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Single Launch Lunar Habitat Derived From NSTS External Tank

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Abbreviations and Acronyms

amu	atomic mass unit
ATHC	air temperature and humidity control
BFO	blood-forming organs
BRYNTRN	baryon transport
CREME	cosmic ray effects on microelectronics
dia	diameter
ECLS	environmental control and life support
ELV	expendable launch vehicle
ET	external tank
EVA	extravehicular activity
GCR	galactic cosmic ray
GH_2	gaseous hydrogen
GO_2	gaseous oxygen
HLLV	heavy-lift launch vehicle
ISF	industrial space facility
IVA	intravehicular activity
LEO	low Earth orbit
LH_2	liquid hydrogen
LLO	low lunar orbit
LO_2	liquid oxygen
NSTS	National Space Transportation System
OMS	orbital maneuvering system
OMV	orbital maneuvering vehicle
rem	roentgen equivalent man
PLSS	portable life support system
SOFI	spray-on foam insulation
SRB	solid rocket booster
TCS	thermal control system

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Summary

Using current technology, the National Space Transportation System (NSTS) provides a means of placing a large-volume propellant tank in low Earth orbit (LEO) that can be partially disassembled by extravehicular activity (EVA) and the liquid oxygen tank-intertank subsystem outfitted as a lunar habitat at Space Station *Freedom*. The previous addition of a resource node, air lock, and environmental control and life support (ECLS) module to Space Station *Freedom* will permit maximum use of intravehicular activity (IVA) for outfitting the habitat's interior. Additional aids for assembling the habitat include an orbital maneuvering vehicle (OMV) and a mobile servicing center with robotic end effectors which will reduce the amount of EVA required.

A single launch of the NSTS orbiter can place the external tank in LEO, provide orbiter astronauts for the disassembly of the external tank, and transport the required subsystem hardware for outfitting the lunar habitat. Two unmanned heavy-lift launch vehicles could transport propellant-filled tanks to LEO for plug-in assembly with the habitat just prior to launch. The habitat-propulsion subsystem is capable of propelling the lunar habitat from LEO and then soft-landing the habitat on the lunar surface. Lunar surface site preparation is not required. The postlanded operations will require the astronauts to assemble a radiator panel, the possible installation of a secondary power system, and the addition of regolith by conveyor for radiation shielding prior to occupancy.

The feasibility of supplying the lunar habitat with personnel and equipment is contingent on the availability of space transfer vehicles and a lunar lander.

1. Introduction

The National Space Transportation System (NSTS) consists of an orbiter, external tank, and two solid rocket boosters as shown in figure 1.1. The solid rocket boosters are used for approximately 2 min during each launch and are recovered. The NSTS external tank is an expendable structure used for approximately 8.5 min during each launch to provide liquid oxygen (LO_2) and liquid hydrogen (LH_2) to the main engines of the orbiter (ref. 1). The tank is designed to carry sufficient propellant to enable it (attached to the orbiter) to reach low Earth orbit (LEO). At present, the external tanks are jettisoned just prior to LEO insertion and subsequently tumble and break up in the atmosphere before falling over open seas. A concept is described for placing an external tank in orbit, making the assembly safe, separating the LH_2 tank from the intertank, and outfitting the LO_2 tank-intertank unit as a lunar habitat.

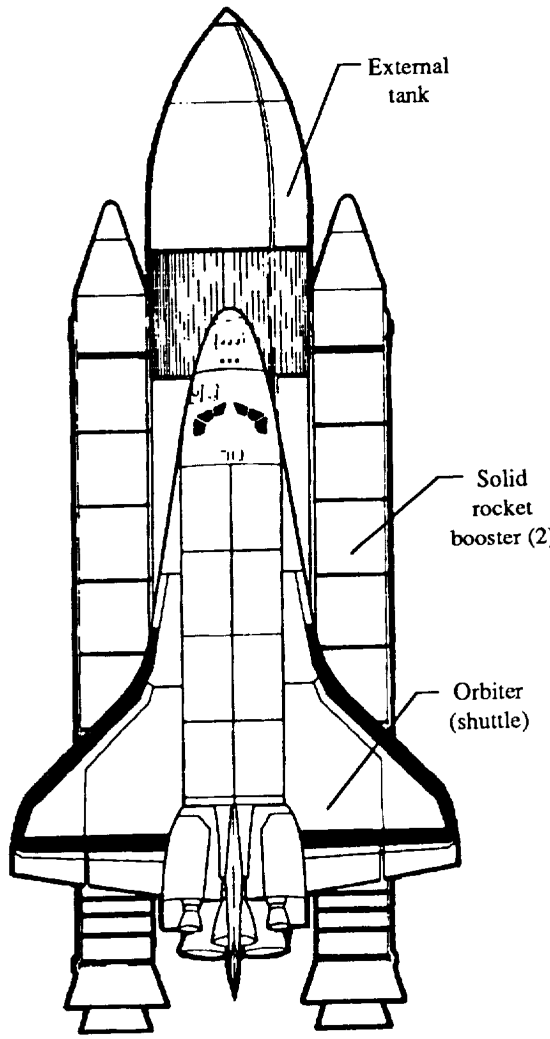

Figure 1.1. National Space Transportation System (NSTS). (Adapted from ref. 1.)

1.1. Description of External Tank

The external tank is an assembly of two pressure vessels joined by a cylindrical intertank structure. The ogive-shaped forward tank contains LO_2 and the aft cylindrical tank contains LH_2 for supply to the three main engines of the orbiter. The external tank is 27.5 ft in diameter by 153.8 ft in length with an empty weight of 69 000 lb. The pressure vessels are fabricated of chemically milled aluminum plate with fusion-welded seams. Figure 1.2 (adapted from refs. 2 and 3) shows the subassemblies of the external tank and their sizes and masses. The proposed lunar habitat would use the subassembly of the intertank joined with the LO_2 tank.

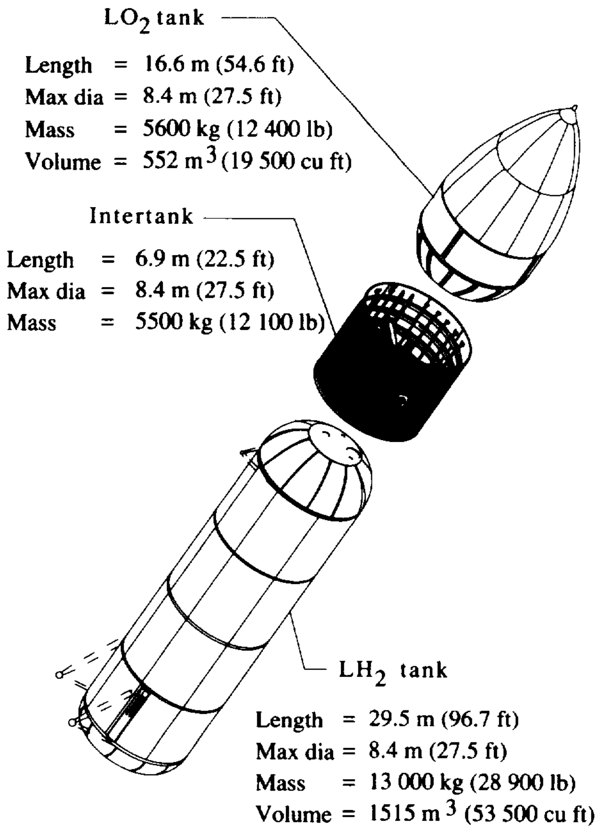

Figure 1.2. NSTS external tank subassemblies. (Adapted from refs. 2 and 3.)

1.2. Rationale for Using External Tank as Lunar Habitat

The capability of placing an external tank plus the payload of the orbiter into low Earth orbit in a single launch is within current NSTS technology. The LO_2 tank-intertank subassembly appears to have a sufficient pressure-tight habitable volume which could house a 12-man crew. The installation of flooring, instrumentation, and subsystem components could provide a lunar habitat which could be propelled from low Earth orbit to soft-land on the lunar surface. The base of the intertank would provide excellent structural support to position the tank vertically on the lunar terrain.

The LH_2 tank is much larger than the LO_2 tank and it also could be considered for use as a lunar habitat but further study would be required to consider soft-landing the LH_2 tank on the lunar surface without damage.

Many questions arose as to the usability of the spent external tank after achieving low Earth orbit and how it could be outfitted with what type of subsystems to provide a continuing life-support capability on the lunar surface. Section 1.3 outlines the study objectives which were accomplished to determine the feasibility of a lunar habitat assembled from a LO_2 tank-intertank subassembly.

1.3. Study Objectives

A study was conducted to determine the feasibility of outfitting a portion of an NSTS external tank in low Earth orbit as a lunar habitat and transporting it to the lunar surface. The objectives were as follows:

- Determine methods of installation and assembly of subsystems hardware and components for the lunar habitat
- Examine low Earth orbit assembly node operations
- Determine micrometeoroid and radiation protection requirements
- Propose an environmental-control and life-support system for a 12-man lunar habitat
- Establish thermal control for a lunar habitat
- Propose a self-contained propulsion system for the lunar habitat
- Review the space transportation infrastructure to support the lunar habitat
- Determine the as-landed operations of the lunar habitat
- Estimate the EVA and IVA requirements for in-orbit assembly of the lunar habitat

These study areas are discussed in detail in later sections of the report.

For completeness, other areas were examined such as ascent heating effects. The effect of ascent heating on the structural integrity of the external tank was reviewed to assure the LO_2 tank-intertank subsystem was suitable for reuse as a pressurized lunar habitat. Several specialists were contacted within NASA, Martin Marietta Manned Space Systems, U.S. Air Force, and the Space Studies Institute regarding ascent heating effects. The information that was obtained indicated that the external tank is not thermally or structurally degraded to the extent that it would prevent its reuse for orbital applications but further analysis is required.

1.4. Mission Description

The use of external tanks for research and development applications by the United States private sector is encouraged by a presidential directive issued in 1988 (ref. 4). An external tank is normally expended with each NSTS orbiter flight and is available for other uses after providing its contained propellants for the propulsion needs of the orbiter. One proposed use of an expended external tank is to equip its

LO_2 tank-intertank subassembly as a lunar habitat in low Earth orbit. The outfitting of the habitat and checkout processes would take place at Space Station *Freedom* or an assembly platform in LEO. The habitat's self-contained propulsion system would propel the habitat from LEO and autonomously land on the lunar surface. The crew and supplies would be transported from LEO to the habitat via space transfer vehicles and lunar landers. The habitat would require periodic resupply on a nominal 70-day basis for a crew of 12.

A mission time line is identified in figure 1.3. Establishing a permanently inhabited lunar base by the year 2000 is contingent on the development of an orbital maneuvering vehicle, a space transfer vehicle with lunar lander, and Space Station *Freedom* or a spacecraft assembly platform in LEO.

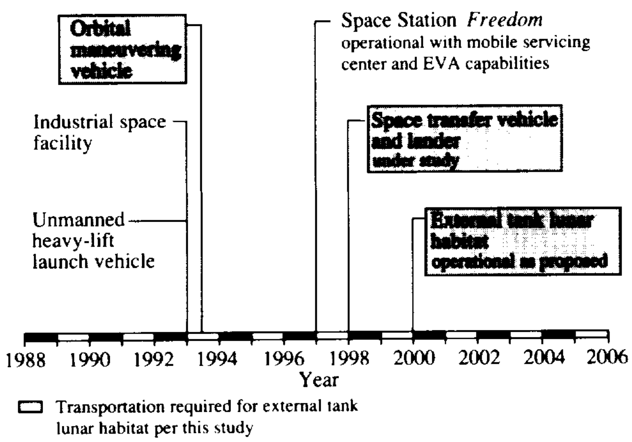

Figure 1.3. Projected space transportation infrastructure for lunar habitat.

The lunar habitat would serve as a lunar base from which activities such as the following could originate:

The lunar habitat would provide a means of understanding the physiological adaptive responses of human beings when subjected to reduced gravitational forces on the moon (1/6 of Earth's gravity)

Additional lunar habitats could be added in close proximity to the lunar base to provide redundant habitat facilities or to increase the crew size accommodations of the lunar base

A separate lunar habitat could be equipped as a laboratory for conducting laboratory experiments to reduce risks to the crew in the event of an experiment malfunction

Additional lunar habitats could be landed to serve as outposts within roundtrip travel distances of a lunar surface vehicle from the lunar base. An outpost habitat could be located on the far side of the moon and serve as an observatory

The lunar habitat concept can provide a generic habitable volume for a crew to support any lunar surface activity

2. Habitat System/Component Mass and Volume Estimates

Brief conceptual design studies were performed in sufficient detail to provide estimates of the mass and volume requirements of various systems and support structures essential for outfitting the tank as a lunar habitat. Conceptual designs were developed for astronaut LO_2 tank access, internal structures, LO_2 tank air lock, micrometeoroid/orbital debris shield, radiation protection, ECLS system, thermal-control system, and propulsion system.

