + \frac{1}{N} \right)$$

$$\text{Surface Area: } SA_{cp} = 4\pi^2\eta LNR^2 \left(1 + \frac{1}{2N} \right)$$

$$\text{Projected Area: } PA_{cp} = \pi\eta NR^2 \left(2 + \frac{1}{N} \right) \sum_{\lambda=1}^L [2 + \eta(1 + 2\lambda)]$$

$$\begin{aligned} \text{Floor Area: } FA_{cp} = & 2\pi N \sum_{\lambda=1}^L [2(R + 3\eta\lambda R - 2\lambda\eta R - 1)^{1/2} \\ & + (R + 3\eta\lambda R - \frac{3\eta R}{2}) \left(1 + \frac{1}{2N} \right) \eta R \\ & + 2(R + 3\eta\lambda R - 9)(6\eta R - 9)^{1/2}] \end{aligned}$$

TABLE 2. SHAPE EQUATIONS (CONTINUED)

VII. TWO-AXES-STRETCHED ELLIPSE OF REVOLUTION

Volume:
$$V_e = \frac{2\pi R^3}{3} \left\{ 3\beta^2(\alpha + \epsilon) + 3\beta(1-\beta) \left[\delta^2 - (1-\beta)^2 \right]^{\frac{1}{2}} \right. \\ \left. + 2 \left[\delta^2 - (1-\beta)^2 \right]^{\frac{3}{2}} + 3\delta^2 \beta \sin^{-1} \left(\frac{1-\beta}{\delta} \right) - \delta^3 \right\}$$

Habitable Volume:
$$HV_e = \frac{2\pi R^3}{3} \left\{ 2 \left[\delta^2 - (1-\beta)^2 \right]^{\frac{1}{2}} - 2\delta^3 \right. \\ \left. + 3\beta(1-\beta) \left[\left(\delta^2 - (1-\beta)^2 \right)^{\frac{1}{2}} + 3\delta^2 \beta \sin^{-1} \frac{1-\beta}{\delta} \right] \right\}$$

Surface Area:
$$SA_e = 4\pi \alpha R^2 + 2\pi \beta^2 R^2 \\ + \frac{\pi \epsilon}{\delta} \sum_{i=1}^{R/\Delta R} (x_1 + x_2) \left[x_1^2 - x_2^2 + 2\beta R(x_2 - x_1) \right]^{\frac{1}{2}}$$

Projected Area:
$$PA_e = 4\pi R^2 (1-\gamma) \left\{ \alpha + \frac{\epsilon}{\delta} \left[\delta^2 - (1-\gamma-\beta)^2 \right]^{\frac{1}{2}} \right\}$$

Floor Area:
$$FA_e = 4\pi \sum_{n=1}^N (R - 3n + 2.5) \left\{ \alpha R \right. \\ \left. + \frac{\epsilon}{\delta} \left[\delta^2 R^2 - (R - 3n + 2.5)^2 \right]^{\frac{1}{2}} \right\}$$

(a) Sphere

(b) Cylinder

(c) Dumbbell and
Beaded Torus (d) Circular and
Cylindrical Torus

(e) Crystal Palace

(f) Two-axis-stretched
Ellipse of Revolution

Figure 12. LEOBC Shape Candidates

is apparent that from strictly a volume consideration (Figure 13), the cylindrical structure with a very large length-to-radius ratio is the most efficient shape for a space city. This shape was the first considered by O'Neill and his students at Princeton University in 1974.¹⁷ These cities were to be 20 miles long with a 3 mile diameter. The use of enclosed volume as a governing parameter is important when the intent is to provide inhabitants a feeling of openness as is experienced on earth.

A second volume comparison factor is the amount of habitable volume in a given structure. Habitable volume is that volume which falls within a specified pseudogravity range and establishes the necessary radius to provide a habitable volume for each shape. Habitable volume as a function of radius, or the number of floors, for a pseudogravity range of 0.15 is found in Figure 14.

As surface area of a structure increases, the mass of that structure also increases. For a space station, that higher mass is reflected in an increased number of launches and, hence program costs. For these reasons the surface area of each shape is an important comparison factor, with smaller surface areas being desired. Surface area comparisons are shown in Figure 15.

Real estate acreage is a highly desirable commodity in any location. This will be especially true for the first business locations in space. The projected area of any structure can be considered its real estate, on which laboratories, offices and residences can be placed. Candidate shape projected areas are depicted in Figure 16.

Figure 13. Shapes' Volumes

Figure 14. Shapes' Habitable Volume

Figure 15. Shapes' Surface Areas

Figure 16. Shapes' Projected Areas

Floor area is an extension of the projected area in that it shows how much usable area is available or how effectively real estate is used in a given structure. This is shown in Figure 17.

Each of the previous parameters indicate how much of a given item each shape has to offer. In order to effectively compare these shapes though, a measure of efficiency is required. Therefore, various ratios were established for this purpose. Figure 18 shows how much of the total volume in a given structure falls inside the desired pseudogravity range. On the negative side, the enclosed volume which is not habitable still needs pressurization and hence increases the launches required to pressurize that structure. Therefore, the closer this ratio is to 1.0, the better the volume efficiency.

The ratio of surface area to volume or habitable volume are two other measures of efficiency that relay the level of effort necessary to construct a structure of a particular size. The lower the ratio, the fewer launches necessary to enclose a given volume. These ratios are shown in Figures 19 and 20.

The amount of real estate, or projected area, for a given shape as a percentage of surface area indicates how effective a shape is in providing actual working space. These ratios are shown in Figure 21.

Floor area per unit volume and per unit surface area show how effectively each shape can be used to provide actual working space. In both these instances, a high value is considered beneficial. These are compared in Figures 22 and 23.

In Comparing each shape, a point system was established where the highest merit is worth 10 points and each lower merit is given

Figure 17. Shapes' Floor Area

Figure 18. Ratios of Habitable Volume to Volume.

Figure 19. Shapes' Volume/Surface Area

Figure 20. Shapes' Habitable Volume/Surface Area

Figure 21. Shapes' Projected Area/Surface Area

Figure 22. Shapes' Floor Area/Volume

Figure 23. Shapes' Floor Area/Surface Area

one less point. The lowest merit, with eight shapes being compared, is given a value of three points. In cases where each shape has the same level of merit, a constant value is awarded. However, the next lowest merit is valued such that the worst shape always receives three points. It should be noted that comparisons are made based on the same number of floors and not on rotational radius. Table 4 summarizes the evaluation of each shape and shows their ranking. From this evaluation, the cylindrical torus has the highest rating. However, this shape is eliminated as a candidate due to its susceptibility to buckling.¹⁵³ For this reason, the circular torus was chosen as the shape of LEOBC's living and office space volume.

TABLE 4. SHAPE EVALUATION TABLE

	SPHERE	DUMBBELL	BEADED TORUS	CYLINDER	TORUS CIR	CYL	LEOBC	CP*
Volume	9	3	4	10	6	8	7	5
Habitable Volume	9	3	4	7	6	10	8	5
Surface Area	6	10	8	3	9	4	7	5
Projected Area	8	3	4	10	5	9	6	7
Floor Area	8	3	4	10	6	9	7	5
Habitable Volume/Volume	3	10	10	4	10	10	10	10
Surface Area/Volume	8	6	6	9	7	4	10	3
Surface Area/Habitable Volume	8	6	6	9	7	4	10	3
Projected Area/Surface Area	9	7	7	10	8	9	8	7
Floor Area/Volume	4	6	6	3	8	10	7	9
Floor Area/Surface Area	8	4	4	9	6	10	5	7
Total	80	61	63	84	78	87	85	66
Ranking	4	8	7	3	5	1	2	6

* CP = Crystal Palace

CHAPTER 5

INTERIOR DESCRIPTION AND ARRANGEMENT

LEOBC is a proposed focal point for low earth orbit business activities in the early years of the 21st century. As such, it offers 0.5 acceleration level in the areas dedicated to living quarters, recreation, offices and laboratories and low g areas for research and manufacturing concerns. It also supports co-orbiting facilities which house processes that require micro-acceleration levels below those available in LEOBC or that could pose a hazard to LEOBC personnel. It can accept the current STS orbiter in the center of its hub to provide completely shielded docking. Three major sections comprise LEOBC: torus, hub and spokes. These are discussed in greater detail below. Top and side views of LEOBC are shown in Figure 24.

TORUS

Designed as a two story structure, LEOBC's torus has a seven meter diameter with a 100 meter major radius. A seven meter minor diameter is used as it provides maximum floor space for a two story configuration with floors spaced three meters apart. Each floor has a 2.5 meter ceiling height with a 0.5 meter space between the floors for routing of utility cables and air ducts. Typical cross-sections of the torus are shown in Figure 25a. Bulkheads, shown in Figure 25b, are located approximately every 12 meters around the torus. Spacing at the torus-spoke junction is slightly less to allow for tolerance buildup and bulkhead thickness. Stairways between the first and second floors are located in every third segment, except at the torus-spoke junction. At these segments, an open platform elevator is provided to aid in moving equipment between the two floors.

Figure 24. LEOBC Top and Side Views

(a) Torus Cross Section

(b) Torus Elevation

Figure 25. LEOBC Torus Cross Section and Elevation

Beneath the first floor, integral storage tanks are included in the structural design for potable water and waste material: one for liquid only and one for liquid/solid waste.

One hundred eighty-eight bachelor units are located on the first floor to house the majority of personnel on LEOBC. A possible floor plan and wall elevations are shown in Figures 26 and 27. Furnishings include a kitchenette, writing desk with chair, a shower and commode, a bureau, closet and storage space. Twelve additional units are located on the second floor.

