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CONCEPTS FOR MANNED LUNAR HABITATS

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
SUMMARY	2
DESIGN GUIDELINES	3
INITIAL HABITAT	4
Concept 1	4
Habitat Elements	4
Lander Configuration and Operational Sequence	5
Environmental Shielding	14
Alternate Approach	16
Technology Assessment	19
Concept 2	23
Habitat Elements	23
Lander Configuration and Operational Sequence	24
Environmental Shielding	28
Alternate Approach	39
Technology Assessment	42
Concept 3	42
Habitat Elements	42
Lander Configuration and Operational Sequence	53
Environmental Shielding	61
Alternate Approach	61
Technology Assessment	66

TABLE OF CONTENTS
(concluded)

	<u>Page</u>
PERMANENT HABITAT	73
ADDITIONAL CONCEPTS OF HABITATS AND SUPPORT EQUIPMENT	76
CONCLUDING REMARKS	77
REFERENCES	78
APPENDIX A. TRADE-OFF CRITERIA	80
APPENDIX B. ADDITIONAL CONCEPTS	84

INTRODUCTION

In the late 1960's, the Space Station Research Group of the Langley Research Center was active in developing a lunar habitat that could be used to extend the stay time of the Apollo astronauts on the moon. The objective of the effort was to fabricate and test a full scale prototype of a habitat that could be transported to the moon in the Apollo Lunar Module (LM) and, once deployed, extend the stay time on the moon to 14 days. By necessity, the prototype habitat had to be inflatable or expandable to attain the packaged-to-deployed ratio required to assure that the habitat could be packaged in the LM yet have sufficient volume when deployed to provide a living habitat for the crew of two. The materials, design, and fabrication technologies required to produce the habitat, named the Stay Time Extension Module (STEM), was provided under contract to the NASA Langley Research Center. Tests of the prototype STEM were conducted jointly by the contractor and Langley. In a parallel effort, a large generic expandable module that could function as a space station habitability or laboratory module was developed by the contractor using materials and construction techniques similar to those used during the STEM development. A full scale prototype module nicknamed MOBY DICK was developed and tested. Upon completion of the STEM and MOBY DICK developments and upon termination of the Apollo Project all work on these expandable concepts ceased. These developments had, however, demonstrated a baseline technology for large, expandable manned structures. The STEM and MOBY DICK efforts are documented in references 1-3.

The Langley Research Center did not sponsor additional work on lunar habitats until 1988 at which time the Spacecraft Analysis Branch of the Space Systems Division participated in a cooperative effort with the NASA Johnson Space Center (JSC) to define details of systems for a JSC concept of a large, inflatable habitat. Langley provided design details for the Environmental Control and Life Support System, Thermal Control System, and an analysis of radiation hazards and effectiveness of protection provided. These efforts are documented in unpublished white papers. Paralleling these system studies, the Spacecraft Analysis Branch sponsored a contractual effort to study the potential application of the Space Transportation System (STS) external oxygen tank as a lunar habitat. A concept for the capture and outfitting of the tank at Space Station Freedom with subsequent set-up on the lunar surface as a lunar habitat for a crew of twelve was developed (ref. 4).

Based upon these previous efforts, the JSC Planet Surface System Office requested the Langley Research Center to study alternate concepts for surface habitats and to recommend one or more habitats as candidates for more detailed study. Also to be included in the study was the identification of new technology associated with the design concepts as reviewed in Appendix B. The work effort was formally assigned the designation, WBS #: 8.4.3, "Planet Surface System." The documentation of this work effort is the subject of this report.

SUMMARY

The design philosophy that will guide the design of early lunar habitats will be based on a compromise between the desired capabilities of the base and the economics of its development and implantation. Preferred design will be simple, make use of existing technologies, require the least amount of lunar surface preparation, and minimize crew activity. Three concepts for an initial habitat supporting a crew of four for 28 to 30 days are proposed. Two of these are based on using Space Station Freedom structural elements modified for use in a lunar-gravity environment. A third concept is proposed that is based on an earlier technology base on expandable modules. The expandable offers significant advantages in launch mass and packaged volume reductions.

It appears feasible to design a transport spacecraft-lander that, once landed, can serve as a habitat and a stand-off for supporting a regolith environmental shield.

A permanent lunar base habitat supporting a crew of twelve for an indefinite period can be evolved by using multiple initial habitats. There appears to be no compelling need for an entirely different structure of larger volume and increased complexity of implantation.

DESIGN GUIDELINES

The Planet Surface Systems Requirements Document published by JSC was used to guide the study; however, it was not imposed on the LaRC study. It did appear prudent to adopt the two phase development of an initial habitat with a crew of four for a 28- to 30-day mission and a later permanent habitat with a crew of twelve for an indefinite length mission. The only other rigid guideline applied to the study was that habitat concepts had to be compatible with existing launch systems or launch systems not more advanced than the Shuttle C. Although formally imposed guidelines were sparse, a two part concept design philosophy was developed early, and it remained pervasive throughout the study. The first part is related to programmatic issues. The thought is that once the need and/or scientific desire for a permanent lunar base has been accepted, the go-no go decision to proceed will be based on a practical compromise between the desired capabilities of the base and the economics of its development and implantation. The program could be scuttled in its infancy if engineers attempt to propose grandiose designs (concepts) that require extensive new technology, completely new launch systems, and massive logistics operations. Thus, the opposite approach guided this study. Propose designs that are as simple as possible and make use of elements from previous and on-going programs such as STS and Space Station Freedom (SSF). Of course, this approach must be tempered with the knowledge that the uniqueness of the lunar environment and the complexities of living and working in it will require some development of advanced technology.