The systems would be assembled in the LO_2 tank-intertank at Space Station *Freedom* from subassemblies packaged in protective containers. The containers would be rectangular in cross section and sized to permit entry through a 91.4-cm-diameter (36-in.) manhole as shown in figure 2.1. The quantities and masses of containers are given in table 2.1 and identified as to whether the containers will be installed in the interior or exterior of the LO_2 tank. The masses reported in the table are approximate and include quantities required for initial start-up and the interim time period until resupply.

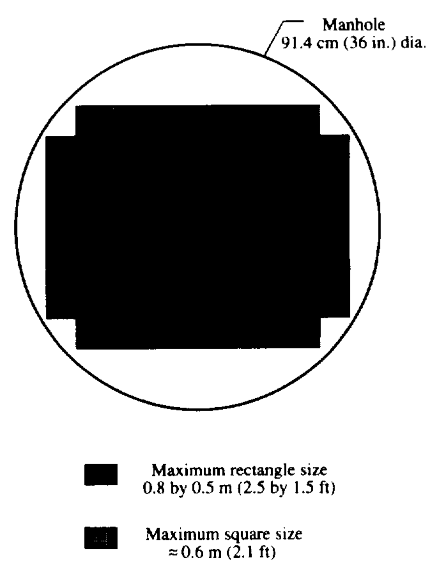

Figure 2.1. Container cross sections showing clearances with manhole.

It has been estimated that 224 containers or items of various sizes and masses would be required for structure, micrometeoroid shield, ECLS, thermal control including radiator panels, and propulsion systems.

The power, communication, guidance, navigation, and on-board control systems were not conceptually designed, but estimates of masses and number of the components utilized data from summaries of present technology (ref. 5). The estimates for electrical power assumed a 30-kW capacity based upon H_2-O_2 fuel cells, whereas the other subsystems were assumed with existing capabilities. The estimates for these subsystems conservatively allotted 1200 kg (2600 lb) and indicated 70 containers would be required in the total inventory of 294 containers or items for installation during in-orbit assembly and flight preparation of the lunar habitat.

Table 2.1. Containers/Items Required To Outfit Lunar Habitat in Low Earth Orbit

System	LO_2 tank interior			LO_2 tank exterior		
	Quantity	Mass, kg	Mass, lb	Quantity	Mass, kg	Mass, lb
Structures:						
Flooring and struts	33	2500	5500			
Air lock				1	800	1770
Micrometeoroid protection:						
Shield				16	3550	7830
ECLS:						
Habitability	20	820	1800			
Water management	14	1030	2260			
Air revitalization	7	730	1600	12	3450	7600
Food, storage, and preparation	25	2500	5500			
Waste management	4	350	770			
Integration equipment	2	160	350			
Subtotal	72	5590	12 280	12	3450	7600
Thermal control:						
Acquisition						
Internal transport loops	9	1130	2500			
Air temperature and humidity control	14	750	1650			
Transport				11	310	680
Rejection						
Heat pump				1	80	180
Radiator assembly				25	480	1060
Subtotal	23	1880	4150	37	870	1920
Power, communications, and guidance, navigation, and control	40	600	1330	30	600	1330
Propulsion:						
Tanks within intertank (empty)				10	2000	4400
Tanks outside intertank (empty)				16	3270	7200
Modified RL-10 O_2-H_2 engines				4	2400	5300
Subtotal				30	7670	16 900
Totals	168	10 570	23 260	126	16 940	37 350

3. System/Component Design Description

3.1. Astronaut LO_2 Tank Access

A primary concern for disassembly and outfitting an external tank in low Earth orbit was EVA access to the external tank through a 36-in-diameter manhole. The EVA access was determined for two astronaut space suits: the NSTS orbiter suit and the proposed zero prebreathe suit for Space Station *Freedom*.

The NSTS orbiter space suit has been worn in neutral buoyancy tests at the Marshall Space Flight Center where astronauts and equipment passed through a 36-in-diameter manhole as shown in figure 3.1.

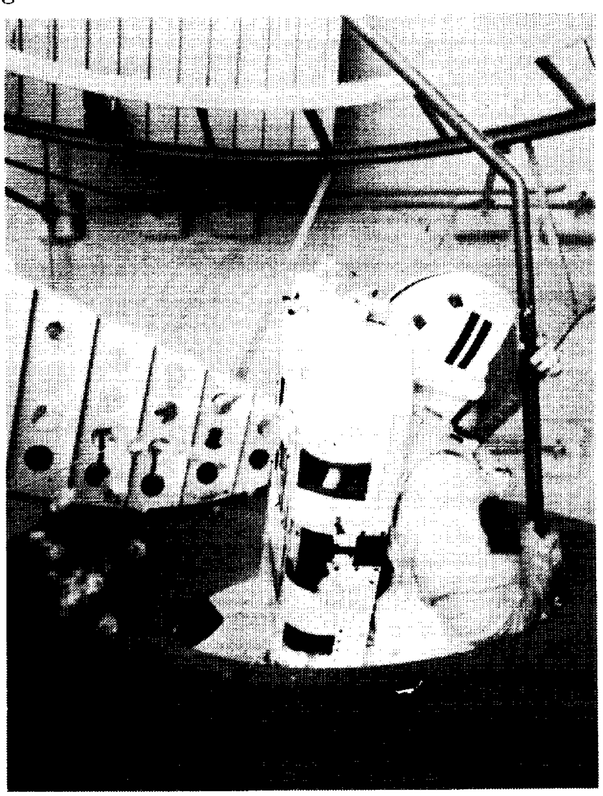

Figure 3.1. Astronauts demonstrating accessibility to external tank interior when wearing NSTS orbiter space suit.

A review of the dimensions of the proposed zero prebreathe space suit for Space Station *Freedom* indicates that the astronaut can pass through the 36-in-diameter external tank manhole opening as well as the 36- by 40-inch air lock opening of the NSTS orbiter. The proposed space suit is approximately 31 in. in width from elbow to elbow (ref. 6).

3.2. Habitat Flooring

The flooring for the habitat will be constructed of sandwich panels having a low-density core and panel facings of metal or reinforced plastic. There are four floors planned for the habitat, each circular and divided into eight sections. Each section is capable of being folded at hinge lines to reduce the width of the floor section and permit passage through the 36-in-diameter (91.4-cm) manhole into the interior of the LO_2 tank. The first floor as shown in figure 3.2 has a uniform arc length at the outer diameter, but the assembly joints between panels radiate from the center of the floor access opening, which is offset from the center of the circular floor. The offset access opening is aligned with the aft ellipsoidal dome manhole. The second, third, and fourth floors each consist of eight floor sections with each section assembly joint aligned with the center of the circular floor where the man access opening radius is also centered (figs. 3.3, 3.4, and 3.5). Truss nodes are located about the circumference of the assembled floors. Tubular truss struts are used to provide support between the second, third, and fourth floors and are assembled with the truss nodes. The manned access openings of the second, third, and fourth floors align as to size and angular orientation and with the axis of the tank.

Figure 3.6 is a view from the forward end of the LO_2 tank looking aft. A dashed outline of the offset access opening of the first floor is shown in its relationship to the reference intertank access door location. The bold dashed lines indicate the truss struts and their attachment to the truss nodes. The orientation of the truss structure places the truss struts close to the inside wall of the tank to maximize the usable floor space. The triangular orientation of the truss provides rigidity and support for the flooring; additional information is provided in section 6.1.4.

A floor octant is shown in figure 3.7 as unfolded (extended) to indicate the location of piano hinges. The folded octant configuration is shown to indicate clearance when passed through a 36-in-diameter manhole. Table 3.1 provides the number of floor octants and struts required for the habitat. The total mass of floor octants and struts is 2469 kg (5444 lb).

Figure 3.8 indicates that a Space Station *Freedom* astronaut can pass through a habitat floor access opening while climbing a ladder between floors. The keyhole-shaped access opening is designed to provide a 36-in-diameter clearance so that objects passing through the manhole of the tank can also pass through the access openings in the floors without obstruction. The ladder is offset from the 36-in. diameter, and toe clearance is provided at each floor level for the astronaut's feet.

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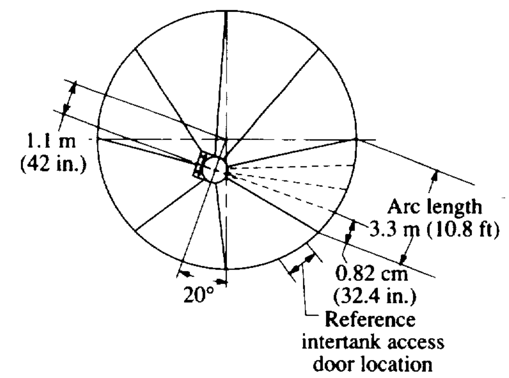


Figure 3.2. First floor of lunar habitat. Floor outside diameter, 8.4 m (27.5 ft); Total floor area minus Area of access opening, 54 m^2 (584 ft^2).

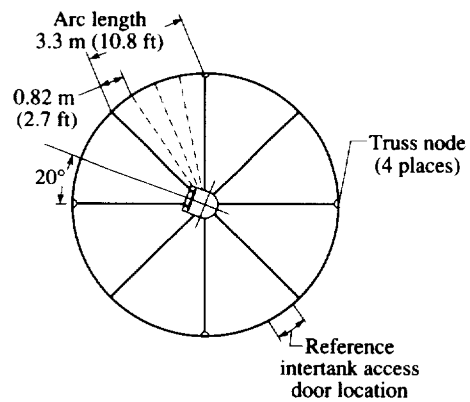


Figure 3.3. Second floor of lunar habitat. Floor outside diameter, 8.4 m (27.5 ft); Total floor area minus Area of access opening, 54 m^2 (584 ft^2).

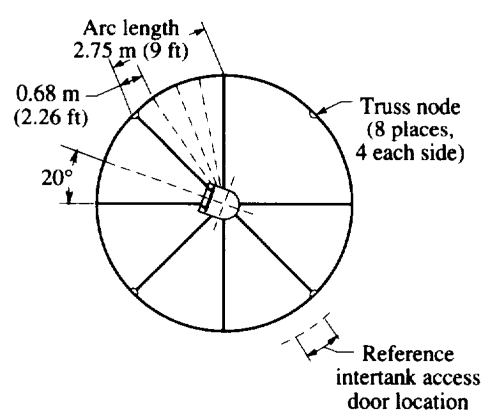


Figure 3.4. Third floor of lunar habitat. Floor outside diameter, 7 m (23 ft); Total floor area minus Area of access opening, 37.6 m^2 (405 ft^2).

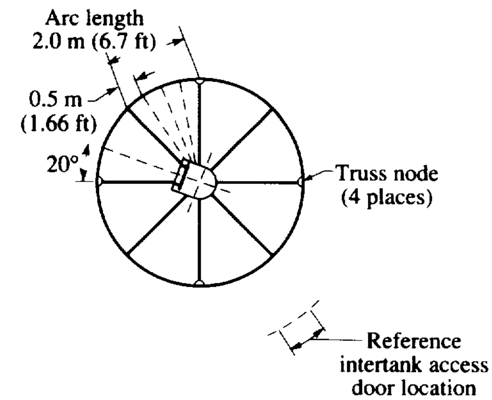


Figure 3.5. Fourth floor of lunar habitat. Floor outside diameter, 5.2 m (17 ft); Total floor area minus Area of access opening, 20 m^2 (217 ft^2).

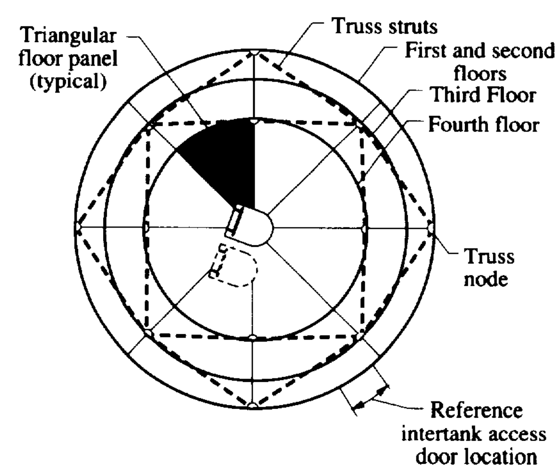


Figure 3.6. Alignment of floors and truss struts inside lunar habitat.

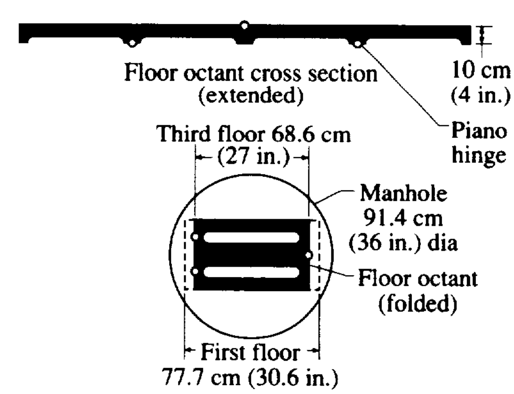


Figure 3.7. Folding floor panels of lunar habitat.