Single residential units are baselined for LEOBC because of the stated need for privacy from Soviet and American space crews. Additionally, private units may relieve tension and reduce illnesses thought to be increased by a feeling of crowdedness in an isolated and confined environment such as a space station.¹⁵⁶

As shown in Figure 25, the second floor is not allocated to living quarters but is left as open rooms. This is the area that can be leased for offices and gravity-oriented laboratories where results obtained from zero-g processing can be evaluated. In this manner, basic lab equipment used on Earth can be used at LEOBC without modifications. These labs will help eliminate additional STS flights required to evaluate products under development in low earth orbit. Also found on the second floor are the medical unit, central kitchen and cafeteria, recreational area, maintenance and janitorial supply room and commons areas at each spoke-torus junction. Dimensional information and total space allocation are given in Tables 5 and 6. With a population of 200 personnel, these dimensions offer an overall area per individual of 112 square meters and a volume of 369 cubic

Figure 26. LEOBC Efficiency Floor Plan

Figure 27. LEOBC Efficiency Elevations

TABLE 5. LEOBC GEOMETRIC SPECIFICATIONS

Description	Dimensions		Description	Dimensions	
Major Radius	100.00 m	328.08 ft	Surface Area		
Minor Radius	3.50	11.48	Hub	8,375 m ²	90,152 ft ²
Hub Radius	30.00	98.43	Spoke(x4)	3,299	35,506
Hub Height	40.00	131.23	Torus	13,817	148,730
Spoke Radius(max)	4.00	13.12	Volume(total)		
Floor Spacing	3.00	9.84	Hub	62,856 m ³	2,219,730 ft ³
Bulkhead Spacing	12.00	39.37	Torus	24,180	853,927
Floor Area & Volume					
<u>Floor</u>	<u>Radius</u>		<u>Area</u>		<u>Volume</u>
First	102.5 m	336.29 ft	3,115 m	33,961 ft ²	10,050 m ³ 354,925 ft ³
Second	99.5	326.44	3,063	32,967	8,986 32,967
Third	29.5	96.78	2,658	28,610	7,874 28,610
Fourth	26.5	86.94	3,507	37,744	8,963 37,744
Fifth	23.5	77.10	3,612	38,875	8,292 38,875
Sixth	20.5	67.26	3,444	33,074	3,444 33,074
Seventh	17.5	57.41	3,110	33,471	20,769 733,436
			22,549 m ²	424,702 ft ²	73,837 m ³ 2,607,520 ft ³

TABLE 6. LEOBC SPACE ALLOCATIONS (TORUS ONLY)

Function	First Floor		
	<u># of Units</u>	<u>Area/Unit</u>	<u>Total Area</u>
Residence	188	10.49 m ²	1,972.55 m ²
Commercial	-	-	-
Commons	4	62.55	250.20
Kitchen	-	-	-
Dining	-	-	-
Recreation	2	20.91	41.82
	4*	62.55	250.20
	-	-	-
Medical	-	-	-
Maintenance	-	-	-
Total	194		2,257.56 m ²
Second Floor			
Residence	12	10.19 m ²	122.2 m ²
Commercial	81	20.30 -	1,664.60
Commons	4	54.15	218.36
Kitchen	1	20.30	20.30
Dining	2	20.30	40.60
Recreation	2	20.30	40.60
	4*	54.15	218.36
	2	20.30	40.60
Medical	1	20.30	20.30
Maintenance	1	20.30	10.15
Total	106		2,146.85

*These are multi-use units, first listed under Commons and Dining.

meters. This is 42% more area and 54% more volume per individual than was recommended by the 1977 Summer Study conducted at the NASA Ames Research Center.¹⁵³ For habitats of 100 people, they recommended 79.1 m^2 and 240 m^3 when personnel are staying on board for one to two years.

Sports activities in the torus can be conducted in the recreational segment. This is a four-wall, enclosed court, slightly smaller than a regulation racquetball court. It can be adapted for various sports, including basketball, racquetball, handball, volleyball, walleyball (a four-wall version of volleyball), tennis, badminton or squash. An artist's concept is seen in Figure 28.

HUB

The hub's primary function is to provide access to the rotating LEOBC and to serve as low g processing and research areas. It also houses all the mechanical services required for life support on LEOBC. This includes environmental control, waste treatment, power generation, storage facilities and cargo handling.

Extending to a radius of 30 meters, the hub's outer shell has a 10 meter long cylindrical section with elliptical end caps. These end caps have a 21-meter semi-major axis and a 10-meter semi-minor axis. The origin is located 9 meters from the axis of rotation and 5 meters above the longitudinal axis. The pressurized portion of the hub lies between the 9 meter and 30 meter radius. Inside 9 meters, a cylindrical core is open to space on one end to accept an STS orbiter. A docked orbiter is shown in LEOBC's core in Figure 29.

Inside the hub are a total of five floors where plant services, communications, storage and commercial areas are located. Water and

Figure 28. LEOBC Recreation Court

Figure 29. LEOBC Cross Section

air recycling functions are found on the outermost floor of the hub, or LEOBC's third floor. Power generation and cryogenic storage areas are found on the fourth floor. Consumables stores, maintenance shops and the control center are located on the fifth floor. Floors six and seven, with the lowest acceleration levels, are dedicated to research and manufacturing processes that do not require acceleration levels below 0.1 g. The seventh floor is also used for cargo handling and can be used for satellite repair or initial fabrication processes for orbital or interplanetary vehicles.

SPOKES

The hub and torus are connected by four spokes located every ninety degrees around the circumference of the hub. These spokes are rigidly attached to the hub and hang like stalactites toward the torus. At the torus, they ride on a suspension system that allows four degrees of freedom: radial displacement and rotation about each axis. With this type of connection, expansion of the torus due to pressurization and rotation will not transmit additional bending loads into the torus.

Inside each spoke are conduits for electricity, air, water, waste and gases required in the torus. Normally, each spoke will carry one fourth of the needs in the torus, but they are designed to handle up to half of the torus' requirements in the event that one or two spokes need to be shut down or are damaged.

In addition to utilities, there is also an elevator system in each spoke for personnel and supplies transfer. These elevators are self-contained units as the spokes are unpressurized.

CHAPTER 6

LEOBC CONSTRUCTION CONSIDERATIONS

Construction of LEOBC will require more launches than any space program previously undertaken. In estimating the number of launches necessary to bring LEOBC to full operational capability the following procedure was employed: 1) establish a baseline launch vehicle, 2) determine the number of pieces necessary to construct LEOBC, 3) assume a packing scheme for payload definition, 4) determine the number of launches necessary if STS payloads are volume-limited, 5) estimate LEOBC structural mass, 6) determine maximum number of pieces per launch based on component mass, 7) estimate internal mass, and 8) determine number of launches for mass-limited payloads carrying internal mass. These steps will allow a minimum and maximum estimate on the time necessary to contract LEOBC.

The baseline launch vehicle to be used for LEOBC construction and operational support is the current Space Transportation System. This provides the capability to lift 27,500 kg into low earth orbit in a payload envelope that is 4.572 meters in diameter and 18.288 meters long. For volume-limited launches, usable payload diameter and length are reduced to 4.40 m and 18.00 m to allow for airborne support equipment (ASE) needed to hold the payload.

The number of structural and floor panels per launch is defined as the integer value plus one of the height of an inscribed rectangle in the 4.40 meter diameter payload volume divided by a minimum spacing of 15 cm. The base of this rectangle is the width of the particular panel being carried into orbit. Mass-limited launches carry 90% of the lifting capacity as payload with the remaining 10% reserved for ASE.

In estimating the number of structural and floor panels required to construct LEOBC, payload bay dimensions and ASE allowances mentioned above were used to establish component dimensions. For the torus, structural and floor panel length of 12 meters is set by the 52 bulkheads equally spaced around the major circumference. Six of these panels, with an arc width of 60° , or 3.5 meters across the chord, are needed to complete each segment. These panels are designated T1-T6 and are shown in Figure 30. Also included are dimensions necessary to determine the packing arrangement in the STS payload bay. Four floor panels are needed per segment, two per floor. All are 12 meters long, and are half as wide as the actual floor width. These panels are designated F1a, F1b, F2a and F2b (Figure 31).

Structural panels for the hub fall into one of the following five categories:

- I Outer radius barrel
- II Small radius of curvature
- III Large radius of curvature
- IV Hub Extension
- V Inner radius barrel

These areas are highlighted in Figure 32. Categories I, III and V require one distinct panel while categories II and IV require three panels for complete definition. Individual hub structural panel planar dimensions necessary to determine payload bay stacking are shown in Figures 33 and 34. Floors in the hub span the distance between the +z and -z elliptical surfaces at radii of 29.5, 26.5, 23.5, 20.5 and 17.5 meters. Each floor, except the one located at a radius of 29.5 meters, requires two sections to span the distance and

Figure 30. LEOBC Torus Structural Panels

Figure 31. First- and Second-Floor Floor Panels

Figure 32. LEOBC Hub Structural Panels

(a) Hub Panel H1

(b) Hub Panel H2

(c) Hub Panel H3

(d) Hub Panel H4

(e) Hub Panel H5

(f) Hub Panel H6

Figure 33. Hub Structural Panels H1 through H6

(a) Hub Panel H7

(b) Hub Panel H8

(c) Hub Panel H9

Figure 34. Hub Structural Panels H7 Through H9

fit in the STS payload bay. Circumferentially, the number of panels needed for each floor varies from 60 to 36, depending on the floor radius.

A summary of panel dimensions, actual and planar, is given in Tables 7 and 8. Information includes location (radius of centroid), arc lengths, surface area, payload envelope dimensions, quantity required, number of panels per launch, number of dedicated launches required and remaining panels.

The number of panels per STS launch was determined by first assuming that volume in the payload bay was the limiting factor. This assumption should hold for the floor panels but must be validated for the structural panels. For this reason an estimate of shell thickness was made for the torus and hub panels using stress equations for pressure vessels. Wall thickness for the torus was estimated using equation 5,

$$t = \left[\frac{P_o r}{2} + \frac{P_f g}{\pi} \right] \frac{R}{\sigma_w - p g R} \quad \text{eq 5}$$

which was used to determine the Stanford Torus shell thickness.¹⁵⁷

(The calculations for determining the thicknesses of the torus and hub shells are presented in Appendix E.) Hub thicknesses for the barrel sections at radii of 30 and 9 meters are estimated by using equation 6.¹⁴⁵

$$t = \frac{1}{\sigma_w} \left[P_o R^2 + F^2 \right] \quad \text{eq 6}$$

TABLE 7. LEOBC STRUCTURAL AND FLOOR PANEL DESCRIPTION SUMMARY

COMPO- NENT	RADIUS OF CENTROID	ARC LENGTH			
		CIRCUM- FERENTIAL	RADIAL	AXIAL	AREA
T1	103.342	12.506	3.665		46.017
T2	102.895	11.347	3.665		44.957
T3	97.106	10.983	3.665		43.781
T4	96.658	10.650	3.665		42.945
T5	97.106	10.983	3.665		43.781
T6	102.895	11.347	3.665		44.957
H1	30.000	3.142		10.000	31.416
H2	29.655	12.577	3.257		40.456
H3	27.954	12.147	3.228		37.784
H4	35.426	11.205	3.214		34.201
H5	17.754	3.351	15.420		35.773
H6	8.925	3.770		10.000	37.699
H7		3.770		7.000	16.127
H8	0.000	12.566	2.000		12.566
H9	8.925	3.770	10.000		37.699
F1a,b	102.500	12.085	2.450		29.608
F2a,b	99.500	11.723	3.464		40.608
F3	29.500	3.310		14.338	47.457
F4	26.5	3.330		10.527	35.056
F5	23.5	3.281		12.234	40.142
F6	20.5	3.220		13.367	43.044
F7	17.5	3.054		14.144	43.200