Table 3.1. Habitat Inside Structure Summary Showing Total Mass of Floor Panels and Struts

Item	Number of items	Dimensions, cm	Dimensions, in.	Mass of each, kg	Mass of each, lb	Total mass, kg	Total mass, lb
Floor 1 octant	8	≈ 381 × 82.3 × 40.6	≈ 150 × 32.4 × 16	≈ 98.9	≈ 218	791.5	1745
Floor 2 octant	8	≈ 381 × 82.3 × 40.6	≈ 150 × 32.4 × 16	≈ 98.9	≈ 218	791.5	1745
Floor 3 octant	8	≈ 313.9 × 68.6 × 40.6	≈ 123.6 × 27 × 16	≈ 68.5	≈ 151	548.8	1210
Floor 4 octant	8	≈ 222.5 × 50.8 × 40.6	≈ 87.6 × 20 × 16	36.7	81	293.9	648
Struts	16	≈ 365.8 × 20.3 × 20.3	≈ 144 × 8 × 8	2.7	6	43.5	96
Total	48					2469.2	5444

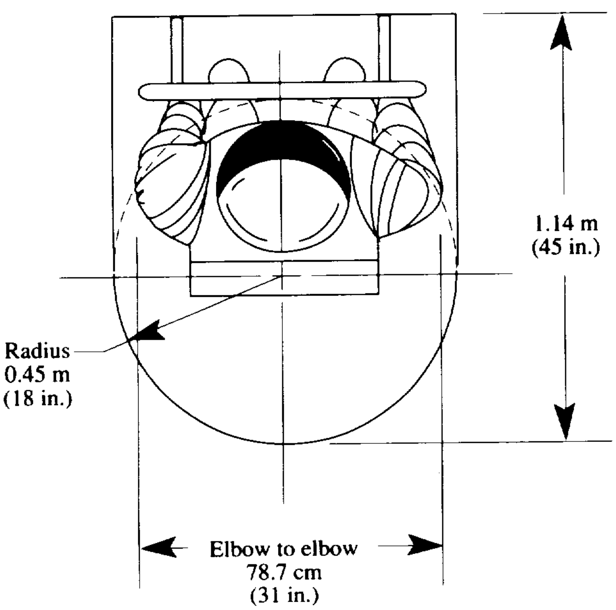


Figure 3.8. Astronaut in proposed Space Station *Freedom* space suit climbing through typical access opening in habitat flooring.

3.3. Air Lock

Figure 3.9 indicates the geometry of the air lock fabricated as a gas-tight pressure vessel connecting the manhole of the ellipsoidal dome of the LO_2 tank with the access door provided in the intertank. An air lock external access door permits long straight objects to enter the air lock and pass through into the LO_2 tank. An additional door provides astronaut access into the interior of the intertank in the as-landed configuration of the habitat.

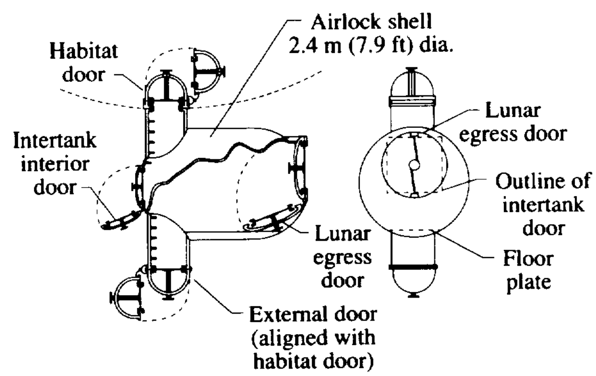


Figure 3.9. Air lock concept with four doors.

3.4. Micrometeoroid/Orbital Debris Hazard Analysis

Particulate matter in free space may represent a potential danger to unshielded structures. The basic NSTS LO_2 tank structure has a pressure shell whose walls vary in thickness from 0.2 to 1.0 cm (0.08 to 0.400 in.); however, over 90 percent of the vessel has walls of thickness 0.25 cm (0.1 in.) or greater. In order to estimate the danger of penetration of the unshielded tanks by micrometeoroids, an average wall thickness of 0.25 cm is used for the structure along with the NASA 1969 Meteoroid Environment Model (ref. 7), which is used to define particle density, flux, and velocity. With nominal data from the environment model for a preliminary hazard evaluation, the particle density is taken as 0.5 g/cm^3, and the observed free space average velocity of 20 km/sec is used. Meteoroid flux is assumed to be isotropic.

Threshold penetration of an aluminum wall of thickness t in centimeters may be estimated from a relation derived for single thin metal plates and is given in reference 7 as

$$t = 0.54\rho^{1/6}m^{0.352}V^{0.875}$$

where ρ, m, and V are particle density in grams per centimeter^3, mass in grams, and normal impact velocity in kilometers per second, respectively. Substitution of the specified values of t, ρ, and V in this relation results in a value for the minimum particle mass which will penetrate the wall:

$$m_{\text{min}} = 9.1 \times 10^{-5} \text{ gram}$$

Assuming the probability of particle impact adheres to a Poisson distribution, the probability that no collisions occur on an exposed area A in time τ is given by reference 8 as

$$P(0) = \exp(-\varphi A \tau)$$

where φ is the flux of particles having mass m_{min} or greater. The flux is obtained from the environment model by

$$\varphi(m) = (4.266 \times 10^{-5})(m)^{-1.213}$$

for a particle mass between 10^{-6} and 1.0 gram. In this relation, mass in grams results in flux values for mass m in units of particles per meter^2-second. The effective area of the configuration is 115 m^2, and total exposure time is assumed to be 6 months. These values for A, τ, and m_{min} result in a probability for no penetration of

$$P(0) = 0.62$$

indicating that the configuration has a 38-percent chance of penetrable impact and that micrometeoroid protection is mandatory.

The provision of an outer shield to contain lunar regolith for radiation shielding has a similarity to conventional micrometeoroid shield designs which can consist of an outer shield, or "bumper," and a back-up plate at some distance behind the bumper shield. Such shield designs are described in reference 9, which addressed meteoroid protection for the Comet Halley probe. The thickness of the outer shield on the LO_2 tank will be dictated by structural constraints related to regolith containment and is estimated to be no smaller than 3 mm in thickness. The mass of the bumper shield was determined from the sum of the areas of the cylindrical and ogive sections of the tank. The areas of the ogive and cylinder are 181 m^2 (1948 ft^2) and 260 m^2 (2799 ft^2), respectively. The total area, 441 m^2 (4747 ft^2), is multiplied by the wall thickness of 3 mm (0.118 in.) to obtain a shield volume of 1.32 m^3 (46.6 ft^3). For aluminum of density 2.7 g/cm^3 (0.1 lb/in^3), this results in a shield mass of 3560 kg (7848 lb). The mobile servicing center will aid the astronauts in assembly of the bumper shield in LEO. This outer shield layer then serves as protection from micrometeoroids in LEO and during transit to the moon.

The ratio of bumper shield thickness to impact particle diameter is an important design parameter, and according to the analysis of reference 9, a value of 0.3 for this ratio is appropriate. For a shield thickness of 0.3 cm, the subsequent evaluation pertains to particles having a diameter of 1 cm. The additional assumption of particle sphericity results in a mass of 0.79 gram for this meteoroid. The thickness of the back-up sheet t_b at a distance S behind the bumper shield may be calculated from the relation (ref. 9).

$$t_b = 0.075m^{1/3}V/S^{1/2}$$

The distance S is established by the estimated regolith shield thickness (50 cm) required for radiation protection (see section 3.5) and the corresponding value of t_b is 0.2 cm (0.08 in.), which is the minimum thickness of the LO_2 tank wall.

With this configuration of bumper shield and vessel wall and the standard environment flux of particles greater than 1 cm diameter, the probability of no penetration becomes

$$P(0) = \exp(-8.96 \times 10^{-8})$$

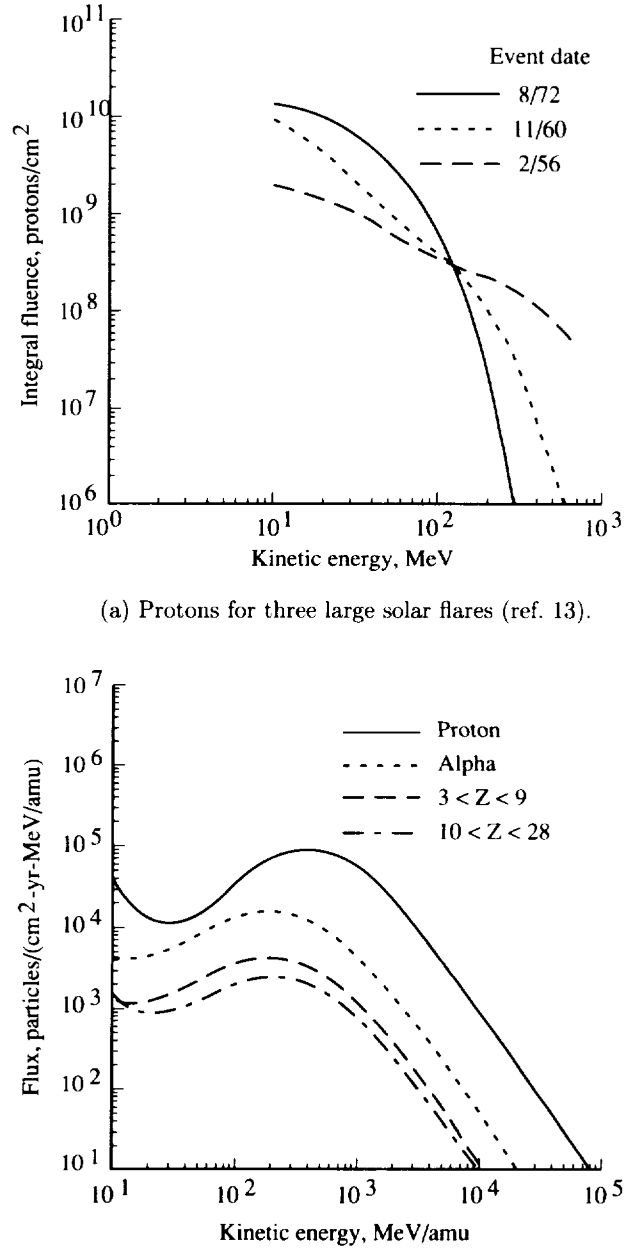
or the probability of catastrophic impact is $\approx 9 \times 10^{-8}$ during a 6-month period.

Potential hazards similar to the natural meteoroid environment in low Earth orbit arise from orbital debris deposited during previous space activities. Large uncertainties presently exist in the flux, mass, and velocity distributions of this debris. Recent estimates state that the orbital debris flux of particles with mass larger than 1 gram are about an order of magnitude greater than the micrometeoroid flux at 500 km (270 n.mi.), with lesser values at lower altitudes (ref. 10). For the NSTS-LO_2 tank, this additional hazard is estimated not to increase the probability of catastrophic impact to more than 10^{-6} for a 6-month period in LEO. This value of one chance in a million for catastrophic impact exceeds by far the current Space Station *Freedom* requirements (ref. 11). Thus, the installation of the regolith containment shield provides considerable micrometeoroid protection for the tank while in LEO and in transit to the moon.

3.5. Radiation Protection Analysis on Lunar Surface

The lunar habitat will be unmanned during transit from LEO to the lunar surface and therefore no special radiation protection is required. The high-energy charged-particle environment outside the Earth's magnetosphere dictates that substantial radiation shielding is necessary for maintaining crew health and safety during long stays on the lunar surface. Radiations of most concern for such lunar missions are protons emitted by large solar flares and the galactic cosmic ray (GCR) components consisting of stripped nuclei of the chemical elements. For the candidate lunar habitat, a radiation shield consisting of lunar soil or regolith is envisioned as a practical means of providing adequate radiation protection. A recent study (ref. 12), dealing with regolith shields for large flare radiation protection, indicates that a 50-cm thickness of regolith should provide sufficient attenuation of the radiation resulting from these rare, but very hazardous, events. The galactic cosmic rays consist of a relatively steady low flux of extremely high energy ($\gg$ 1 GeV) particles coming from regions outside the solar system. They are highly penetrating, and their interaction with matter is of great complexity. This study will also include estimates of the effectiveness of a 50-cm regolith shield for the GCR radiation and for large solar flares.

Particle fluences for three large solar flares (Feb. 1956, Nov. 1960, and Aug. 1972) have been selected for this analysis. These large solar proton flares are among the most hazardous in terms of dose potential observed in the last half-century (ref. 13), and their fluence spectra are shown in figure 3.10(a). The GCR environment is that specified in the Naval Research Laboratory CREME environment model (ref. 14) as shown in figure 3.10(b). These flux-energy distributions, have been used as inputs for the transport codes which describe propagation of the radiation through the shield material. The nucleon transport code BRYNTRN (ref. 15) has been applied to the transport of flare radiation. This code has subsequently been combined with a heavy-ion code (ref. 16) to provide a description of GCR transport in regolith. The lunar soil model, based on Apollo return samples, is described in reference 12.



(a) Protons for three large solar flares (ref. 13).

(b) Galactic cosmic ray nuclei during solar cycle minimum (ref. 14).

Figure 3.10. Flux versus energy distributions.

The doses incurred as a result of radiation flux attenuated by various shield thicknesses are also computed in the transport codes. Of most importance for high-energy nucleons is the dose to blood-forming organs (BFO dose) which, in this study, is taken to be the dose value at 5 cm in simulated human tissue (H_2O). Upper limits of the BFO dose for U.S. astronauts are currently recommended at 50 rem/yr, not to exceed 25 rem in a given 30-day period (ref. 17).

The regolith shielded NSTS lunar habitat geometry (cylinder/capped ogive configuration) has been analytically modeled for the radiation calculations, and radiation doses due to flux arriving at particular target points from all directions are computed. Resultant contours of constant doses for the configuration interior are then constructed. The preliminary analyses presented herein are for a shield for a 50-cm layer of regolith about the habitat as shown in figure 3.11.

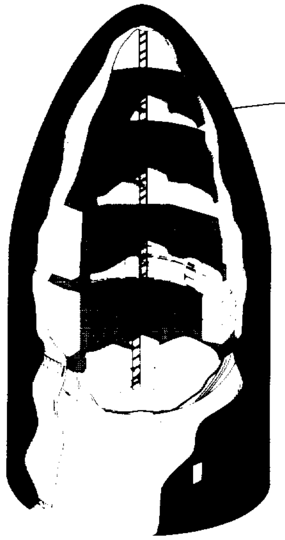


Figure 3.11. Cutaway view of lunar habitat with micrometeoroid shield containing lunar regolith.

Figure 3.12 (from ref. 18) shows the dose maps for the three large flares and the annual dose for GCR. The August 1972 event, which produced the largest total proton flux ever observed, results in the lowest dose levels because most of its flux was not highly penetrating. The February 1956 flare had a relatively large flux of higher energy (1 GeV or greater) particles and produces the largest overall dose within the 50-cm shield. With the configuration in its vertical position on the lunar surface, dose maxima occur near the symmetry axis in the upper part of the ogive section. In general, lower dose rates are incurred in the bottom portions of the habitat in proximity to the walls, but overall variations in dose levels throughout the habitat are relatively small.

A similar dose pattern is predicted for the GCR component, where the maximum dose rate approaches 12 rem/yr. It must be emphasized that the nucleon/heavy ion code used for the GCR calculation is considered to be an interim to a final version which is to include improved cross sections, pion and muon generation, and target fragmentation by protons. Nevertheless, reasonable estimates of GCR doses are obtained in the present calculations.

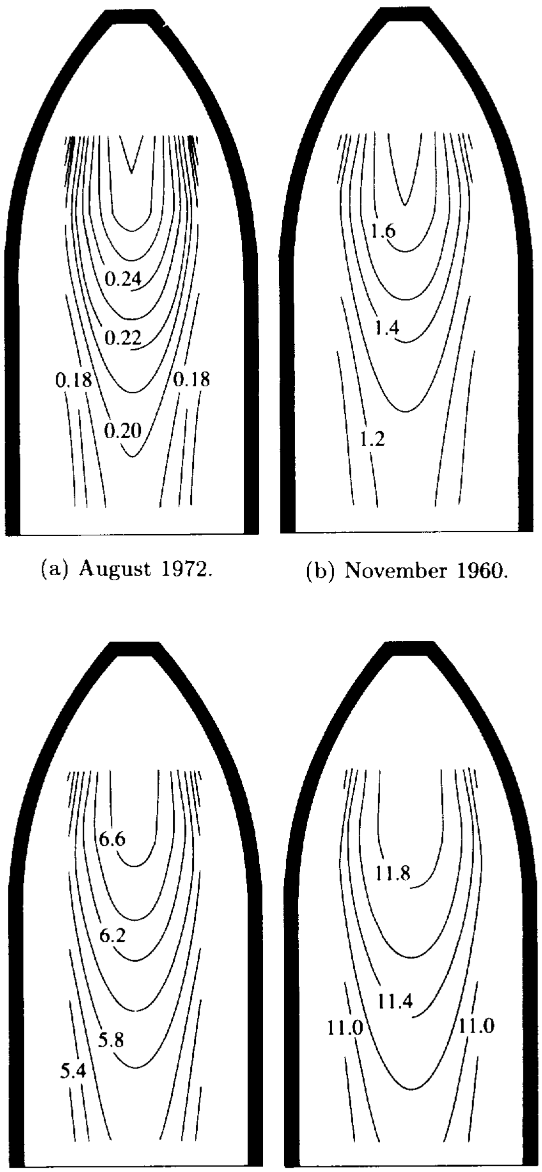
Several conservative assumptions have been made in the dose predictions:

1. GCR flux for solar minimum conditions has been used as input; at solar cycle maxima, this flux is lower by factors from about 1/3 to 1/2
2. No detailed human body geometry has been considered in the BFO calculations; results are presented for an equivalent sphere of tissue having a 5-cm radius
3. Additional shielding due to pressure shell, structural components, and peripheral equipment have not been included in the analysis; furthermore, the sum of the dose maxima predicted for GCR and flares, $\approx (12 + 7 \text{ rem})$, is highly unlikely to occur within a given year, since the large flares are observed to occur in periods of solar maximum; consequently, radiation doses in the habitat with a 50-cm regolith shield are anticipated to remain well below the 50 rem/yr annual limits

3.6. Environmental Control and Life Support System

3.6.1. Approach. A typical mission model was selected to provide a focus for ECLS subsystem selection and the calculation of expendables, both of which were necessary for producing a quantitative estimate of packaging and transport operations. A previous study conducted by the Johnson Space Center (ref. 19), established an intermittent, 12-man, 70-day mission model as the baseline for a permanently manned lunar base. This baseline was used to focus the design of the ECLS System for this study. The ECLS System design is typical of the physicochemical regenerative systems currently envisioned for Earth orbiting space stations and manned lunar bases. Once a generic system was defined and typical processes selected, the Langley ECLS subsystem data base (refs. 20 and 21) provided weight and volume data for subsequent calculations. In previous mission analysis studies, the weight, volume, and power totals were the final products sought. However, in this study, the questions were: Can the system components be transported through an air lock of specific size, and how much EVA effort will be involved? The hatch opening was known to be 36 in. in diameter, and a 1-in. clearance was assumed to be needed all around the hatch. Thus, the resulting usable hatch diameter is 34 in. To be useful as a carrier of ECLS subsystems and components, a container would need a minimum dimension of 24 in.

Since 24 in. was assumed to be the width of a container, all containers were sized to pass through the air lock. Using a standard container cross section of 24 by 25.5 in. and the component volumes from the ECLS system data base, the length of the container or multiple containers were calculated for each subsystem, component, or group of expendables.



(a) August 1972. (b) November 1960.

(c) February 1956. (d) Annual dose due to cosmic rays.

Figure 3.12. Contours of BFO (5-cm depth) dose equivalent for modeled habitat with 50-cm regolith shield for various flare spectra. (From ref. 18.)

The results of the ECLS system packaging study should be viewed as conceptual. The entire sequence of packaging, transport, assembly, and check-out is complex; and the practicality of accomplishing that task in LEO, away from the availability of specialized mechanical shops and support laboratories, has yet to be established. Having acknowledged these unknowns, the ECLS system packaging study was conducted to assess the scope of the effort if such an approach proves to be feasible.

3.6.2. Assumptions. The assumptions used to support subsystem and component selection and calculate the weight and volume of expendables are as follows:

Mission: 12-man, 70-day resupply

Application: Manned lunar base

Outfitting: LEO by EVA and IVA

Pressure suits and portable life support system (PLSS) units: Worn by astronauts, not part of the packaging

Habitat atmosphere: 101.3 kPa (14.7 psia), 79 percent nitrogen, 21 percent oxygen by volume

Redundancy: None except emergency supply of 3 days of metabolic oxygen (stored as gas)

Air lock: Five operations per 24 hours, 10-percent loss each operation

Leak rate: Loss of atmosphere of 2.1 kg per 24 hours (4.6 lb per 24 hours)

Cryogenics: Cryogenic nitrogen and oxygen are stored outside the habitat; all other components are stored inside the habitat

Nitrogen and oxygen: Available from lunar source or resupply from Earth

3.6.3. Subsystems and components. The ECLS system includes

Food and food locker: Freeze dried and frozen foods for 12-man, 70-day supply

Galley: 2 units

Refrigerator/freezer: 2 units

Disposable eating utensils

Stored potable water: 12-man, 2-day supply (until reclaimed water available)

Water reclamation: Water is reclaimed from hygiene waste water, humidity condensate, and urine/urine flush water by separate processing units; there are two units in the hygiene loop, two in the urine/urine flush loop, and one in the condensate loop; the water reclamation techniques coupled with the low water use rate that results from using disposable provisions (not a clothes washer or dishwasher) permits the conceptual closing of the water loop

Emergency 3-day supply of metabolic oxygen: High-pressure gas storage at 22.75 MPa (3300 psia)

Carbon dioxide removal (regenerable): 2 units with overboard dump of carbon dioxide

Fecal collection and processing: 2 units

Trash compaction: 1 unit

Urine collection: 4 units

Contaminant monitoring and control: 2 units

Whole-body shower: 3 units

Personal hygiene: 12 kits

Clothing, towels/linens, bedding: disposable

PLSS maintenance: 2 units

System monitoring and control console

Integration equipment: 2 units

Cryogenic oxygen and nitrogen: seven tanks of nitrogen and five tanks of oxygen provide gases for initial pressurization, leakage, air-lock loss, metabolism, and 20-percent contingency; stored oxygen is carried for metabolism for the first 70 days; after that period, oxygen is provided from a lunar LO_2 production plant (ref. 19); therefore, oxygen reclamation hardware is not included in the mass and volume tabulations in table 2.1

Based on the above brief system description and the container sizing approach previously described, the resulting details of ECLS system packaging are presented in table 3.2.

3.7. Thermal Control System

A thermal control system (TCS) is conceptually designed for operation in a habitat on the lunar surface (ref. 22). The TCS is designed to actively remove the estimated internal heat load of 20 kW which includes the latent, metabolic sensible, and experiment/equipment heat loads. It was assumed that 20 kW of the 30 kW available must be removed from the pressurized portion of the habitat. Mass and volume estimates are calculated for the heat acquisition, transport, and rejection subsystems for a base located near the lunar equator (table 2.1). Ultimately, the size and selection of the transport and rejection subsystems will depend upon the location and topographic features of the site.

*3.7.1. **Passive control.*** A thermal analysis is performed to estimate the external heat gains and losses between the lunar environment and the habitat to determine if additional load requirements would be imposed on the active thermal-control system. The analysis assumes a uniform exterior foam-insulation thickness of 2.54 cm (1 in.) and a uniform regolith thickness of 50 cm (19.7 in.). With the appropriate selection of the solar absorptivity divided by emissivity of the outer micrometeoroid shield, the external heat gains and losses can be sufficiently minimized. Thus, no added demands are imposed on the internal acquisition subsystem that the air-temperature and humidity-control (ATHC) subsystem design cannot accommodate.

*3.7.2. **Heat acquisition.*** The acquisition subsystem includes the ATHC subsystem and the internal fluid transport loops. The ATHC subsystem provides humidity control, ventilation, and avionics fan cooling. To make the task of installing the ventilation/avionics fan cooling system manageable, most of the ventilation lines can be built into the flooring and connected to a centrally located distribution duct originating at the fan locations in the lower-level utility area. Approximately two thirds of the equipment and experiments are fan cooled while the other one third are cooled with cold plates. Single phase pumped water loops acquire the ATHC heat loads and provide the experiments with cold-plate cooling. The most difficult task in the installation of the acquisition subsystem is laying the acquisition fluid lines. Most of the equipment requiring cold-plate cooling will already have preassembled components allowing them to be "plugged" into the appropriate fluid line. Mass and volume estimates are shown in table 3.3.

*3.7.3. **Heat transport and rejection.*** The internal heat load is transferred to an external transport loop via bus-heat exchangers. The bus-heat exchangers are located near a 43.2-cm-diameter (17-in.) port where the internal lines penetrate the tank wall. A heat-pump system is used to raise the final rejection temperature of the radiators well above the sink temperature during the hottest portions of the lunar day, and a compressor bypass loop is used during the lunar night (ref. 22). The transport lines penetrate the intertank structure through the existing LO_2 feedline aperture to connect with the radiators. The radiators are two-sided with a total rejection area of 67 m^2 (720 ft^2) and are oriented parallel to the plane of the solar ecliptic.