TABLE 8. LEOBC STRUCTURAL AND FLOOR PANEL LAUNCH DATA SUMMARY

COMPO- NENT	DIMENSIONS (m)				QTY/ LAUNCH	NO. OF LAUNCHES	REMAINING PIECES
	a*	b*	l*	QTY			
T1	3.5	2.695	12.498	52	15	3	7
T2	3.5	2.695	12.449	52	15	3	7
T3	3.5	2.695	12.083	52	15	3	7
T4	3.5	2.695	11.717	52	15	3	7
T5	3.5	2.695	12.083	52	15	3	7
T6	3.5	2.695	12.449	52	15	3	7
H1	3.364	2.864	10.00	60	19	3	17
H2	3.210	3.028	12.475	30	20	1	10
H3	3.210	3.038	12.059	30	20	1	10
H4	3.212	3.036	11.123	30	20	1	10
H5	3.348	2.855	15.297	90	19	4	14
H6	3.742	1.339	10.000	15	8	1	7
H7	3.742	1.339	7.000	15	16	1	0
H8	4.000	4.000	0.150	1	-	-	-
H9	3.742	1.339	15.000	30	8	3	6
F1a	2.450	3.679	12.078	52	24	2	4
F1b	2.450	3.679	12.078	52	24	2	4
F2a	3.464	2.745	11.715	51	18	2	15
F2b	3.464	2.745	11.715	51	18	2	15
F3	3.088	3.135	14.338	60	20	3	0
F4	3.328	2.878	10.527	100	19	5	5
F5	3.279	2.934	12.234	90	19	4	14
F6	3.217	3.002	13.356	80	20	4	0
F7	3.050	3.171	14.144	72	21	3	9
Spoke	4.250	4.250	18.500	4	1	4	0
Number of Full, Single Component Launches						60	
Number of Partial or Mixed Component Launches						11	

where,

$$F = \begin{cases} \frac{P_0(R_o^2 - R_i^2)}{2\bar{R}} \left[\frac{\bar{R} - R_i}{R_o - R_i} \right] & \text{for } R = 30 \\ \frac{P_0(R_o^2 - R_i^2)}{2\bar{R}} \left[\frac{R_i - \bar{R}}{R_o - R_i} \right] & \text{for } R = 9 \end{cases} \quad \text{eq 7}$$

For the elliptical surface, equation 8 was used.¹⁵⁸

$$t = \frac{P_0 R_2}{2\sigma_w} \left[5 - \frac{4R_2}{R_1} + \left(\frac{R_2}{R_1} \right)^2 \right]^{1/2} \quad \text{eq 8}$$

Panel thicknesses versus pressure, as predicted by these equations are plotted in Figure 35. Since the thickness of panels H2 through H5 are a function of radius, an area-weighted average thickness is plotted. Panel H5 is so much thicker than the others because equation 8 does not produce reliable results as the surface in question becomes perpendicular to the axis of revolution.¹⁵⁸

A more detailed analysis of the H5 panel area would utilize finite element analysis to obtain a more accurate thickness profile. Another approach would be to use a skin-stringer construction rather than stressed skin. These alternatives would be explored in the next phase of concept development but are beyond the scope of this paper. For the purpose of estimating the number of launches for construction, a goal of one H5 panel per launch has been established.

In addition to pressure considerations, radiation protection from three sources (Van Allen Belt, solar and cosmic) needs to be considered when establishing a primary structural thickness for any space station. Unfortunately, each type of radiation requires

Figure 35. LEOBC Thickness for Various Pressures and Altitudes with Constant Radiation Exposure Levels.

different counter measures to reduce the hazards. Van Allen Belt radiation is effectively reduced as structural thickness is increased to a point where mass per unit area reaches $10\text{--}25 \text{ g/cm}^2$.¹⁵⁹ Solar flare particles require much greater thicknesses for protection and may call for a special "storm cellar." Cosmic radiation, however, becomes a greater danger source as thickness increases due to the increased probability of collisions with structural material atoms. The solution to this problem is still an open issue and its resolution is beyond the scope of this paper. However, to illustrate the impact that radiation protection has on station design, aluminum skin thickness as a function of orbital altitude is plotted for two dose limits over six months in conjunction with thickness variation as a function of pressure in Figure 35. From this comparison, it can be seen that, depending on altitude, radiation can be the driving requirement for establishing a minimum structural thickness for some of the LEOBC structural panels. For this reason, panel thickness is based on an internal pressure of 1 atm or a minimum thickness of 7 cm. The exception to this is panel H9, which is an internal panel and not directly exposed to cosmic radiation. Final panel thicknesses and mass per unit area are shown in Figure 36. Number of panels per launch is shown in Figure 37. These thickness estimates increase the number of launches from 61, as estimated by volume-limited payloads, to 254. This data is summarized in Table 9.

Four additional launches will be necessary to place the spokes in orbit. Each spoke is designed to fit into the STS payload bay by telescoping down to 17.5 meters from an extended length of 70 meters (Fig. 38).

Figure 36. Structural Panel Mass

Figure 37. LEOBC Panels Per STS Launch

TABLE 9. REVISED LEOBC STRUCTURAL AND FLOOR PANEL LAUNCH DATA SUMMARY

COMPO- NENT	DIMENSIONS (m)				QTY/ LAUNCH	NO. OF LAUNCHES	REMAINING PIECES
	a	b	l	QTY			
T1	3.5	2.695	12.498	52	3	17	1
T2	3.5	2.695	12.449	52	3	17	1
T3	3.5	2.695	12.083	52	3	17	1
T4	3.5	2.695	11.717	52	3	17	1
T5	3.5	2.695	12.083	52	3	17	1
T6	3.5	2.695	12.449	52	3	17	1
H1	3.364	2.864	10.00	60	4	15	0
H2	3.210	3.028	12.475	30	1	30	0
H3	3.210	3.038	12.059	30	2	15	0
H4	3.212	3.036	11.123	30	4	7	2
H5	3.348	2.855	5.297	90	1	90	0
H6	3.742	1.339	10.000	15	8	1	7
H7	3.742	1.339	7.000	15	16	1	0
H8	4.000	4.000	0.150	1	-	-	-
H9	3.742	1.339	15.000	30	4	7	2
F1a	2.450	3.679	12.078	52	24	2	4
F1b	2.450	3.679	12.078	52	24	2	4
F2a	3.464	2.745	11.715	51	18	2	15
F2b	3.464	2.745	11.715	51	18	2	15
F3	3.088	3.135	14.338	60	20	3	0
F4	3.328	2.878	10.527	100	19	5	5
F5	3.279	2.934	12.234	90	19	4	14
F6	3.217	3.002	13.356	80	20	4	0
F7	3.050	3.171	14.144	72	21	3	9
Spokes	4.25	4.25	18.00	4	1	4	0
Number of Full, Single Component Launches						254	
Number of Partial or Mixed Component Launches						8	

TABLE 10 SUBSYSTEM OPTIONS

LIFE SUPPORT	POWER GENERATION	THERMAL CONTROL
CLOSED SYSTEM	SOLAR CELLS	PASSIVE
PARTIALLY REGENERATIVE	FUEL CELLS	ACTIVE
OPEN SYSTEM	NUCLEAR	
CENTRALIZED	RANKING CYCLE	
LOCALIZED	GRAYTON CYCLE

Figure 38. LEOBC Telescopic Spoke

Interior furnishings, water and atmosphere necessary to bring LEOBC into full operational capability will require even more launches. Since these items have a density greater than the average density for a mass-limited launch, the number of launches required will be estimated assuming that 90% of the STS payload will be usable payload. Interior furnishings mass is estimated by using the established floor design load of 300 kg/m^2 and a 25% load factor. The resulting 75 kg/m^2 value is then multiplied by the total floor area inside LEOBC, giving an internal furnishing mass of 1,691,200 kg. A minimum of sixty-four STS launches will be required to bring this material to LEOBC. The calculations for estimating internal mass are found in Appendix E.

For comparison, the NASA Ames Research Center sponsored study in 1977 used a value of 43,000 kg per person for internal mass approximations.¹⁵³ Using this for LEOBC would result in an internal mass of 8,600,000 kg, which is five times greater than proposed. The use of the lower value for LEOBC is justified by observing that in most office areas less than half the floor space is occupied by furniture and that approximately half of the area in LEOBC's torus is left unfurnished. Also the basis for the 43,000 kg factor was the 1975 NASA Ames Study where interior furnishings were manufactured from residual material from processed lunar ore. This material is much denser than wood, plastic and corrugated panels which will comprise most of LEOBC's furnishings.

Specific subsystems, such as life support, power, and thermal control, are contributory variables to any space station design as it relates to total mass and final configuration (see Table 10).

However, the trade studies and final selection for each subsystem are beyond the scope of this project. Therefore, a generic approach was taken in establishing internal mass by assuming that all materials and subsystems to be brought on board LEOBC are included in the nominal floor loading parameter of 75 kg/m^2 .

Potable water, which will be stored in the torus as shown in Appendix E, adds an additional 584,100 kg to the mass which must be transported to LEOBC. Due to excess lift capability when launching panels T1-T6, H2 and H9, 3770 kg of water will be carried aloft in a spherical tank with a 1.0 meter radius filled to 90% capacity. One tank per flight can be carried with panels T1-T6 and H9 while two tanks can be carried on each H2 flight. Thus, water will be carried on all 104 launches necessary to put panels T1-T6 on orbit and 26 of the 30 required to put H2 panels on orbit.

The amount of oxygen and nitrogen necessary to pressurize LEOBC to 1.0 atm totals 88,146 kg. By dedicating full-lift capability to atmospheric cryogenics, 21,240 kg of nitrogen and 5310 kg of oxygen can be taken to LEOBC on each launch. Four launches will then be necessary to pressurize LEOBC with the excess from the fourth launch providing a 20.5% reserve of oxygen and nitrogen on board.

In total, the number of launches necessary to bring LEOBC to full operational capability (FOC) is 334. An estimated waterfall timeline showing activities to FOC is shown in Figure 39 along with major milestones. Assumptions used for this estimate include:

- o a two year design phase for the floor panels,
- o a five year design phase for the structural shell,
- o a new production line opening every six months,

- o a fabrication rate of one panel per month,
- o and a six month processing period from manufacture of the last panel per payload and the subsequent STS launch.

Material launches are set at one month centers with crew and supplies sent aloft on parallel flights. Initial operational capability (IOC) can be established when LEOBC is pressurized and life support, guidance, navigation and control subsystems have been placed on board.