Table 3.2. ECLS System Packaging

(a) Inside habitat

Unit and function	Number of containers	Dimension, cm	Dimension, in.	Mass* of each, kg	Mass* of each, lb	Total mass*, kg	Total mass*, lb
Habitability							
Personal hygiene	3	61 × 61 × 65	24 × 24 × 25.5	34	75	102	225
Shower	3	183 × 61 × 65	72 × 24 × 25.5	96	211	287	633
Clothing, towels/linens, bedding	6	183 × 61 × 65	72 × 24 × 25.5	43	94	256	564
	2	122 × 61 × 65	48 × 24 × 25.5	29	64	58	128
	6	91.4 × 61 × 65	36 × 24 × 25.5	18	40	109	240
Water management							
Potable stored water	3	61 × 61 × 65	24 × 24 × 25.5	91	200	272	600
Water reclamation	2	183 × 61 × 65	72 × 24 × 25.5	101	222	201	444
	2	183 × 61 × 65	72 × 24 × 25.5	79	174	158	348
	3	153 × 61 × 65	60 × 24 × 25.5	53	117	159	351
	1	122 × 61 × 65	48 × 24 × 25.5	37	82	37	82
	2	91.4 × 61 × 65	36 × 24 × 25.5	81	178	161	356
	1	91.4 × 61 × 65	36 × 24 × 25.5	35	77	35	77
Air revitalization							
Carbon dioxide removal (regenerable)	1	122 × 61 × 65	48 × 24 × 25.5	213	470	213	470
Contaminant monitoring and control	1	153 × 61 × 65	60 × 24 × 25.5	41	91	41	91
	2	91.4 × 61 × 65	36 × 24 × 25.5	127	281	255	562
System monitoring and control	1	122 × 61 × 65	48 × 24 × 25.5	113	250	113	250
PLSS maintenance units	1	91.4 × 61 × 65	36 × 24 × 25.5	29	65	29	65
Emergency oxygen (gaseous), 3-day supply	1	91.4 × 61 × 65	36 × 24 × 25.5	75	166	75	166
Food, storage, and preparation							
Food, food storage, preparation	3	183 × 61 × 65	72 × 24 × 25.5	64	141	192	423
	6	183 × 61 × 65	72 × 24 × 25.5	49	108	294	648
	9	122 × 61 × 65	48 × 24 × 25.5	186	409	1670	3681
	6	122 × 61 × 65	48 × 24 × 25.5	41	90	245	540
	1	91.4 × 61 × 65	36 × 24 × 25.5	60	132	60	132
Waste management							
Fecal collection and processing	2	183 × 61 × 65	72 × 24 × 25.5	116	256	232	512
Urine collection	1	91.4 × 61 × 65	36 × 24 × 25.5	52	115	52	115
Trash compaction	1	183 × 61 × 65	72 × 24 × 25.5	64	140	64	140
Integration equipment							
Integration equipment	2	183 × 61 × 65	72 × 24 × 25.5	80	174	160	348
Total	72					5530	12 191

(b) Outside habitat

Unit and function	Number of containers	Dimension, cm	Dimension, in.	Mass* of each, kg	Mass* of each, lb	Total mass*, kg	Total mass*, lb
Air revitalization							
Cryogenic oxygen and nitrogen	7	101.6	40	286	631	2004	4417
	5	81.3	32	286	631	1431	3155
Total	12					3435	7572

* Includes container mass.

Table 3.3. Internal Thermal Control System Estimates

System component	Packages			Total package volume		Total mass	
	Quantity	Dimension					
		cm	in	m^3	ft^3	kg	lb
Air temperature and humidity control	4	61 × 61 × 65	24 × 24 × 25.5	0.96	34	115	250
	3	122 × 61 × 65	48 × 24 × 25.5	1.44	51	225	500
	7	183 × 61 × 65	72 × 24 × 25.5	5.07	179	410	900
Subtotal	14			7.47	264	750	1650
Water transport loops and cold-plate cooling	3	61 × 61 × 65	24 × 24 × 25.5	0.74	26	235	520
	4	122 × 61 × 65	48 × 24 × 25.5	1.93	68	105	230
	2	183 × 61 × 65	72 × 24 × 25.5	1.44	51	790	1750
Subtotal	9			4.11	145	1130	2500
Total	23			11.58	409	1880	4150

All the external system components except the radiator panels and the heat pump assembly fit inside the habitat for transport to the lunar surface. The individual radiator panels are strapped to the outside of the micrometeoroid shield, and the heat-pump system is mounted within the intertank structure where it remains protected for use on the lunar surface. The major tasks involved with the construction of the transport and rejection subsystems are the installation of the vapor and liquid transport lines to and from the radiator panels and the erected orientation of the radiator panels. The mass and volume estimates of the subsystems are shown in table 3.4.

3.8. Propulsion System Concept and Requirements

The propulsion system concept combines the advances planned for thrusters such as the Centaur RL-10 (ref. 5) with a propellant logistics technique defined for a lunar node study (ref. 23) to achieve transfer flight capabilities that allow dwell time in lunar orbit. Plans for improved thrusters include multiple restart, throttling to 10 percent, and operation with a specific impulse of 4707 N-sec/kg (480 sec) for a ratio of oxygen to hydrogen ratio of 7 to 1. Propellant logistics utilize a number of individual tanks that are filled on Earth and delivered to orbit for insertion or attachment. Transfer of propellant tanks would be accomplished by remote means either free flying or docked to an unmanned companion platform. Using filled tanks eliminates the need for transfer of cryogenic liquids in microgravity, and in addition, operation with only a limited number of active tanks minimizes slosh disturbance effects on the guidance system. The concept utilizes 10 cylindrical propellant tanks within the intertank and 16 cylindrical tanks carried externally, with external tanks being jettisoned when emptied. Interconnecting manifolds feed four thrusters which are externally mounted to the intertank in a manner that applies the thrust to the ends of the SRB beam. Figure 3.13 shows the location of the air lock and indicates the sizes for the propellant tanks clustered within the intertank and the propellant tanks attached to the exterior of the micrometeoroid shield. Figure 3.14 indicates the location of the air lock in relationship to the radial arrangement of tanks inside and outside the intertank structure. Items that are shaded are installed in LEO. The four thrusters are shown in their relationship to the intertank diameter.

Studies sponsored by the National Aeronautics and Space Administration have determined the velocity increments associated with flights from LEO to the lunar surface which include provisions for dwell in lunar orbit (refs. 24, 25, and 26). The degree of conservatism exercised for a manned Apollo program is not required; hence, velocity increments are as follows:

3150 m/sec (10 335 ft/sec) for Earth escape

50 m/sec (164 ft/sec) for mid-course correction

850 m/sec (2789 ft/sec) to lunar circular orbit at 100 km (62 miles)

2100 m/sec (6890 ft/sec) for lunar descent

Table 3.4. External Thermal Control System Estimates

System component	Quantity	Packages: Dimension, cm	Packages: Dimension, in.	Total package volume, m^3	Total package volume, ft^3	Total mass, kg	Total mass, lb
Transport	4	46 × 46 × 183	18 × 18 × 72	1.53	54	50	110
	2	58 × 58 × 183	23 × 23 × 72	1.25	44	25	50
	1	41 × 61 × 127	16 × 24 × 50	0.31	11	45	100
	1	36 × 51 × 114	14 × 20 × 45	0.20	7	30	60
	2	Depth = 76; Length = 122	Depth = 30; Length = 48	1.13	40	80	180
	1	61 × 61 × 61	24 × 24 × 24	0.23	8	80	180
Subtotal	11			4.65	164	310	680
Heat pump	1	152 × 91 × 61	60 × 36 × 24	0.71	25	80	180
Subtotal	1			0.71	25	80	180
Rejection	12	914 × 31 × 3	360 × 12 × 1	0.85	30	245	540
	12	Depth = 48; Length = 31	Depth = 19; Length = 12	0.68	24	215	480
	1	61 × 31 × 31	24 × 12 × 12	0.06	2	20	40
Subtotal	25			1.59	56	480	1060
Total	37			6.95	245	870	1920

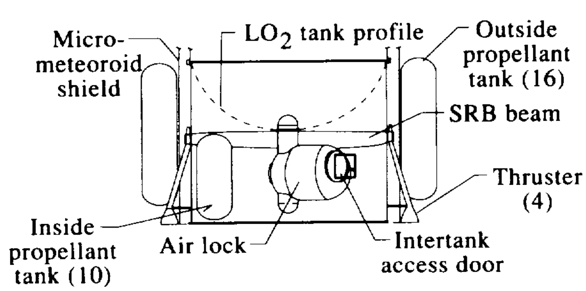


Figure 3.13. Intertank with propellant tanks, thrusters, micrometeoroid shield, and air lock installed.

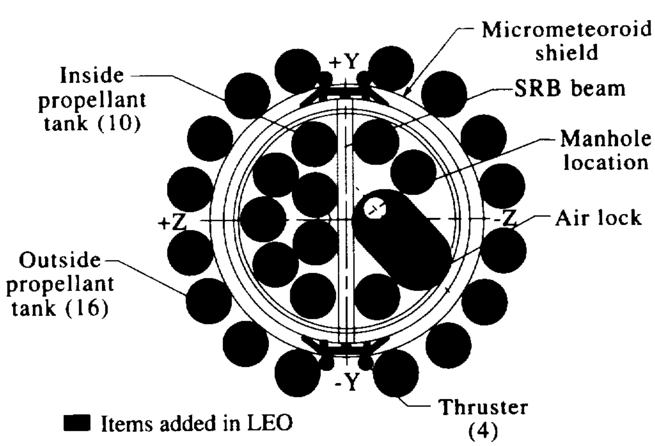


Figure 3.14. Intertank aft end view of propellant tanks, thrusters, micrometeoroid shield, and air lock installed.

The transfer flight can be accomplished with a direct descent to the lunar surface with velocity requirements reduced about 500 m/sec (1640 ft/sec); direct descent would be the first option for such a flight. However, the habitat configured to support a 12-person, 70-day stay results in a landed mass estimated at 35 440 kg (72 925 lb), but the propulsion system as described can accommodate such a mass in a flight that allows dwell in low lunar orbit. Therefore, the propulsion calculations utilize such a scenario.

The habitat departs from LEO with a total mass of 148 327 kg (327 061 lb) which includes a propellant load of 109 717 kg (241 925 lb). An initial burn at full thrust consumes 72 367 kg (159 695 lb) and empties 13 of the 16 external tanks. Acceleration increases throughout the burn and reaches a practical limit of 4.5 m/sec^2 (0.5g). Engine throttling then controls acceleration during all subsequent burns. Velocity corrections and decelerations into a circular lunar orbit require three or more burns and consume 12 793 kg (28 208 lb). These burns empty the external tanks. The intended landing site determines the lunar orbit inclination and the dwell time in lunar orbit. Descent utilizes the most propellant-efficient trajectory available and, thereby, achieves a touchdown mass of 38 340 kg (84 539 lb), which includes a propellant margin of 3000 kg (6615 lb) for the 12-man habitat configuration. The cryogenic propellant residual then supplies the fuel cells during the postlanding self-test. Upon completion and verification of the habitat, the entire system will switch into a standby mode to await arrival of the crew. Whereas the entire flight sequence for the habitat proceeds autonomously, man will have an interactive capability. The communication and guidance systems will be capable of receiving and implementing updates or modifications to any of the planned sequences.

The delivery of filled propellant tanks to LEO assumes availability of an unmanned heavy-lift launch vehicle (HLLV) with a capacity of 68 040 kg (150 000 lb). In such a scenario, the filled propellant tanks would be delivered on two flights over a 6-week time period and result in about a 2-percent boiloff for the initially delivered LH_2 and 1 percent for LO_2 (ref. 2). These gases would be consumed by the on-board fuel cells in the electrical power system. Transfer flight to the lunar surface assumes about 210 hours total duration, the same as Apollo. Residual propellants initially supply the fuel cells for on-board electrical power. The follow-up manned landings then resupply cryogenics for both fuel cell operation and makeup atmospheric oxygen.

A synergy for multiple use of propellants led to the selection of an O_2-H_2 fuel cell as the on-board electrical power generation unit. In addition to the utilization of propellant residuals, fuel cells provide power independent of any external source and without the complexities of on-board radioactive materials. The specific mission selected for the habitat would then define any supplemental electrical power generation systems. Habitats powered by fuel cells have the capability to serve as remote stations revisitable at anytime and for any duration of interest.

The majority of components for the propulsion system will be mounted on the exterior of the intertank structure and within the intertank volume. The advantage of using a mobile servicing unit with robotic end effectors would be to facilitate the assembly of the propulsion subsystem; thus, the amount of EVA required would be reduced.

4. Transportation Infrastructure and Assembly Node Concepts

The transportation infrastructure would consist of, as a minimum, the NSTS, the Space Station *Freedom* or an assembly node platform, an orbital maneuvering vehicle, expendable launch vehicles (ELV), and a lunar lander with a means of cislunar transport. The lunar habitat is shown in figure 4.1 as propelled to low lunar orbit and descending to soft-land on the lunar surface.

4.1. National Space Transportation System (NSTS)

The NSTS is required for transport of the external tank to orbit joined with the orbiter and to provide the external tank for outfitting as a lunar habitat after being inserted in LEO. The advantages of using the external tank are based on the capability of current technology to deliver a large volume structure to low Earth orbit. The orbiter payload reduction due to taking the external tank to orbit is shown in figure 4.2 (adapted from ref. 27). Please note that the solid line of the graph indicates the orbiter capability under a normal flight sequence. The dashed line indicates the altitude achieved versus the consequent payload capability when the external tank is taken to low Earth orbit. The penalty is incurred because of additional orbital maneuvering system (OMS) propellant mass required to permit orbit circularization of the orbiter with the external tank joined. The additional propellant mass required will be dependent upon payload mass and orbital altitude.

4.2. Assembly Node Concepts for Lunar Habitat

The lunar habitat requires an assembly node in low Earth orbit for outfitting the LO_2 tank-intertank subsystem. The four nodes that were evaluated are shown in figure 4.1 and are as follows:

The shuttle orbiter would have a structure erected from its cargo bay which would receive a mobile servicing center. The orbiter crew could perform EVA limited to a total of 24 EVA hours during each 5- to 7-day orbit staytime, thereby limiting the time per flight for the assembly process in orbit. The assembly of the lunar habitat using the orbiter would require a significant number of flights and was considered impractical.

A proposed industrial space facility (ISF) was considered whereby an erectable structure would be added to the facility to serve as an assembly bay. The ISF has attitude control and limited environmental-control and life-support capability. The industrial space facility, as now configured, would limit astronaut stay time and require a large number of flights for habitat assembly along with resupply of ISF consumables to outfit a lunar habitat. This assembly node concept was considered impractical.

The Space Station *Freedom* was considered as a logical assembly node with the addition of an ECLS module, resource node, and air lock to permit the major habitat outfitting operations to be performed as IVA in a shirt-sleeve environment. An orbital maneuvering vehicle based at Space Station *Freedom* would aid in disassembly of the external tank and berth the LO_2 tank-intertank with the air lock. The

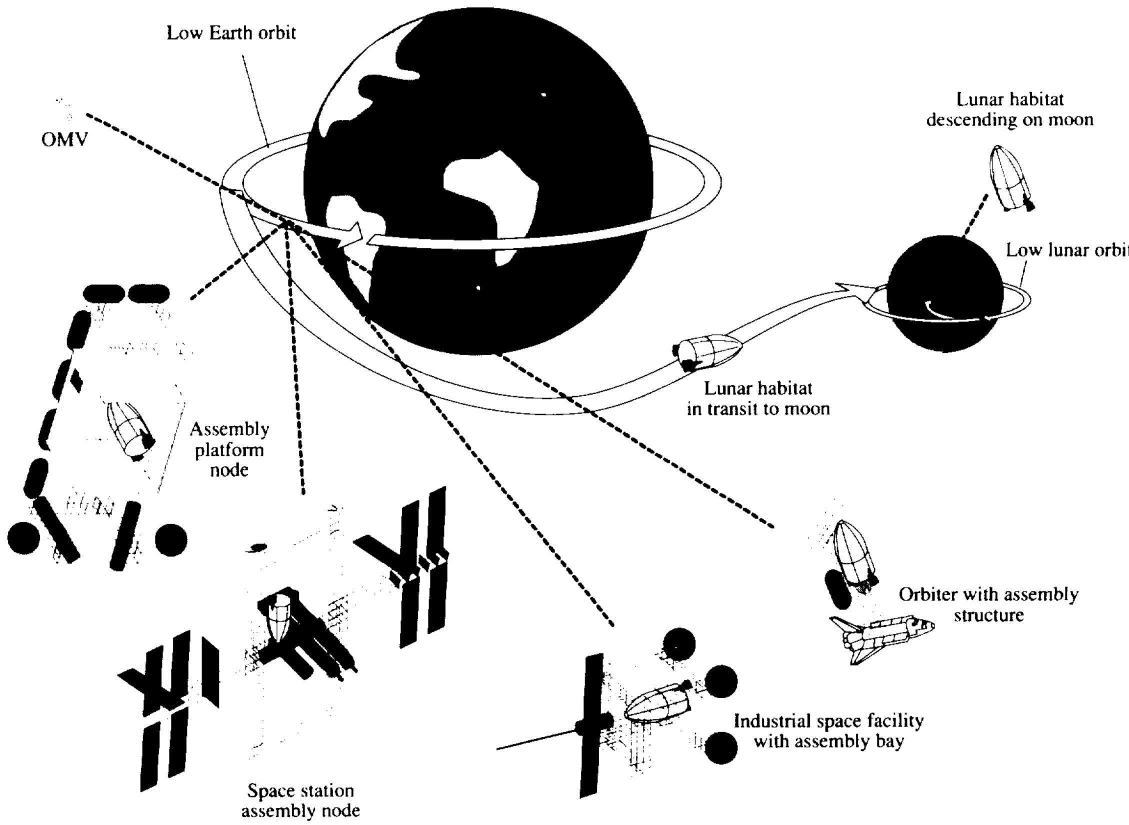


Figure 4.1. Assembly nodes and transportation concepts of lunar habitat.

space station's external structure with mobile servicing center would aid in positioning the propulsion plumbing, thrusters, and micrometeoroid shield, with a minimum of EVA required. Space Station *Freedom* was chosen as the logical assembly node.

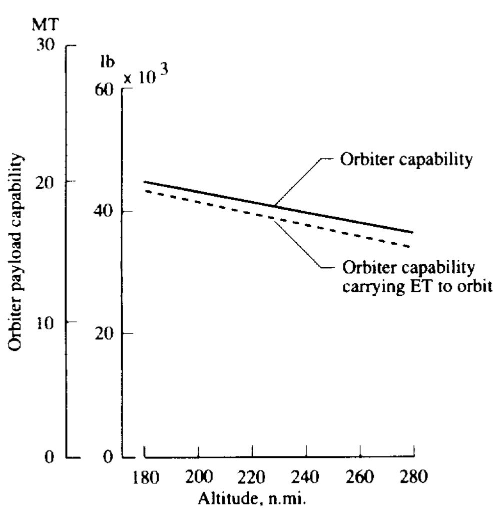


Figure 4.2. NSTS orbiter payload capability when carrying external tank to low Earth orbit. (Adapted from ref. 27.)

In the event that Space Station *Freedom* could not be used as an assembly node because of ongoing scientific experimentation, then a free-flying platform is proposed. The platform would be erected of truss structure to form a berthing and assembly bay and equipped with an ECLS module, resource node, and air lock to permit the major outfitting operations to be performed as IVA in a shirt-sleeve environment. A mobile servicing center could be used for outfitting the exterior of the habitat with a minimum of EVA required. This concept is a backup plan to the Space Station *Freedom* assembly node.

5. External Tank Disassembly in LEO by EVA

The external tank consists of two pressure vessels joined by a cylindrical intertank structure as shown in figure 1.2. It is assumed that the external tank is in a Shuttle nominal altitude of 160 n.mi. The tank, therefore, is well within the range of an OMV operating from Space Station *Freedom* (ref. 28). The OMV can be used to stabilize the external tank while the astronauts disassemble it. The disassembly process requires deactivating the tumble valve system; venting and purging the LO_2 tank and feed line; draining, venting, and purging the LH_2 tank; and removing the explosive charges of the range-safety system. The LO_2 tank-intertank requires removal of 178 bolts for separation from the LH_2 tank in LEO. The LO_2 tank-intertank subassembly will remain bolted together for outfitting as a habitat. The OMV can save the hydrogen tank for other uses by reboosting it into a higher altitude orbit. Alternately, the OMV could deboost the hydrogen tank, causing it to destruct on reentry into the Earth's atmosphere. The OMV can then transport the intertank and the oxygen tank to Space Station *Freedom* at its nominal orbit altitude of about 250 n.mi.

The exterior surfaces of the LO_2 tank, intertank, and LH_2 tank are coated with a 1-in. thickness of spray-on foam insulation (SOFI). Although some localized debris (consisting primarily of the foam-plastic insulation) may be generated during disassembly of the LH_2 tank from the intertank, the orbital lifetime of this material, starting at an altitude of 160 n.mi., is expected to be less than 10 hours (ref. 29).

6. Habitat Assembly Operations

The conversion of a LO_2 tank-intertank unit to a lunar habitat in LEO requires carefully planned and executed steps. The process starts with the outfitting and testing of all habitat systems in the LO_2 tank-intertank subassembly on Earth, followed by disassembly of the systems for packaging in containers for later reassembly in LEO. After the external tank is delivered to LEO and made safe, the LO_2 tank-intertank unit is separated, transported, and berthed at Space Station *Freedom* for complete reassembly of the systems and components. Upon completion of a systems' checkout, the lunar habitat would be separated from Space Station *Freedom* so that the propellant-filled tanks and cryogenic oxygen and nitrogen tanks can be added. The lunar habitat would be propelled for an unmanned soft-landing on the lunar surface where a self-check process would occur. After the arrival of a crew, the thermal radiator would be assembled and regolith added for radiation shielding purposes prior to occupancy of the habitat. The assembly operations are described in more detail in the following paragraphs.

6.1. Assembly Steps

The assembly steps for the lunar habitat start with Earth-based assembly and are concluded with postlanded assembly and surface operations.

6.1.1. Earth-based assembly and verification. The structural and subsystem components of the habitat would be installed and integrated on Earth. The tank could be scarred to simplify the installation of support structures; additionally, the erectable floor panels could be fabricated to receive all the subsystem components, for example, associated wiring, ventilation ducts. The habitat would then be fully assembled, and all components would be interconnected and operationally verified before disassembly for packaging and delivery to Space Station *Freedom* for reassembly and checkout.

6.1.2. Space Station Freedom committed facilities. In order to outfit the lunar habitat in LEO, the Space Station *Freedom* will have to be outfitted with a resource node, air lock, and an additional module to house ECLS equipment and provide a habitat area for the assembly crew. The resource node, air lock, and module are an addition to the Space Station *Freedom*'s facilities and have been identified as necessary to facilitate the assembly of a lunar habitat. The resource node, attached at an uncommitted port of the Space Station *Freedom*, permits berthing the external tank to provide access to the tank's interior through an existing manhole at the forward tip of the tank. (See fig. 6.1.) The ECLS module, connected through the resource node, supplies a habitable atmosphere to the tank's interior to permit the astronauts to outfit the tank in a shirt-sleeve environment; an additional advantage is the reduction of EVA, since most of the work can be accomplished by IVA. However, the addition of a micrometeoroid shield to the tank's exterior and the installation of a propulsion system to the structure must be accomplished by EVA aided by a mobile servicing center with robotic-end effectors. An OMV based at Space Station *Freedom* will berth the LO_2 tank-intertank and transfer components from the NSTS orbiter for assembly of the lunar habitat. A separate free-flying assembly platform could be used for assembly and outfitting the lunar habitat in the event that the Space Station *Freedom*'s facilities were not available for this use.

6.1.3. Subsystem component delivery to LEO. Equipment for outfitting the tank to function as a lunar habitat will be delivered in containers from the NSTS orbiter to the Space Station *Freedom* by an OMV. Subsystem components could also be delivered to the Space Station *Freedom* by the shuttle orbiter or other launch vehicles. The equipment and supply containers required to outfit the interior of the LO_2 tank would be weightless in orbit; therefore, they could be maneuvered through the Space Station *Freedom*'s ECLS module,

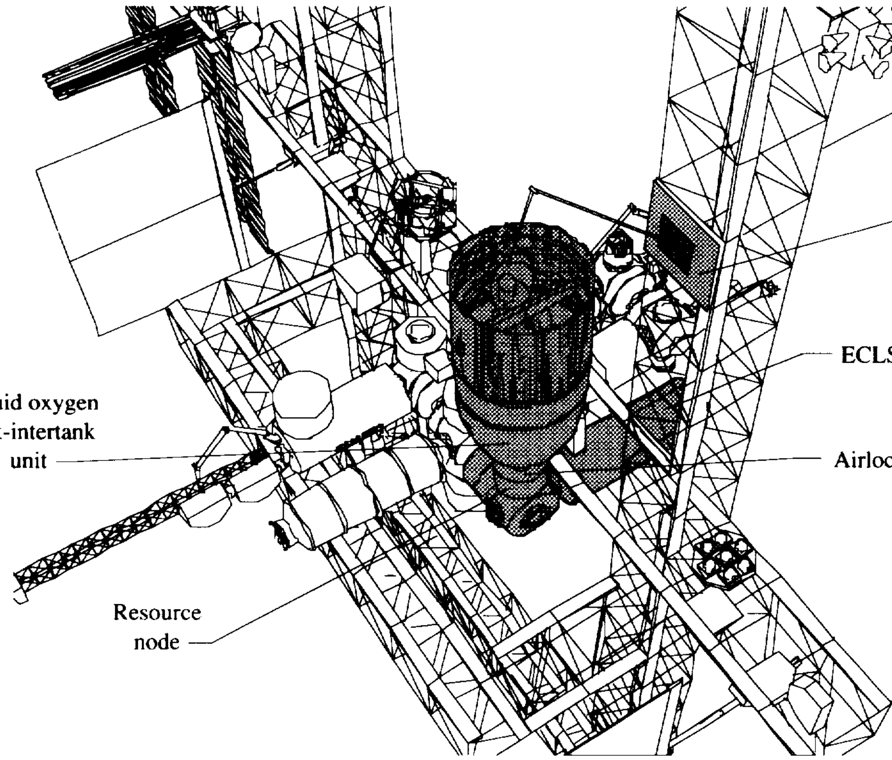


Figure 6.1. LO_2 tank-intertank subsystem berthed at Space Station *Freedom* for outfitting as lunar habitat.

resource node, and air lock into the tank for assembly. Equipment and supply containers for the tank's exterior would be stowed (attached) to Space Station *Freedom*'s exterior structure awaiting assembly by astronauts performing EVA and assisted by a mobile servicing center.