CHAPTER 7

CLOSING REMARKS

Since this effort was initiated, three key developments have occurred which bring LEOBC closer to reality: 1) the Space Transportation System has achieved operational status, 2) the President of the United States has approved a Space Station program for NASA and 3) Commercialization of Space has begun to emerge and is seen as a major economic industry by 2000.

NASA's Space Transportation System's first launch was on April 12, 1981, and has been followed by twelve missions. During these missions, Space Shuttle crew members have deployed satellites, retrieved free-flying pallets and errant satellites, repaired spacecraft, redeployed spacecraft, proven the advantages to material processing and manufacturing in zero-g environments and flown a spacelab mission. These missions and activities have proven the viability and versatility of the launch vehicle baselined to carry LEOBC components into orbit. At the same time, key areas of the STS program are being transferred from NASA's control to private corporations. This currently includes ground processing at Kennedy Space Center and, in the future, orbital operations located at Johnson Space Center. Additionally, according to J. M. Beggs, the Shuttle fleet could be owned by a private corporation by 1988 or 1989.¹⁶⁰ This could begin much earlier if current negotiations between Astrotech and NASA are successful.¹⁶¹ These negotiations are aimed at the purchase of an existing orbiter and funding production of a fifth vehicle by Astrotech. Long range goals for Astrotech call for possible ownership of the entire STS fleet.

The authorization for Space Station development by President Reagan during his 1984 State of the Union address also points to a greater level of activity in space. The establishment of Space Station as a goal says we are committed to space development and will always have a place to work in space. This is a key element to any large scale construction program in orbit such as LEOBC. Space stations are necessary for crew quarters, logistics center, preliminary zero-g experimentation, product development and production. However, as has happened with every launch vehicle and is foreseeable with the STS Orbiter, requirements always grow to meet and finally exceed current capabilities. This will most likely happen with Space Station as well.

Evidence for this possibility is presented in the 25 June 1984, Aviation Week & Space Technology issue, dedicated to Commercialization of Space. McDonnell Douglas and Johnson & Johnson are eyeing the Space Station as the location for their orbital processing and manufacturing.¹³⁴ 3M would like to use the shuttle and Space Station as a research center.¹⁶² John Deere & Co. is moving its zero-g experiments from parabolic flights to a Shuttle flight program.¹⁶³ In addition, various other companies are reviewing Joint Endeavor Agreements with NASA and other avenues to produce space-manufactured products. In all, 14 companies that are pursuing space product research and development are included in a cross-section of companies compiled by the Center for Space Policy at Cambridge, Massachussetts.¹⁶⁴

If only half of these desire to operate in Space Station, with one specialist per company on-board, the initial capacity limit of Space Station (6-10) will be reached. Thus, if the expansion into space is only partially realized, additional space stations will be needed, possibly leading to the need for an industrial park such as LEOBC with co-orbiting facilities for those processes which require minimal disturbing forces. Evaluation and testing of products could then be carried out at LEOBC in earth-typical labs.

What are the prospects for space commercialization? The Center for Space Policy projects gross annual revenues in excess of \$65 billion from specific space commercialization endeavors with \$41.6 billion coming from space processed materials.¹⁶⁵ Rockwell International projects revenues from these same areas at \$30 billion per year. Taxes, according to Center for Space Policy, would be approximately 20% of this income, or \$8.3 billion. These revenues could be used to offset additional NASA budget expenditures necessary to implement programs such as those espoused by Waltz in 1981.¹²⁵ This course was recently echoed by NASA's task force on free enterprise in Space when it said that, "The government should invest in high-leverage technologies and space facilities that encourage private investment."¹⁶⁶ In addition, White House and NASA policy statements in preparation may propose seed funding for commercial space ventures, market support for space-produced products, access to national space facilities and reduced shuttle launch fees to increase the rate of space commercialization.¹⁶⁵

These developments bring LEOBC closer to reality than it was when this project was initiated four years ago. Time and economics, as well as market requirements, will ultimately define LEOBC's location and design. The approach proposed here is but one that is compatible with currently existing hardware.

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APPENDIX A

SPACE STATION/HABITAT CONCEPTS

TABLE 11 HISTORICAL LISTING OF MANNED SATELLITE DESIGNS

1923	Herman Oberth - Conceptual description only, no drawings. First serious proposal. Suggested means of supplying artificial gravity and building in orbit.
1928	Baron Guido Von Pirquet - Conceptual design only. First concept embodying system of mutually beneficial satellites.
1928	Hermann Nordung - First design set on paper. Heavy rotating satellite with solar powered generators. Observatory positioned away from main structure.
1929	Hermann Oberth - "Spaceport" and "Fixed-Orbit Station". Designs illustrated extreme differences between structures designed for orbit and those designed for earth.
1929	Hermann Oberth - "Asteroid-Mounted Space Telescope". Suggested use of asteroid as a basic satellite structure. Orbit change produced by reaction electrodes.
1948	Ross & Smith - Twenty-four man satellite for observation, communication and research. Rotating station provided artificial gravity while movable arm permitted entrance and exit.
1951	Wherner von Braun - "Space Wheel". Concept originated in connection with "Mars Project". Originally 20-segment wheel, later changed to circular shaped rim. Largest and widest known.
1951	H. H. Koelle - This design was portion of paper taking into consideration the tie-in with orbital carrier vehicle with the objective of minimum cost. Essentially ring-shaped with spherical and cylindrical segments.
1953	K. W. Gatland - General presentation on fabrication.
1954	Krafft Ehrlicke - "Four Man Orbital Station". Concept included design of "Astrotug" for assembling station segments.
1959	Boeing Aircraft Company - Research station utilizing upper stage components and housing 12 men.

TABLE 11 (CONTINUED)

- 1959 Krafft Ehricke - "Outposts". Conceptual presentation of satellites based on Atlas-type launch vehicle with growth potential to large stations.
- 1959 Koelle, H. H., Engler, F. E. and Massey, J. W. "Design Criteria and Their Application to Economical Manned Stations".

TABLE 12 ADDITIONAL MANNED SATELLITE DESIGNS

1895	Konstantin Tsiolkovsky - Space station concept in science fiction story. Given from a technical viewpoint.
1903	Konstantin Tsiolkovsky - Included rotation for artificial gravity, the use of solar energy and a greenhouse for a closed economy into 1895 design.
1929	J. D. Bernal - Described cosmic ark for interstellar travel. Capable of supporting 10,000 people. Built from astroidal material.
1952	L. R. Shepherd - "Noah's Ark". Vehicle for interstellar travel. Oblate spheroid with artificial gravity.
1960	Freeman Dyson - Proposed habitats in heliocentric orbits which would form complete sphere about sun. This "Dyson Sphere" would use sun's energy so completely only infrared energy would escape.
1960	Kramers, S. B. and Byers, R. A. - A modular space station and support system concept presented to the IAS Manned Space Station Symposium in 1960. The station consisted of cylinder and spheres and was rotated to provide 1 g at the living area radius.
1963	Dandridge Cole - Proposed hollowing out asteroids for use as observation posts and farming.
1974	Gerard O'Neill - "Island I". A stubby cylinder 1500 feet in diameter, patterned after "Bernal Sphere". "Island III" - A four mile diameter by twenty mile long space city.
1975	1975 NASA/Ames Study Group - "Stanford Torus". Torus with approximately four mile circumference and a 400 foot minor radius. Sized for 1g at one rpm, capable of supporting 10,000 people.
1975	Krafft Ehricke - "Astropolis" and "Androcell". Large, self-contained, rotating complexes housing many inhabitants. Capable of travelling throughout and beyond solar system and duplicating other world environments in special modules.
1977	NASA/Ames Study Group - "Crystal Palace".

APPENDIX B

SPACE STATION MISSIONS

TABLE 13 SKYLAB MISSIONS

	DATE LAUNCHED DATE RETURNED	VEHICLE TYPE & NUMBER	CREW
1.	14 May 1977 12 July 1979	Skylab	-
2.	25 May 1973 22 June 1973	Skylab I (Apollo)	Pete Conrad Joseph Kerwin Paul Weitz
3.	28 July 1973 25 Sept. 1973	Skylab II (Apollo)	Alan Bean Jack Lousman Owne Barriott
4.	16 Nov. 1973 8 Feb. 1974	Skylab III (Apollo)	Gerald Carr Edward Gibson William Pogue

TABLE 14 MISSIONS TO SALYUT STATIONS

	DATE LAUNCHED DATE RETURNED	VEHICLE TYPE & NUMBER	CREW
1.	29 Sept. 1977 29 July 1982	Salyut 6	-
2.	9 Oct. 1977 11 Oct. 1977	Soyuz 25 Soyuz 25	V. Kovalenok V. Ryumin
3.	10 Dec. 1977 15 Mar. 1978	Soyuz 26 Soyuz 27	Y. Romanenko G. Grechco
4.	10 Jan. 1978 16 Jan. 1978	Soyuz 27 Soyuz 26	V. Dzhanibekov D. Makarov
5.	20 Jan. 1978 8 Feb. 1978	Progress 1	-
6.	3 Mar. 1978 10 Mar. 1978	Soyuz 28 Soyuz 28	A. Gabarev V. Remek
7.	15 Jun. 1978 2 Nov. 1978	Soyuz 29 Soyuz 31	V. Kovalenok A. Ivanchenkov
8.	27 Jun. 1978 5 July 1978	Soyuz 30 Soyuz 30	P. Klimik M. Hermaszewski
9.	July 1978 2 Aug. 1978	Progress 2	-
10.	8 Aug. 1978 24 Aug. 1978	Progress 3	-
11.	26 Aug. 1978 3 Sept. 1978	Soyuz 31 Soyuz 29	V. Bykovskiy S. Jaehn
12.	4 Oct. 1978 26 Oct. 1978	Progress 4	-
13.	25 Feb. 1979 19 Aug. 1979	Soyuz 32 Soyuz 34	V. Lyakhov V. Ryumin
14.	12 Mar. 1979 3 Apr. 1979	Progress 5	-
15.	11 Apr. 1979 11 Apr. 1979	Soyuz 33 Soyuz 33	N. Rukavistinkov G. Ivanov

TABLE 14 (CONTINUED)