6.1.4. In-orbit assembly. The outfitting process of the LO_2 tank in LEO is somewhat like building a ship in a bottle and will consist of passing containers and structures through the manholes for assembly or erection within the tank's interior. Figure 6.2 is a cutaway view of the LO_2 tank and indicates the location of an existing slosh baffle and a vortex baffle that are part of the tank assembly. The four webs of the vortex baffle are positioned to provide an unobstructed access through the manhole into the LO_2 tank. The location of the webs is shown in figure 6.3 and the webs could be removed if required.

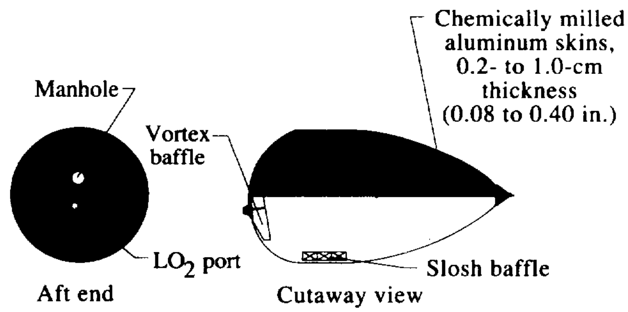


Figure 6.2. LO_2 tank profile. (Adapted from ref. 1.)

The unmodified LO_2 tank is a butt-fusion-welded gas-tight pressure vessel of aluminum alloys. Aluminum plates are shaped and chemically milled to form an ogive-shaped forward end joined to a cylinder, and the aft tank end is closed with a modified ellipsoidal dome. The LO_2 tank is hydrotested to assure safe flight operation at 172.3 kPa (25 psia), well above the internal pressure of 101.3 kPa (14.7 psia) intended for the lunar habitat. The LO_2 tank is equipped with two manholes—one just below the nose cone at the forward tip of the tank and one in the aft ellipsoidal dome where there is also a 43-cm-diameter (17-in.) port. (See figs. 6.2 and 6.4.)

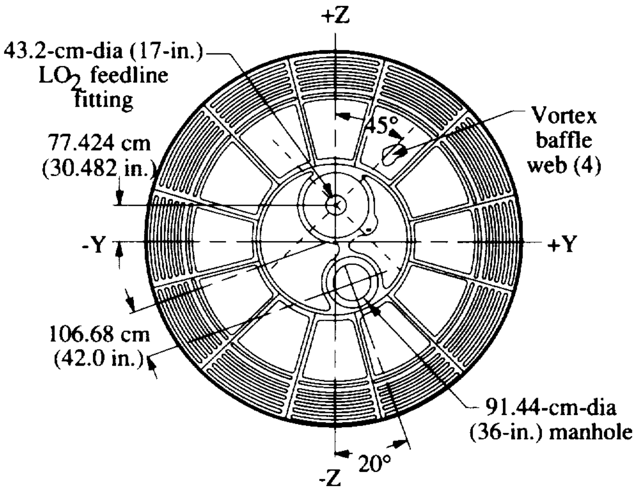


Figure 6.3. Aft end view of LO_2 tank looking forward. (Adapted from ref. 1.)

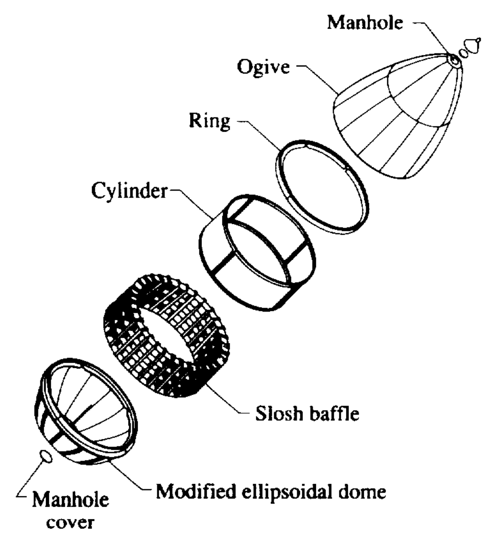


Figure 6.4. LO_2 tank with slosh baffle. (Adapted from ref. 1.)

The existing slosh baffle provides circular structural support to the sandwich panel flooring attached to the top and bottom of the baffle. Between the two floors there would be a control center with electronic equipment and/or instrumentation positioned on the slosh baffles that serve as support shelving. The shelving dimensions are provided in figure 6.5. Two additional floors are installed in the upper portion of the tank and supported by truss struts. A ladder with an electrical tread lift provides a redundant means for the astronauts and equipment to pass from floor to floor.

An aluminum-alloy shield with a thickness of 3 mm (0.118 in.) is attached to the exterior of the tank to provide protection from space debris and micrometeoroid penetration. The shield could be assembled from gore sections readily transportable in the cargo bay of a shuttle or other transportation means. The habitat's internal structure consists of sandwich panels that fold to permit entry through the 36-in-diameter manhole openings on the tank. The sandwich panels unfold to form octants of the four floor levels that are supported within the tank by the existing slosh baffle and erectable 5-cm-diameter truss elements (fig. 6.6). The total usable floor space is 165.6 m^2 (1790 ft^2).

An air lock will join the 36-in-diameter manhole in the ellipsoidal dome of the tank to the access door of the intertank and provide personnel egress to the lunar surface. A second exit in the air lock provides access to the intertank region. A third exit from the air lock allows long objects to be passed directly through the air lock to the external tank to facilitate in-orbit assembly.

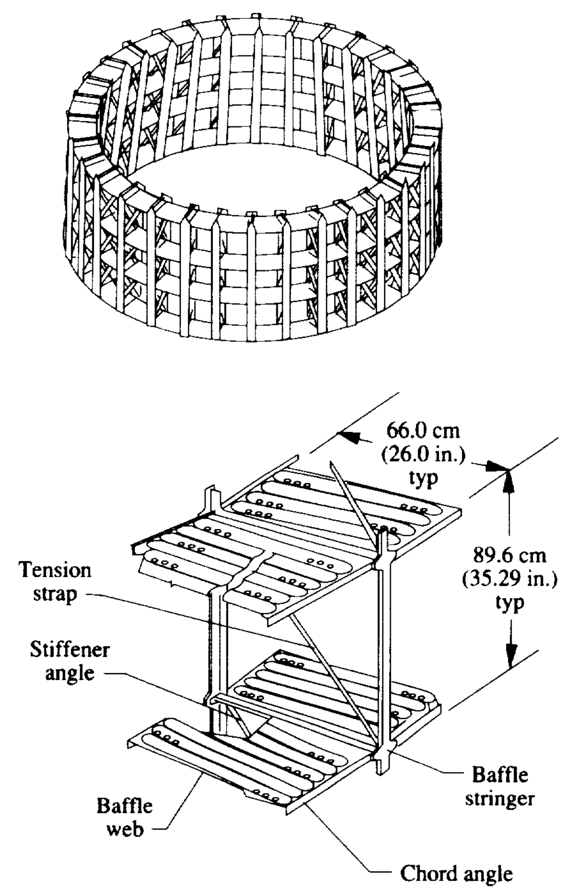


Figure 6.5. Slosh baffle assembly details. (Adapted from ref. 1.)

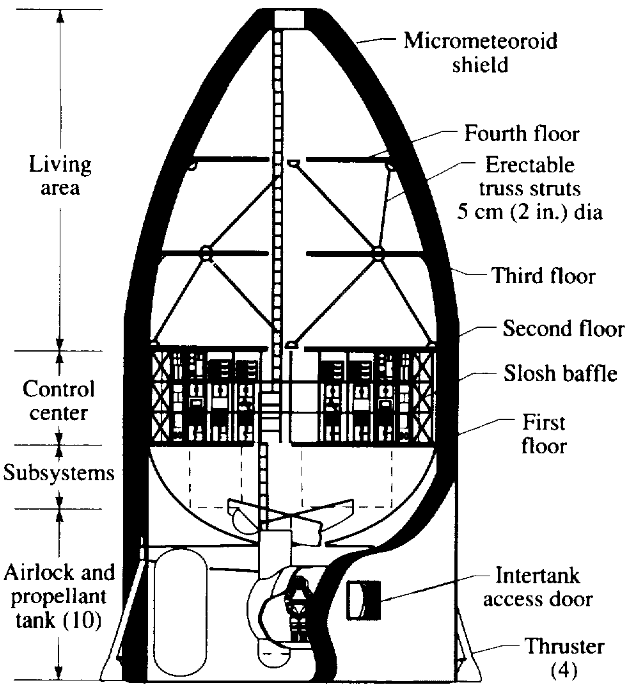


Figure 6.6. Lunar habitat as landed.

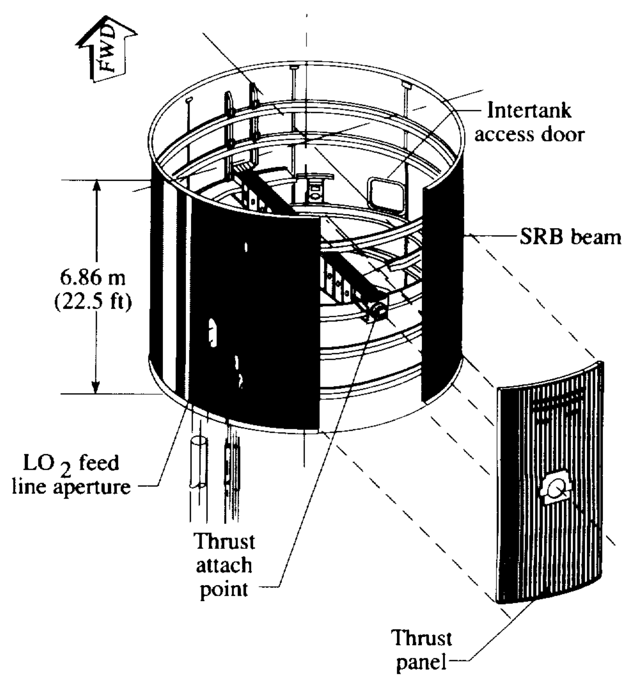


Figure 6.7. Intertank constructed of stringer-stiffened panels joined to ring frames. Thrust panel is shown removed. (Adapted from ref. 1.)

The ECLS system will require 72 containers to package the subsystems and components that are to be installed within the LO_2 tank. This includes all the ECLS system except for the 12 spherical, cryogenically stored nitrogen and oxygen tanks that are independent of propulsion tanks and are installed within the intertank.

The intertank is a cylindrical structure of stringer-stiffened panels joined to ring frames. A solid rocket booster (SRB) beam extends across the intertank diameter. The ends of the SRB beam become thruster attach points for the lunar habitat. A door opening is provided for accessing the intertank compartment and becomes the entrance to an air lock joined to the aft tank manhole. The access door opening is rectangular and provides a clear opening size of 108 cm (42.7 in.) high by 122 cm (48 in.) wide. Figure 6.7 shows the construction details of the intertank (ref. 1).

Vapor and liquid transport lines from within the habitat would pass through a 17-in-diameter port in the ellipsoidal dome of the tank to connect with a heat pump mounted within the intertank region. A radiator panel 3.66 m (12 ft) in width and 9.14 m (30 ft) in height would be attached to the exterior of the lunar habitat for transport to the lunar surface. The radiator would be relocated approximately 15 m (50 ft) from the habitat on the lunar surface. The transport lines would be interconnected to the heat pump (fig. 6.8).