	DATE LAUNCHED DATE RETURNED		VEHICLE TYPE & NUMBER	CREW
16.	13 May 1979 8 June 1979		Progress 6	-
17.	6 June 1979 13 June 1979		Soyuz 34 Soyuz 32	
18.	28 June 1979 20 July 1979		Progress 7	-
19.	16 Dec. 1979 26 March 1980		Soyuz T-1	-
20.	27 Mar. 1980 26 Apr. 1980		Progress 8	-
21.	9 Apr. 1980 11 Oct. 1980		Soyuz 35 Soyuz 37	L. Popov V. Ryumin
22.	27 Apr. 1980 22 May 1980		Progress 9	-
23.	26 May 1980 3 June 1980		Soyuz 36 Soyuz 35	V. Kubasov B. Farkas
24.	5 June 1980 9 June 1980		Soyuz T-2 Soyuz T-2	Y. Malyshev V. Aksenov
25.	23 July 1980 30 July 1980		Soyuz 37 Soyuz 36	V. Gorbalko P. Tuan
25.	29 June 1980 19 July 1980		Progress 10	-
26.	18 Sept. 1980 26 Sept. 1980		Soyuz 38 Soyuz 38	Y. Romanenko A. T. Mendez
27.	28 Sept. 1980 9 Dec. 1980		Progress 11	-
28.	27 Nov. 1980 10 Dec. 1980		Soyuz T-3 Soyuz T-3	L. Kizim G. Strekalov
29.	24 Jan. 1981 21 March 1981		Progress 12	-

TABLE 14 (CONTINUED)

	DATE LAUNCHED DATE RETURNED	VEHICLE TYPE & NUMBER	CREW
30.	12 Mar. 1981 30 May 1981	Soyuz T-4 Soyuz T-4	V. Kovalenok V. Sayinykh
31.	22 March 1981 30 March 1981	Soyuz 39 Soyuz 39	V. Dzanibekov J. Gurragcha
32.	14 May 1981 22 May 1981	Soyuz 40 Soyuz 40	L. Popov R. D. Prunariu
33.	19 April 1982	Salyut 7	-
34.	13 May 1982 10 Dec. 1982	Soyuz T-5 Soyuz T-7	A. Berezovoy V. Lebedev
35.	24 June 1982 2 July 1982	Soyuz T-6 Soyuz T-6	V. Dzanibekov A. Ivantichikov J. Chretien
36.	19 Aug. 1982 21 Aug. 1982	Soyuz T-7 Soyuz T-5	L. Popov A. Serebrov S. Sovitskaya
37.	23 May 1982 6 June 1982	Progress 13	-
38.	10 July 1982 14 Aug. 1982	Progress 14	-
39.	19 Sept. 1982 11 Oct. 1982	Progress 15	-
40.	31 Oct. 1982 13 Dec. 1982	Progress 16	-
41.	21 April 1983 22 April 1983	Soyuz T-8	V. Titov A. Serebrov G. Strekalov
42.	27 June 1983 23 Nov. 1983	Soyuz T-9 Soyuz T-9	V. Lyakhov A. Aleksandrov
43.	2 March 1983 23 Aug. 1983 19 Sept. 1983	Cosmos 1443 Cosmos 1443 Reentry Vehicle Cosmos 1443 Station tug	-

TABLE 14 (CONTINUED)

	DATE LAUNCHED DATE RETURNED	VEHICLE TYPE & NUMBER	CREW
44.	17 Aug. 1983 18 Sept. 1983	Progress 17	-
45.	20 Oct. 1983 16 Nov. 1983	Progress 18	-
46.	8 Feb. 1984 2 Oct. 1984	Soyuz T-10	L. Kizim V. Solover O. Atkov
47.	21 Feb. 1984 March 1984	Progress 19	-
48.	2 April 1984 11 April 1984	Soyuz T-11 Soyuz T-10	Y. Malyshev G. Stickalov R. Sharma
49.	15 April 1984 7 May 1984	Progress 20	-
50.	9 May 1984 26 May 1984	Progress 21	-
51.	28 May 1984 15 July 1984	Progress 22	
52.	17 July 1984 29 July 1984	Soyuz T-12 Soyuz T-12	V. Dzanibelces I. Volk S. Savitskaya
53.	14 Aug. 1984	Progress 23	-

APPENDIX C

SHAPE EQUATIONS DEVELOPMENT

In developing the basic shape equations, various methods were used. Where the equation is obvious, or common knowledge, no explanation or derivation is presented. However, when a specific approach is used, it will be identified and, in the first use, explained.

Equations are developed for each of the following parameters:

- Volume - Total enclosed volume
- Habitable Volume - That volume which lies within the region
 bounded by the ratio $\Delta g/g$
- Surface Area - Area of shell
- Projected Area - Area defined by maximum habitable volume
 width times its circumference
- Floor Area - That floor space which has a minimum
 ceiling height of two meters.

I. Sphere

A. Volume

$$V_s = \frac{4}{3} \pi R^3$$

eq 9

B. Habitable Volume

From the Theorem of Pappus, the volume of revolution is defined by equation 10 or 11.

$$V_s = 2\pi \int_F y \, dA$$

eq 10

$$V_s = 2\pi \int x \, dA$$

eq 11

If that volume is revolved about the x or y axis, respectively.

Using equation 10 and adding the limits of integration yields.

$$HV_s = 4\pi \int_0^R (2x - x^2)^{1/2} \int_{R(1-x)}^{\sqrt{R^2 - x^2}} y dy dx \quad \text{eq 12}$$

Integration by y and evaluating at y_1 and y_2 results in

$$HV_s = 2\pi \int_0^R (2x - x^2)^{1/2} [R^2(2x - x^2) - x^2] dx \quad \text{eq 13}$$

The final result is found by integrating by x and evaluating at x_1 and x_2 . This is shown in equation 14.

$$HV_s = \frac{4\pi R^3}{3} (2x - x^2)^{3/2} \quad \text{eq 14}$$

C. Surface Area

$$SA_s = 4\pi R^2 \quad \text{eq 15}$$

D. Projected Area

$$PA_s = 2\pi R_y W_y \quad \text{eq 16}$$

Where

$$R_v = R(1 - v) \quad \text{eq 17}$$

and

$$W_v = 2R(2v - v^2)^{1/2} \quad \text{eq 18}$$

therefore

$$PA_s = 4\pi R^2(1 - v)(2v - v^2)^{1/2} \quad \text{eq 19}$$

The maximum projected area for a sphere is produced when v is equal to 0.2929.

F. Floor Area

The total number of floors available in a particular sphere is determined by dividing the habitable volume height, namely vR , by the value set for floor spacing. For the

purpose of this study, this value has been set equal to three meters. Therefore, the radius, as a function of the number of floors in any spherical structure is given by equation 20.

$$R = \frac{3N+1}{Y} \quad \text{eq 20}$$

Total floor area is now determined by the summation of individual floor widths times the circumference over the total number of floors, as shown in equation 21.

$$FA_s = 2\pi \sum_{n=1}^N R_n W_n \quad \text{eq 21}$$

Where

$$R_n = R - 3n + 2 \quad \text{eq 22}$$

and

$$W_n = 2[R(6n-4) - (3n-2)] \quad \text{eq 23}$$

Following substitution of eq 22 and eq 23 into eq 21, the floor area, as a function of spherical radius and floor number, is given by eq 24.

$$FA_s = 4\pi \sum_{n=1}^N [R - 3n + 2] [R(6n - 4) - (3n - 2)^2]^{1/2} \quad \text{eq 24}$$

II. Dumbbell, Multiple Dumbbell and Beaded Torus

Equations for the multiple dumbbell and beaded torus are identical to those of the dumbbell except they contain an added multiplier, M , for the number of dumbbell pairs. For the multiple dumbbell, M may assume any real integer. However, for the beaded torus, is a discontinuous torus formed by individual spheres. In this instance, M is defined by

$$M = \text{Int} \left[\frac{\pi}{2 \sin^{-1} \eta} \right] + 1 \quad \text{eq 25}$$

and the radius necessary to accommodate M dumbbell pairs in a beaded torus is

$$R = \frac{\eta R}{\sin \frac{\pi}{2M}} \quad \text{eq 26}$$

Due to those similarities, only the dumbbell equations will be explained.

A. Volume

$$V_d = \frac{8}{3} \pi \eta^3 R^3 \quad \text{eq 27}$$

Figure 41. Dumbbell, Beaded Torus Habitat Characteristics

B. Habitable Volume

By using the disk method of integration, habitable volume is defined by

$$HV_d = \pi \int_a^b [f(x)]^2 dx \quad \text{eq 28}$$

where

$$f(x) = [\eta^2 R^2 - (x - R(1-\eta))^2]^{1/2} \quad \text{eq 29}$$

giving

$$[f(x)]^2 = 2xR(1-\eta) - R^2(1-2\eta) - x^2 \quad \text{eq 30}$$

By substituting equation 30 into equation 28, adding the limits of integration and remembering there are two volumes for each dumbbell, habitable volume is given by the integral

$$HV_d = 2\pi \int_{R(1-\eta)}^R [2xR(1-\eta) - R^2(1-2\eta) - x^2] dx \quad \text{eq 31}$$

Following integration and evaluation at the upper and lower limits, habitable volume, as a function of rotational radius, aspect ratio and gravity gradient, is

$$HV_d = \frac{2\pi R^3}{3} \left\{ 3(1-\eta)(2\eta - \eta^2) - 3(1-2\eta) - \eta[3(1-\eta) + \eta^2] \right\} \quad \text{eq 32}$$

Recalling that for the dumbbell, γ and R are chosen such that $\gamma \geq 2\eta$, the habitable volume becomes

$$HV_d = \frac{8}{3} \pi \eta^3 R^3 \quad \text{eq 33}$$

C. Surface Area

$$SA_d = 8\pi \eta^2 R^2 \quad \text{eq 34}$$

D. Projected Area

$$PA_d = 2\pi W_\gamma^2 \quad \text{eq 35}$$

where

$$W_\gamma = [\eta^2 R^2 - (\eta R - \gamma R)^2]^{\frac{1}{2}} \quad \text{eq 36}$$

therefore

$$PA_d = 2\pi R^2 (2\eta\gamma - \gamma^2) \quad \text{eq 37}$$

again, since $\gamma = 2\eta$, the maximum value of W_γ is $R\eta$, giving the maximum projected area of

$$PA_d = 2\pi \eta^2 R^2 \quad \text{eq 38}$$

E. Floor Area

For the dumbbell, and every other two-radii shape, the minor radius is given as

$$r = \frac{3N+1}{2} = \eta R \quad \text{eq 39}$$

and the floor area is

$$FA_d = 2\pi \sum_{n=1}^N \frac{W_n^2}{4} \quad \text{eq 40}$$

where

$$W_n = 2[\eta R(6n-4) - (3n-2)]^{\frac{1}{2}} \quad \text{eq 41}$$

for $R\eta \geq R - 1$, and

$$W_n = 2[6\eta nR - 9n^2]^{\frac{1}{2}} \quad \text{eq 42}$$

when $R\eta \leq R - 1$. This change occurs because the upper floors' widths are determined by their 2-meter clearance rather than their actual width. To accommodate this change in W_n , a new term, N_1 is defined,

$$N_1 = \text{Int}\left[\frac{\eta R - 2}{3} + 1\right] \quad \text{eq 43}$$

and the summation is carried out in two steps, as illustrated on the following page.

$$FA_d = 2\pi \left\{ \sum_{n=1}^{N_1} [7R(6n-4) - (3n-2)^2] + \sum_{n=N_1+1}^N [6\eta nR - 9n^2] \right\} \quad \text{eq 44}$$

III. Cylinder

A. Volume

$$V_c = \frac{4\pi R^3}{3} \left(1 + \frac{3}{4} \alpha \right) \quad \text{eq 45}$$

B. Habitable Volume

Using the Theorem of Pappus, habitable volume for a cylinder with spherical end caps is found by using 46.

$$HV_c = 4\pi \int_0^{\frac{R\alpha}{2}} \int_{R(1-v)}^R y \, dy \, dx + 4\pi \int_{\frac{R\alpha}{2}}^{R[\frac{\alpha}{2} + (2v-v^2)^{1/2}]} \int_{R(1-v)}^{[R^2 - (x - \frac{R\alpha}{2})^2]^{\frac{1}{2}}} y \, dy \, dx \quad \text{eq 46}$$

Integrating by y and evaluating at $R_1 = 0$ and $R_2 = R\alpha/2$

yields

$$HV_c = 2\pi \int_0^{\frac{R\alpha}{2}} R^2 (2v - v^2) \, dx + 2\pi \int_{\frac{R\alpha}{2}}^{R[\frac{\alpha}{2} + (2v-v^2)^{1/2}]} \left\{ R^2 [(2v - v^2) - \frac{x^2}{4}] - R\alpha x - x^2 \right\} \, dx \quad \text{eq 47}$$

This result is now integrated by x to obtain the habitable volume as a function of radius, gravity gradient and aspect ratio, as shown in equation 48.

Figure 42. Cylindrical Habitat Characteristics

$$HV_c = \frac{4}{3} \pi R^3 \left[(2\gamma - \gamma^2)^{3/2} + \frac{3\alpha}{4} (2\gamma - \gamma^2) \right] \quad \text{eq 48}$$

C. Surface Area

$$SA_c = 4\pi R^2 \left(1 + \frac{\alpha}{2} \right) \quad \text{eq 49}$$

D. Projected Area

$$PA_c = 2\pi R_\gamma W_\gamma \quad \text{eq 50}$$

Recall that $R_\gamma = R(1 - \gamma)$ and $W = R(2\gamma - \gamma^2)^{1/2}$ from equations 17 and 18. Therefore, R_γ for the cylinder is the same as for the sphere and W_γ is increased by the cylinder barrel length, αR . With these substitutions into equation 50, the projected area becomes

$$PA_c = 4\pi R^2 (1 - \gamma) \left[(2\gamma - \gamma^2)^{1/2} + \frac{\alpha}{2} \right] \quad \text{eq 51}$$

For a cylinder with spherical end caps, the maximum projected area depends on the value of γ . To be consistent with the sphere, a value of 0.2929 shall be used.

E. Floor Area

$$FA_c = 4\pi \sum_{n=1}^N R_n W_n \quad \text{eq 52}$$

Where R_n and W_n are obtained from equations 22 and 23.

Therefore, equation 52 can be written as

$$FA_c = 4\pi \sum_{n=1}^N (R-3n+2) \left\{ [R(6n-4) - (3n-2)]^{1/2} + \frac{R\alpha}{2} \right\} \quad \text{eq 53}$$

IV. Torus and Cylindrical Torus

A. Volume

1. Circular Cross-Section Torus

$$V_t = 2\pi^2 \eta^2 R^3 \quad \text{eq 54}$$

2. Cylindrical Cross-Section Torus

$$V_{ct} = 2\pi^2 \eta^2 R^3 \left(1 + \frac{2\alpha}{\pi\eta} \right) \quad \text{eq 55}$$

B. Habitable Volume

The habitable volume of a torus can be found using the shell method of integration for a volume of revolution. This is expressed as

$$V_t = 2\pi \int_a^b x [f(x)] dx \quad \text{eq 56}$$

where $f(x)$ for the circular torus is

$$f(x) = [\eta^2 R^2 - (x-R)^2]^{1/2} \quad \text{eq 57}$$

Figure 43. Toroidal Habitat Characteristics

Using the substitutions $u = x - r$ and $du = dx$, equation 56

becomes

$$V_t = 4\pi \int_{u_1 = R[\eta(1-\nu)-\nu]}^{u_2 = R\eta} (u+R) [\eta^2 R^2 - u^2] du \quad \text{eq 58}$$

Expanding this, the integral becomes

$$V_t = 4\pi \left\{ \int_{R[\eta(1-\nu)-\nu]}^{R\eta} u [\eta^2 R^2 - u^2]^{1/2} du + \int_{R[\eta(1-\nu)-\nu]}^{R\eta} R [\eta^2 R^2 - u^2]^{1/2} du \right\} \quad \text{eq 59}$$

Integrating by u and evaluating yields

$$V_t = \frac{2\pi R^3}{3} \left\{ 2[2\eta(\nu-\nu^2) + \eta^2(2\nu-\nu^2) - \nu^2]^{3/2} + 3\eta^2\pi - 3[2\eta(\nu-\nu^2) + \eta^2(2\nu-\nu^2) - \nu^2]^{1/2} - 3\eta^2 \sin^{-1} \frac{\eta(1-\nu)-\nu}{\eta} \right\} \quad \text{eq 60}$$

2. Cylindrical Torus

For the cylindrical torus, $f(x)$ is given by

$$f(x) = \frac{R\alpha}{2\eta} + [\eta^2 R^2 - (x-R)^2]^{1/2} \quad \text{eq 61}$$

and, since the volume of a cylindrical shell of height

$\alpha R/(2-\eta)$ is

$$V = \frac{\pi \alpha R^3}{2\eta} (1+\eta^2)(2\nu-\nu^2) \quad \text{eq 62}$$

The volume of the cylindrical torus can be found by adding this term to equation 61, yielding

$$V_{ct} = \frac{2\pi R^3}{3} \left\{ 2\eta (1-r^2) + \eta^2 (2r-r^2) - r^2 \right\}^{3/2} - \frac{3}{2} \left[2\eta (1-r^2) + \eta^2 (2r-r^2) - r^2 \right]^{1/2} - \frac{3}{2} \eta \sin^{-1} \frac{\eta(1-r)-r}{\eta} + \frac{3\eta^2 \pi}{4} + \frac{3}{2\eta} (1+\eta)^2 (2r-r^2) \} \quad \text{eq 63}$$

Again, as was stated for the dumbbell, the design of this type of structure is such that the entire cross-section falls within the bounds of . Therefore, by substituting $2\eta/(1+\eta)$ for in both equations 60 and 63, they reduce to equations 54 and 55 respectively.

C. Surface Area

1. Circular Torus

$$SA_t = 4\pi^2 \eta R^2 \quad \text{eq 64}$$

2. Cylindrical Torus

$$SA_{ct} = 4\pi^2 \eta R^2 \left(1 + \frac{d}{\eta} \right) \quad \text{eq 65}$$

D. Projected Area

1. Circular Torus

$$PA_t = 4\pi \eta R^2 \quad \text{eq 66}$$

2. Cylindrical Torus

$$P_{ct} = 4\pi\eta R^2 \left(1 + \frac{\alpha}{2\eta}\right) \quad \text{eq 67}$$

E. Floor Area

1. Circular Torus

The floor area for a circular torus is given by equation 68

$$FA_t = 2\pi \sum_{n=1}^N R_n W_n \quad \text{eq 68}$$

where

$$R_n = R(1+n) - 3n + 2 \quad \text{eq 69}$$

and, as was true for the dumbbell, W_n has two values

$$W_n = 2 \left[R(6n-4) - (3n-2)^2 \right]^{1/2} \quad \text{eq 70}$$

for floors beyond the radius $R+1$, and

$$W_n = 2 \left[6\eta n R - 9n^2 \right]^{1/2} \quad \text{eq 71}$$

for floors of radius less than $R+1$. Combining equations 68-71, and recalling that W_{N1} applies for all $n < N1$, where $N1 = \text{Int}\left(\frac{\eta R - 2}{3} + 1\right)$, the floor area can be found by evaluating equation 68.

$$FA_t = 4\pi \left\{ \sum_{n=1}^{N_1} [R(1+\eta) - 3n + 2] [R(6n-4) - (3n-2)^2]^{\frac{1}{2}} \right. \\ \left. + \sum_{n=N_1+1}^N [R(1+\eta) - 3n + 2] [6\eta n R - 9n^2]^{\frac{1}{2}} \right\} \quad \text{eq 72}$$

2. Cylindrical Torus

The floor area for the cylindrical torus is similar to that of the circular torus, except for the added term $R/2$ in the expression for W_n . This gives

$$FA_{ct} = 4\pi \left\{ \sum_{n=1}^{N_1} [R(1+\eta) - 3n + 2] [R(6n-4) - (3n-2)^2 + 2R] \right. \\ \left. + \sum_{n=N_1+1}^N [R(1+\eta) - 3n + 2] [(6\eta n R - 9n^2)^{\frac{1}{2}} + 2R] \right\} \quad \text{eq 73}$$

V. Crystal Palace

A. Volume

The volume of the "Crystal Palace" is determined by using the theorem of Pappus, as cited before.

$$V_{cp} = 2\pi \bar{R} A \quad \text{eq 74}$$

where A is the cross-sectional area, given by

$$A = L\eta^2 R^2 \left[\pi \left(N + \frac{1}{4} \right) + 2N \right] \quad \text{eq 75}$$

with the mean radius, $\bar{R}$ defined as

$$\bar{R} = R \left(1 + \frac{3}{2} L\eta \right) \quad \text{eq 76}$$

Figure 44. Crystal Palace Habitat Characteristics

Substituting equations 75 and 76 into equation 74 gives

$$V_{cp} = \pi^2 \eta^2 R^3 N \left(2 + 3\eta L \right) \left(1 + \frac{2}{\pi} + \frac{1}{N} \right) \quad \text{eq 77}$$

B. Habitable Volume

By definition, the habitable volume for the "Crystal Palace" is equal to the actual volume.