The LO_2 tank-intertank assembly is 19.1 m (62.7 ft) from the forward manhole station to the aft end of the intertank as shown in figure 6.6. Two of the four propulsion thrusters are shown as attached to the end of the solid rocket booster beam. A typical propellant tank (1 of 10) is shown within the intertank. The air lock connects the intertank access door to the aft manhole of the LO_2 tank. The vortex baffle webs are positioned to provide unobstructed access into the tank. The first and second habitat

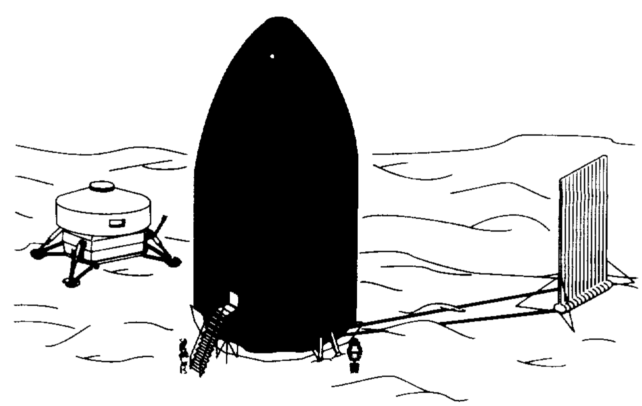


Figure 6.8. As-landed configuration of lunar habitat with radiator erected. Lunar lander is shown in background.

floors of sandwich panel construction are unfolded, joined, and secured to the slosh baffle. Floors three and four are assembled and supported by erectable truss struts. Instrumentation and subsystem components are installed on the slosh baffles which serve as shelving. A ladder is provided from the air lock to the forward manhole of the tank. A micrometeoroid shield is positioned to form a uniform space between the shield and the outer tank wall. This cavity is filled with regolith after landing on the lunar surface. The as-landed lunar habitat is equivalent in height to a six-story building.

*6.1.5. **Postlanded assembly.*** After softlanding, the lunar habitat may not have vertical alignment due to the topography of the lunar terrain. Adjustable footpads would correct this situation. The thermal radiator panel attached to the exterior of the shield would be separated and erected approximately 15 m from the habitat. The radiator panels are positioned vertically, and plugged into the radiator bus heat exchangers oriented parallel to the plane of the solar ecliptic. Additional supporting equipment is provided to maintain the vertical position of the radiator. On the lunar surface, the cavity created between the micrometeoroid protective shield and the tank wall can be filled with lunar regolith to provide protection from space radiation due to solar energetic particles and galactic cosmic radiation. Machines capable of excavating the lunar regolith and transporting it to fill the lunar habitat regolith cavity from the top are described in reference 30. The regolith also provides additional thermal insulation and meteoroid protection. The habitat is then ready to house a crew of 12 for periods of up to 70 days between resupply missions. This crew size and resupply period was part of a mission model being used by the Johnson Space Center to guide lunar base studies (ref. 19) during the time frame of this external tank study. The external tank habitat could support other mission models. Only the logistics of expendables would be affected. The as-landed habitat, erected radiator, and manned cargo lander are shown in figure 6.8.

*6.1.6. **Surface operations.*** A lunar lander would provide men with life-support items and additional subsystem components as required. The resupply cycle of 70 days for 12 men dictated the ECLS and thermal control design criteria for the habitat. A lunar research vehicle could be designed to dock with the intertank air lock door and would provide a means of surface transportation (ref. 31).

7. Extravehicular and Intravehicular Activity Preliminary Estimates

The EVA estimates were selected from comparable assembly operations planned for Space Station *Freedom* (ref. 32). These estimates are listed as elapsed times required for assembly or disassembly of components and structures in LEO. The astronauts would work in teams of two or more for safety reasons; therefore, the actual EVA man-hour estimates should be twice the elapsed time given. Wherever practical, astronaut handrails, handholds or foot restraints should be provided to facilitate the assembly processes in a weightless environment. The astronaut task activities should be planned not to exceed 6 hours of EVA per day because of astronaut fatigue. Artificial lighting would be required to facilitate continuing astronaut EVA when in the Earth's shadow and inside the LO_2 tank-intertank.

The IVA estimates are also based on elapsed time, and since the astronauts are working in a shirtsleeve environment, they are not subject to fatigue as readily as they would be in a space suit. Due to the size of the LO_2 tank, three or more astronauts could work inside the tank during the outfitting steps without interfering with one another.

7.1. Disassembly of Intertank from Hydrogen Tank in LEO

The amount of EVA required to separate the external tank at the structural interface between the intertank and the hydrogen tank would require the following procedures for making it safe:

Remove intertank door
Disable the range safety system and remove the charges
Deactivate the tumble valve system
Vent and purge the LO_2 tank and feedline
Drain, vent, and purge the LH_2 tank

The disassembly operations would proceed by disconnecting and removing the following items:

LO_2 feedline
GO_2 pressurization line
GH_2 pressurization line
GH_2 vent line
Helium inject line
Electrical cables and cable trays
Two manhole covers

The intertank structure could be separated from the hydrogen tank after removal of 178 bolts with suitable powered wrenches. The LO_2 tank-intertank has not been separated from the hydrogen tank in LEO to date. Neutral buoyancy tests should be performed with a mock-up of the external tank to develop improved hand and power tools, verify the disassembly procedures, and develop EVA timelines. The disassembly process should not exceed 12 hours of elapsed EVA time to permit the orbiter astronauts to accomplish delivery of the LO_2 tank-intertank to Space Station *Freedom* in a single NSTS launch.

Alternate separation concepts have been considered such as explosive cutting, sawing, or electron beam cutting the hydrogen tank flange adjacent to the bolted joint to reduce the EVA required to separate the structures.

An OMV based at Space Station *Freedom* would be used during the external tank separation process to deliver the LO_2 tank-intertank to berth at a committed air lock of Space Station *Freedom*. The OMV would also be used to boost the LH_2 tank into a parking orbit for later use or deboost it causing it to destruct on reentry into the Earth's atmosphere.

7.2. Assembly of Habitat Systems in LEO

The EVA and IVA activities are estimated for assembly of the habitat systems in LEO.

7.2.1. Internal structures. The internal structures for assembling the habitat's flooring will require panels that range in length from 2.2 to 3.8 m. The floor panels and struts would be placed inside the tank by EVA prior to closure of the aft manhole of the LO_2 tank. This EVA effort is estimated at 2 hours. The air lock of the habitat is positioned by a mobile servicing center and bolted at the aft manhole by EVA estimated at 3 hours. A blank-off flange with utility feed throughs is used to seal off the LO_2 feedline port in the aft dome by EVA estimated at 0.5 hour. The LO_2 tank can now be pressurized to allow the astronauts to outfit the interior of the LO_2 tank while working in a shirt-sleeve environment. The IVA required to assemble the internal structures is estimated at 12 hours.

7.2.2. Micrometeoroid shield. Micrometeoroid protection is provided by a bumper shield. The shield is transported to LEO as 16 panels nested to fit within the cargo bay of the orbiter. The shield panels are positioned by a mobile servicing center and assembled by EVA about the exterior of the LO_2 tank. Standoff spacers maintain the proper distance between the shield and tank wall. The EVA is estimated at 8 hours.

7.2.3. ECLS system. The ECLS system is packaged in containers which can be stowed in the ECLS module of Space Station *Freedom* for delivery through pressurized passageways into the LO_2 tank. Seventy-two items would be installed with an IVA estimate of 48 hours. Twelve tanks would be installed in the intertank by EVA estimated at 6 hours.

7.2.4. Thermal control system. The thermal control system will require installation of 23 containers inside the LO_2 tank with an IVA estimate of 16 hours. The heat pump will be installed in the intertank and the individual radiator panels strapped to the outside of the micrometeoroid shield with an EVA estimate of 14 hours.

7.2.5. Power, communications, and guidance, navigation, and control systems. The power, communications, and guidance, navigation, and control systems are estimated to be transported in 40 containers for installation inside the LO_2 tank with an estimated IVA time of 25 hours. An additional 30 items are estimated to be installed inside the intertank by performing EVA estimated at 15 hours.

7.2.6. Propulsion system. The propulsion system will require installation of four thrusters and associated plumbing to the intertank structure. The EVA is estimated at 12 hours. The outfitted habitat will be moved a safe distance from Space Station *Freedom* for plug-in assembly of 26 propellant-loaded tanks delivered to LEO by unmanned heavy-lift launch vehicles. The EVA estimated time for tank installation is 10 hours.

7.2.7. Systems checkout. A complete systems checkout would be accomplished before the outfitted lunar habitat was separated from Space Station *Freedom* for launch to the Moon. The IVA estimated time is 40 hours. Contingency EVA is estimated at 12 hours.

7.3. Postlanded Operations

The postlanded lunar habitat operations will require EVA excursions to assemble a radiator approximately 15 m from the habitat and interconnect the lines to equipment housed in the intertank. The estimated EVA for this operation is 4 hours.

7.4. Total Hours of EVA and IVA

The total elapsed time hours for EVA and IVA is shown in table 7.1 which includes the addition of a 20-percent overhead. The EVA estimates were selected from comparable assembly operations planned for Space Station *Freedom*. The 20-percent overhead is to account for overhead factors such as crew tether management, rest periods, body reorientations, worksite adjustments, tool retrieval, configuration changes.

Table 7.1. Preliminary Estimates of Extravehicular and Intravehicular Activities

Activity	Extravehicular, elapsed time, hr	Intravehicular, elapsed time, hr
Disassemble intertank from hydrogen tank in LEO	12.0	
Assemble habitat systems in LEO		
Structures	5.5	12.0
Micrometeoroid protection	8.0	
ECLS	6.0	48.0
Thermal control	14.0	16.0
Power; communications; and guidance, navigation, and control	15.0	25.0
Propulsion	22.0	
Systems checkout	12.0	40.0
	(Contingency)	
Subtotal	94.5	141.0
20-percent overhead	18.9	28.2
Total	113.4	169.2
Postlanded operations	4.0	

8. Concluding Remarks

A lunar habitat concept has been examined that uses a portion of the spent National Space Transportation System (NSTS) external tank as a habitat structure. The external tank could be inserted in low Earth orbit (LEO) along with the required subsystem components with existing NSTS propulsion capability. Orbiter astronauts would disassemble the external tank in LEO by extravehicular activity (EVA). The LO_2 tank-intertank subassembly of the external tank could be outfitted as a lunar habitat in low Earth orbit while berthed at Space Station *Freedom*. Preliminary estimates of the EVA and intravehicular activity (IVA) required to disassemble the external tank, outfit the lunar habitat, and perform the initial postlanded operations are provided. An orbital maneuvering vehicle based at Space Station *Freedom* could aid in the disassembly of the external tank, berthing the subassembly with Space Station *Freedom*, and later, moving the outfitted lunar habitat away from the Space Station *Freedom* for addition of propellant tanks for launch. The unmanned lunar habitat would be propelled from LEO and soft-landed on the lunar surface. Site preparation would not be required.

A lunar lander carrying the crew or resupplies could be propelled from LEO to low lunar orbit (LLO) by a space transfer vehicle. The lunar lander would soft-land in the vicinity of the lunar habitat. The lander would be capable of ascending to LLO and docking with the space transfer vehicle for return to LEO.

On the lunar surface, the lunar habitat would be prepared for occupancy with the assembly of the thermal system radiator, the possible installation of a secondary power subsystem, and the addition of regolith protection. The habitat would then be ready for occupancy by a crew of 12 with a nominal resupply cycle of 70 days. Filling the cavity between the micrometeoroid shield and LO_2 tank wall with regolith will enhance the habitat's protection from micrometeoroid impact. The 50-cm thickness of regolith will also reduce the astronaut's radiation dose to well below the 50 rem/yr annual limits. The habitat would be outfitted to permit continuous crew occupancy. Lunar surface transportation could be provided at a later date to dock with the intertank access door for crew surface exploration. Ideally, at least two habitats would be landed in close proximity so that one habitat could provide a safe haven in the event of a malfunction of the other habitat. A lunar habitat could be soft-landed on the lunar surface and supplied with crew and consumables by the year 2000 contingent upon the development of a space transfer vehicle and a lunar lander.

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Hampton, VA 23665-5225
September 26, 1990

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16. Abstract
A concept for using the spent external tank from a National Space Transportation System (NSTS) to derive a lunar habitat is described. The external tank is carried into low Earth orbit (LEO) where the oxygen tank-intertank subassembly is separated from the hydrogen tank, berthed to Space Station *Freedom* and the subassembly outfitted as a 12-person lunar habitat using extravehicular activity (EVA) and intravehicular activity (IVA). A single launch of the NSTS orbiter can place the external tank in LEO, provide orbiter astronauts for disassembly of the external tank, and transport the required subsystem hardware for outfitting the lunar habitat. An estimate of the astronauts' EVA and IVA is provided. The liquid oxygen-intertank modifications utilize existing structures and openings for man access without compromising the structural integrity of the tank. The modifications include installation of living quarters, instrumentation, and an air lock. Feasibility studies include micrometeoroid and radiation protection, thermal control, environmental control and life support, and propulsion. The converted lunar habitat is designed for unmanned transport and autonomous soft-landing on the lunar surface without need for site preparation.

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