c. Surface Area

The surface area of a solid of revolution can be defined as the product of its perimeter and the path described by its centroid. Therefore,

$$SA_{cp} = 2\pi P \bar{R} \quad \text{eq 78}$$

where

$$P = \pi \eta L R (2N + 1) \quad \text{eq 79}$$

Multiplying equation 79 by the circumference described by the area centroid yields

$$SA_{cp} = 4\pi^2 \eta N R^2 \left(1 + \frac{1}{2N} \right) \quad \text{eq 80}$$

D. Projected Area

The projected area, as defined in Reference 8 is

$$PA_{cp} = \pi \eta N R^2 \left(2 + \frac{1}{N} \right) \sum_{l=1}^L (2 + \eta(1 + 2l)) \quad \text{eq 81}$$

E. Floor Area

Due to the design of the "Crystal Palace", floor area is calculated for a single minor radius ($r = 4$). With this limitation, floor area is

$$FA_{CP} = 2\pi N \sum_{l=1}^L \left[2(R + 2\eta lR - 2)(\eta R - 1)^{1/2} \right. \\ \left. + (R + 3\eta lR - \frac{3}{2}\eta R)(1 + \frac{1}{2N})\eta R \right. \\ \left. + 2(R + 3\eta lR - 9)(6\eta R - 9)^{1/2} \right] \quad \text{eq 82}$$

V. Two-Axis-Stretched Ellipse of Revolution

A. Volume

Using the shell method of integration, the volume is defined by using equation 54, where

$$f(x) = R\alpha + \frac{\epsilon}{\beta} \sqrt{\beta^2 R^2 - (x - \beta R)^2} \quad \text{eq 83}$$

for $\beta R < x < R$, and

$$f(x) = R(\alpha + \epsilon) \quad \text{eq 84}$$

for $0 < x < \beta R$. Substituting equations 83 and 84 into equation 56 and adding limits of integration yields

$$V_e = 4\pi \int_0^{\beta R} xR(\alpha + \epsilon) dx \\ + 4\pi \int_{\beta R}^R x \left[\alpha R + \frac{\epsilon}{\beta} \left[\beta^2 R^2 - (x - \beta R)^2 \right]^{1/2} \right] dx \quad \text{eq 85}$$

Figure 45. Two-Axis-Stretched Ellipse Characteristics

Integrating by x and evaluating gives

$$V_e = \frac{2\pi R^3}{3} \left\{ 3\beta^3(\alpha + \epsilon) + 3\beta(1-\beta)[S^2 - (1-\beta)^2]^{1/2} \right. \\ \left. + 2[S^2 - (1-\beta)^2]^{3/2} + 3S^2\beta \sin^{-1}\frac{(1-\beta)}{S} - S^3 \right\} \quad \text{eq 86}$$

B. Habitable Volume

The habitable volume of the expanded ellipse of revolution

can take on any of three configurations: 1) $\gamma > 1 - \beta$,

2) $\gamma < 1 - \beta$, and 3) $\gamma = 1 - \beta$. Each of these are developed below.

Case 1. $\gamma > 1 - \beta$

$$HV_e = 4\pi \int_{R(1-\gamma)}^{\beta R} x R(\alpha + \epsilon) dx \\ + 4\pi \int_{\beta R}^R x \left\{ R\alpha + \frac{\epsilon}{S} [S^2 R^2 - (x - \beta R)^2]^{1/2} \right\} dx \quad \text{eq 87}$$

Integration and evaluation of this case yields

$$HV_e = \frac{2\pi R^3}{3} \left\{ 3\beta^2(\alpha + \epsilon) - 3(1-\gamma)^2(\alpha + \epsilon) \right. \\ \left. + 3\beta(1-\beta)[S^2 - (1-\beta)^2]^{1/2} \right. \\ \left. + 2[S^2 - (1-\beta)^2]^{3/2} + 3S^2\beta \sin^{-1}\frac{(1-\beta)}{S} - S^3 \right\} \quad \text{eq 88}$$

Case 2. $\gamma < 1 - \beta$

$$HV_e = 4\pi \int_{R(1-\gamma)}^R \left\{ \alpha R + \frac{\epsilon}{S} [S^2 R^2 - (x - \beta R)^2]^{1/2} \right\} dx \quad \text{eq 89}$$

Integration and evaluation of Case 2 yields

$$HVe = \frac{2\pi R^3}{3} \left\{ 2[S^2 - (1-\beta)^2]^{3/2} - 2[S^2 - (1-\gamma-\beta)^2]^{3/2} \right. \\ \left. + 3\beta \left\{ (1-\beta)[S^2 - (1-\beta)^2]^{1/2} - (\gamma-\beta)[S^2 - (1-\gamma-\beta)^2]^{1/2} \right\} \right. \\ \left. + 3S^2\beta \left[\sin^{-1} \frac{(1-\beta)}{S} - \sin^{-1} \frac{(1-\gamma-\beta)}{S} \right] \right\} \quad \text{eq 90}$$

Case 3. $\gamma = 1 - \beta$

$$HVe = 4\pi \int_{\beta R}^R x \left\{ \alpha R + \frac{6}{S} [S^2 R^2 - (x - \beta R)^2]^{1/2} \right\} dx \quad \text{eq 91}$$

Integrating and evaluating equation 91 gives

$$HVe = \frac{2\pi R^3}{3} \left\{ 2[S^2 - (1-\beta)^2]^{3/2} - 2S^3 \right. \\ \left. + 3\beta [(1-\beta)(S^2 - (1-\beta)^2)]^{1/2} \right. \\ \left. + 3S^2\beta \sin^{-1} \frac{(1-\beta)}{S} \right\} \quad \text{eq 92}$$

C. Surface Area

The surface area of the two-axis-stretched ellipse of revolution is given by

$$SA_e = 4\pi\alpha R^2 + \pi\beta^2 R^2 + \sum_{K=1}^K 2\pi \bar{R}_K ds_K \quad \text{eq 93}$$

where

$$ds = [(y_2 - y_1)^2 + (x_2 - x_1)^2]^{1/2} \quad \text{eq 94}$$

and

$$\bar{R} = \frac{x_1 + x_2}{2} \quad \text{eq 95}$$

Figure 46. Differential Element ds in x - y Plane

The relationship between x_1 , x_2 , y_1 , y_2 , $\bar{R}$, and ds is shown in Figure 46. From this figure and the equation for an ellipse, y_1 can be written as

$$y_1 = \alpha R + \frac{\epsilon}{s} [s^2 R^2 - (x_1 - \beta R)^2]^{\frac{1}{2}} \quad \text{eq 96}$$

and y_2 can be written as

$$y_2 = \alpha R + \frac{\epsilon}{s} [s^2 R^2 - (x_2 - \beta R)^2]^{\frac{1}{2}} \quad \text{eq 97}$$

Substituting these values for y_1 and y_2 into equation 93 and integrating by summation over the range of R , the surface area is found to be given by

$$SA_e = 4\pi \alpha R^2 + 2\pi \beta^2 R^2 + \frac{\pi \epsilon}{s} \sum_{i=1}^I (x_i + x_{i+1}) [(x_{i+1}^2 - x_i^2) + 2\beta R (x_{i+1} - x_i)]^{\frac{1}{2}} \quad \text{eq 98}$$

D. Projected Area

As before, the projected area for the two-axis-stretched ellipse of revolution is given by

$$PA_e = 2\pi R_y W_y \quad \text{eq 99}$$

where

$$R_y = R(1 - \gamma) \quad \text{eq 100}$$

and

$$W_v = 2R \left\{ \alpha + \frac{\epsilon}{\delta} [\delta^2 - (1 - v - \beta)^2]^{1/2} \right\} \quad \text{eq 101}$$

leaving, upon substitution into equation 99,

$$PA_e = 4\pi R^2 (1 - v) \left\{ \alpha + \frac{\epsilon}{\delta} [\delta^2 - (1 - v - \beta)^2]^{1/2} \right\} \quad \text{eq 102}$$

E. Floor Area

Floor area for the two-axis-stretched ellipse of revolution is defined as

$$FA_e = 2\pi \sum_{n=1}^N R_n W_n \quad \text{eq 103}$$

where

$$R_n = R - 3n + 2.5 \quad \text{eq 104}$$

and

$$W_n = 2 \left\{ R\alpha + \frac{\epsilon}{\delta} [\delta^2 R^2 - (R - 3n + 2.5 - \beta R)^2] \right\} \quad \text{eq 105}$$

By summing over the entire number of floors in the structure, equation 105 becomes

$$FA_e = 4\pi \sum_{n=1}^N (R - 3n + 2.5) * \left\{ R\alpha + \frac{\epsilon}{\delta} [\delta^2 R^2 - (R - 3n + 2.5 - \beta R)^2] \right\}^{1/2} \quad \text{eq 106}$$

APPENDIX D

SHELL THICKNESS ESTIMATES

Shell thickness estimates were made for LEOBC to corroborate the volume-limited payload estimates used to determine the required number of launches to construct LEOBC. This was accomplished by using the equation listed below:

$$t_t = \left[\frac{P_o \eta}{2} + \frac{P_g}{\pi} \right] \frac{R}{\sigma_w - \rho g_c R} \quad \text{eq 107}$$

$$t_{h_1} = \frac{1}{\sigma_w} \left[P_o^2 R^2 + F^2 \right]^{1/2} \quad \text{eq 108}$$

$$t_{h_2} = \frac{P_o R_2}{2 \sigma_w} \left[5 - 4 \frac{R_2}{R_1} + \left(\frac{R_2}{R_1} \right)^2 \right]^{1/2} \quad \text{eq 109}$$

for the torus, cylindrical and ellipsoidal sections of the hub, respectively. The calculations follow.

Torus Thickness

For the torus, the following values hold:

$P_o = 0.58 \quad \text{atm}$	$P = 300 \text{ kg/m}^2$	$\sigma_w = 8000 \text{ psi}$
$\eta = 0.035$	$g = 0.5 \text{ g}_E$	$\rho = 2.976 \text{ g/cm}^3$
$R = 100 \quad \text{m}$	$g_c = 1$	

Substituting these values into equation 107 gives the following results:

$$t_t = \left[\frac{0.58 \text{ atm}(0.035)}{2} + \frac{300 \text{ kg/m}^2(0.5 g_E)}{\pi} \right] \frac{100 \text{ m}}{8000 \text{ psi} - 2.976 \text{ g/cm}^3(0.5 g_E)(100 \text{ m})}$$

$$= \left[\frac{0.58 \text{ atm}(1.01325 \times 10^6 \frac{\text{dynes/cm}^2}{\text{atm}})(0.035)}{2} + \frac{300 \text{ kg/m}^2(9.8 \text{ m/sec}^2/g_E)(0.5 g_E)(10 \frac{\text{dynes/cm}^2}{\text{N/m}^2})}{\pi} \right] *$$

$$\left[\frac{100 \text{ m} \left(\frac{100 \text{ cm}}{\text{m}} \right)}{8000 \text{ psi} \left(\frac{68947.6 \text{ dynes/cm}^2}{\text{psi}} \right) - 2.976 \text{ g/cm}^3(0.5 g_E) \left(\frac{980 \text{ cm}}{\text{sec}^2} \right) (10000 \text{ cm})} \right]$$

$$= \underline{0.27865 \text{ cm}}$$

Cylindrical Section Thickness

Thickness of the cylindrical sections at radii of 30 and 9 meters is estimated by combining stresses for an internally or externally pressurized tube and for a tube with uniform axial pull. Thickness is first estimated for the pressure case.

Where

$$\rho = 0.58 \text{ atm,}$$

$$\sigma_w = 8000 \text{ psi}$$

$$\text{and } R = 30 \text{ m and } 9\text{m}$$

Therefore

$$t_{30} = 3.1373 \text{ cm}$$

And

$$t_9 = 0.9592 \text{ cm}$$

The axial load on the inner and outer cylinders was found by replacing the axial pressure load by a resultant force at the centroid radius and solving for F_1 , and F_2 (see Figure 46f). P , F_1 , and F_2 have the dimensions atm-meter.

$$F_1 + F_2 = R = \pi P_o (R_o^2 - R_i^2)$$

$$R_o F_1 + R_i F_2 - R \bar{R} = 0$$

$$\bar{R} = \frac{\sum A_r R}{\sum A_r}$$

Figure 47. LEOBC Hub Pressure Resolution

Cylindrical Section Thickness

Thickness of the cylindrical sections at radii of 30 and 9 meters is estimated by combining stresses for an internally or externally pressurized tube with uniform axial load. The internal pressure and material working stress are the same as from the torus.

The axial load on the inner and outer cylinders was found by replacing the axial pressure load by a resultant force at the centroid radius and solving for F_1 and F_2 (see Figure 47). The dimensions of F_1 and F_2 are atm-meters.

$$F_1 = R \left(\frac{\bar{R} - R_i}{R_o - R_i} \right) \quad \text{eq 110}$$

$$F_2 = R \left(1 - \frac{\bar{R} - R_i}{R_o - R_i} \right) \quad \text{eq 111}$$

The thickness is then found by substituting the expression for the resultant pressure load, R (equation 112), into equation 110 and 111, and dividing by the working stress. The expressions for thickness due to the axial load are given by equation 113 and 114.

$$R = \frac{P_o \pi (R_o^2 - R_i^2)}{2 \pi \bar{R}} \quad \text{eq 112}$$

$$t_i = \frac{P_o}{\bar{R} \sigma_w} (R_o + R_i)(R_o - \bar{R}) \quad \text{eq 113}$$

$$t_o = \frac{P_o}{\bar{R} \sigma_w} (R_o + R_i)(\bar{R} - R_i) \quad \text{eq 114}$$

These expressions are then combined with the expressions for thickness due to the hoop stress by taking the square root of the sum of the squares of the thicknesses (equation 115).

$$t = \sqrt{t_h^2 + t_a^2} \quad \text{eq 115}$$

The final expressions for the cylindrical section thicknesses are given by equations 116 and 117.

$$t_i = \frac{P_o}{\sigma_w} \left[\frac{(R_o + R_i)^2 (R_o - \bar{R})^2}{\bar{R}^2} + R_i^2 \right]^{1/2} \quad \text{eq 116}$$

$$t_o = \frac{P_o}{\sigma_w} \left[\frac{(R_o + R_i)^2 (R_i - \bar{R})^2}{\bar{R}^2} + R_o^2 \right]^{1/2} \quad \text{eq 117}$$

These equations give an estimated thickness of 1.29 cm and 4.03 cm for the inner and outer cylindrical walls, respectively. The resultant pressure load is applied at a radius of 21.949 m.

Elliptical Dome Thickness

Thickness for the ellipse of revolution surface is estimated using the equation for any smooth figure of revolution as given in Reference 169. The problem with this equation is that it breaks down as R_2 approaches infinity and it assumes tangential support only. Since the surface in question has axial support at the inner radius where R_2 also approaches infinity, a weighted average for each section is used in determining mass estimates. (equation 118)

$$t_{\text{weighted average}} = \frac{\sum A t}{\sum A} \quad \text{eq 118}$$

where R_1 is the radius of curvature of the meridian and R_2 is the distance measured along the normal to the shell to the axis of revolution. The radius of curvature, from reference 169 is

$$R_1 = \frac{[1 + (dy/dx)^2]^{3/2}}{d^2y/dx^2} \quad \text{eq 119}$$

where y is the function shown in equation 120.

$$y = \frac{b}{a} [a^2 - (x-h)^2]^{1/2} + k \quad \text{eq 120}$$

The first and second derivatives, with respect to x are

$$\frac{dy}{dx} = -\frac{b}{a} (x-h) [a^2 - (x-h)^2]^{-1/2} \quad \text{eq 121}$$

$$\frac{d^2y}{dx^2} = -\frac{b}{a} \left\{ (x-h)^2 [a^2 - (x-h)^2]^{-3/2} + [a^2 - (x-h)^2]^{-1/2} \right\} \quad \text{eq 122}$$

Therefore,

$$R_1 = \frac{1 + \frac{b^2}{a^2} (x-h)^2}{-b/a \left\{ (x-h)^2 [a^2 - (x-h)^2]^{-3/2} + [a^2 - (x-h)^2]^{-1/2} \right\}} \quad \text{eq 123}$$

The distance between the surface of revolution and the axis, along a normal to the surface, R_2 is found by solving for the slope of the normal at x , finding the intercept of the axis of revolution and solving for the distance.

The slope of the normal is given by the negative inverse of the curve, or

$$m_n = -\frac{1}{m_c} \quad \text{eq 124}$$

$$m_n = -\frac{1}{dy/dx} \quad \text{eq 125}$$

From the equation of a line, equation 126, the intercept with the axis of revolution is given as

$$y = mx + b \quad \text{eq 126}$$

$$b = y - mx \quad \text{eq 127}$$

The distance between the surface and the axis of revolution is

$$d = [(x_1 - x_2)^2 + (y_2 - y_1)^2]^{1/2} \quad \text{eq 128}$$

where x_1 is the x-coordinate of the point of interest on the curve, x_2 is 0, y_1 is the y-coordinate of the point of interest on the curve and y_2 is the y-intercept at the axis of revolution. Therefore,

$$R_2 = \{x_1^2 + [y_1 - (y_1 - mx)]^2\}^{1/2} \quad \text{eq 129}$$

Simplifying, this becomes

$$R_2 = x [1 + m^2]^{1/2} \quad \text{eq 130}$$

Substituting the inverse of the expression for the slope of the curve from equation 121 into equation 130, R_2 becomes

$$R_1 = x \left[1 + \frac{a^2}{b^2} \left(\frac{a^2 - (x-h)^2}{(x-h)^2} \right) \right]^{1/2} \quad \text{eq 131}$$

Now that R_1 and R_2 are defined, thickness can be estimated as a function of hub radius. Combining t_1 and t_2 into an equivalent thickness as before, solving for t and replacing eq by w yields

$$t = \frac{P_0 R_2}{2 \sigma_w} \left[5 - \frac{4 R_2}{R_1} + \left(\frac{R_2}{R_1} \right)^2 \right]^{1/2} \quad \text{eq 132}$$

Since this gives a varying thickness as a function of radius, a weighted average thickness is found using equation 133

$$t_{wa} = \frac{\sum_{i=1}^n \frac{P_0 R_2}{2 \sigma_w} \left[5 - \frac{4 R_2}{R_1} + \left(\frac{R_2}{R_1} \right)^2 \right]^{1/2} * 2 \pi \bar{R}_i ds^2}{\sum_{i=1}^n 2 \pi \bar{R}_i ds^2} \quad \text{eq 133}$$

where R_i and ds are as defined by equation 94 and 95 of Appendix C.

APPENDIX E

LEOBC INTERNAL MASS CALCULATIONS

Internal Furnishings

Internal furnishings mass is found by assuming a loading factor of 25% on the floor load design value of 300 kg/m^2 . Total floor area for LEOBC is given in Table TBD as $22,549 \text{ m}^2$. Therefore

$$\begin{aligned} M_{if} &= 0.25 * 300 \frac{\text{kg}}{\text{m}^2} * 22549 \text{ m}^2 \\ &= 1,691,175 \text{ Kg} \end{aligned} \quad \text{eq 134}$$

Atmospheric Mass

Atmospheric mass is determined using ideal gas relationships, this is appropriate due to the low pressures and temperatures involved.

$$n = \frac{P_o V}{RT} \quad \text{eq 135}$$

Where n is the number of moles, R is the universal gas constant, the internal pressure and V is the total volume. For LEOBC, the following values are applicable:

$$\begin{aligned} P_o &= 0.58 \text{ atm} & R &= 0.082057 \frac{\text{Latm}}{\text{°Kgmole}} \\ V &= 73837 \text{ m}^3 & T &= 21^\circ\text{C} \\ n &= 28.8 \text{ g/gmole} \end{aligned}$$

Therefore, the number of moles required is

$$n = 1,775,166.4 \text{ gmole}$$

The mass is found by multiplying the number of moles by the gram formula mass of LEOBC's atmosphere. Since the composition is 20% oxygen and 80% nitrogen, this is

$$\begin{aligned} m &= 0.8(28) + 0.2(32) \\ &= 28.8 \text{ g/mole} \end{aligned} \quad \text{eq 136}$$

The total atmospheric mass is now found to be

$$m = \frac{28.8 \times 1,775,166.4}{1000} = 51,124.8 \text{ kg}$$

Water Mass

The maximum water mass on board LEOBC is limited by the holding tank in the torus. As discussed in the text, this tank is beneath the first floor and is 2 meters wide. Its height is limited to 1 meter with a nominal fill depth of 0.5 meters. (Figure 48) Volume is found by using disk method of summation such that

$$V = \sum_{n=1}^N \pi (\bar{R}_1^2 - \bar{R}_2^2) \Delta x \quad \text{eq 137}$$

Where $\bar{R}_2 = 103\text{m}$, $\Delta x = 0.01$ and

$$\bar{R}_1 = \frac{200 + [(3.5 - x_1)^2 + (3.5 - x_2)^2]^{1/2}}{2} \quad \text{eq 138}$$

Figure 48. LEOBC Potable Water Tank

From this we find a water tank volume of

$$V = 587,343 \text{ m}^3$$

Since water has a density of 1000 kg/m^3 , a total of 587,343 kg can be stored on LEOBC. LEOBC will be considered operational when half of this water is onboard.