The second part of the design approach is based on a combination of engineering, operations, and human factors issues. With the human crew in a hostile environment, far from help, and encumbered by the limitations of long periods of time in pressure suits, the implantation of the habitat must be as simple as possible. The implantation must involve the minimum amount of surface preparation, consume the least amount of time until becoming operational, require the fewest number of specialized equipment units, and minimize strenuous efforts by crewmen. This approach may not be quite as valid for the implantation of the permanent habitat since the crew will have access to a safe, operational initial habitat.

Most of this design guideline philosophy is parallel in content to a set of concept trade-off criteria that was generated early in the study. In the beginning of this study, the plan was to use the trade-off criteria in an exercise to evaluate habitat concepts with the goal of selecting a "best concept." The study was unable to reach this goal. There are too many unknowns outside the scope of this study that must be resolved before a meaningful trade-off can be completed. For example, one of the most influential guidelines driving this study was that surface activities involved in landing and implantation of an operational habitat had to be as simple as possible requiring the least amount of time, astronaut activities, and special equipment. Most of the concepts presented in this study meet that guideline but in doing so, impose an extensive set of operations to be performed in lunar orbit or low Earth orbit (LEO). If the dominant trade criterion (design guideline) were to be that operations at Earth or lunar nodes had to be minimized, concepts and design features would be significantly impacted. The trade-off criteria which were not used in this study but whose content and rationale ultimately resulted in the design guidelines are presented in Appendix A.

INITIAL HABITAT

As stated under Design Guidelines, concepts for an initial habitat are to be focused on a crew of four and an operational period of 28 to 30 days. The crew size of four duplicates the proposed crew size to be supported by the modules in the early phases of the Space Station Freedom (SSF) mission, therefore, the SSF modules are appropriate analogs for the lunar habitats. The mission length of 28 to 30 days impacts the logistics of life supporting expendables but little else. It does impact the approach to environmental shielding. Shielding against galactic cosmic radiation is not required for this short duration, but protection from solar flare activity would be needed for the 28- to 30-day missions. Once beyond consideration of the impact of the crew size and mission duration requirements on the design of an initial habitat, the design guidelines become the concept design drivers and the three concepts presented respond to those guidelines. The three concepts do make use of existing technology, require few surface operations, attempt to simplify implantation steps, and consume the least amount of time.

For each of these concepts, a baseline configuration is presented. The configurations also include a lander and associated regolith coverage technique since the three concepts presented in this study closely link the habitat modules, lander configuration, and regolith coverage techniques. As in most conceptual design studies, alternate approaches emerge. Some of these alternate approaches are presented for the purpose of conveying ideas. The degree to which the alternate approaches are backed with design details vary, and no effort was made to keep their contents parallel in scope.

Individual subsystems required to sustain the habitats are not included in the study. Subsystems such as the Environmental Control and Life Support (ECLS), Thermal Control, Electrical Power, Communications, etc. will be similar for each of the configurations. For the initial habitats the ECLS subsystem is likely to be open loop with the possible exception of a regenerable carbon dioxide adsorber and a limited amount of hygiene water reclamation. The decision is not configuration dependent. Thermal radiators are expected to be placed some distance from the activity of the base to keep them clean and free of dust. Likewise, photovoltaic solar arrays may also be placed a distance from the base, nuclear power must be away from the base, and any collectors of beamed power will most likely not impact the configuration. If it is desired that radiators or arrays be integrated into the habitat structure, e.g. body mounted radiators, each of the configurations can be adopted with relatively similar weight and difficulty penalties.

Concept 1

Habitat Elements:

The basic concept is a habitat that uses Space Station Freedom elements, some at reduced size, to produce a habitat of minimum volume and minimum length (assuming that it is large enough to be acceptable). Minimum volume and length eases all phases of the transportation scenario, and the minimum volume reduces the logistics problem of supplying gases for initial pressurization and subsequent repressurizations. Minimum length is also desirable when combined with another design goal of producing a lander that can serve as a regolith support frame once the habitat has been set down. The habitat features a double or "two-compartment" airlock. This feature was originally proposed for use on Space Station Freedom. It offers two related advantages, one of which may be considered a requirement for manned operation. With the two compartment airlock, all pressure changes associated with

extra vehicular activity (EVA) egress and ingress can be accomplished without affecting the pressure in the habitat module. Thus, any crewperson not involved in the EVA operation is isolated from most of the noise and all of the physiological stress that would be imposed on the body as it responds to the pressure changes involved in pressure equalization and pump-back procedures (pump back will conserve pressurization gases). It is acknowledged that the initial habitat mission could be completed without the double airlock arrangement. In the single airlock mode, the living habitat would need to be isolated from the airlock. Each time the airlock would be operated, all pressurization gas would be lost unless some type of pump back reservoir were available. The double airlock conveniently allows for the conservation of pressurization gases. A reasonable sized pump can be installed in the inner airlock to pump back 90 percent of the gases in the outer airlock before the outer airlock hatch is opened. The double airlock also provides work space, storage space for pressure suits, an area for the donning and doffing of suits, and a degree of lunar dust control. The single airlock approach may trade-off favorably in the short mission of the initial habitat, but it would not be practical for longer periods of time with the permanent habitats undergoing years of airlock operations.

The Concept 1 habitat could be designed to operate at any atmospheric pressure within the range of acceptable pressures for shirt sleeve occupancy. The study group selected 68.95 kPa (10.0 psi) as the most advantageous internal pressure for all of the concepts presented. This pressure appears to provide the best balance of physiological needs and engineering efficiencies.

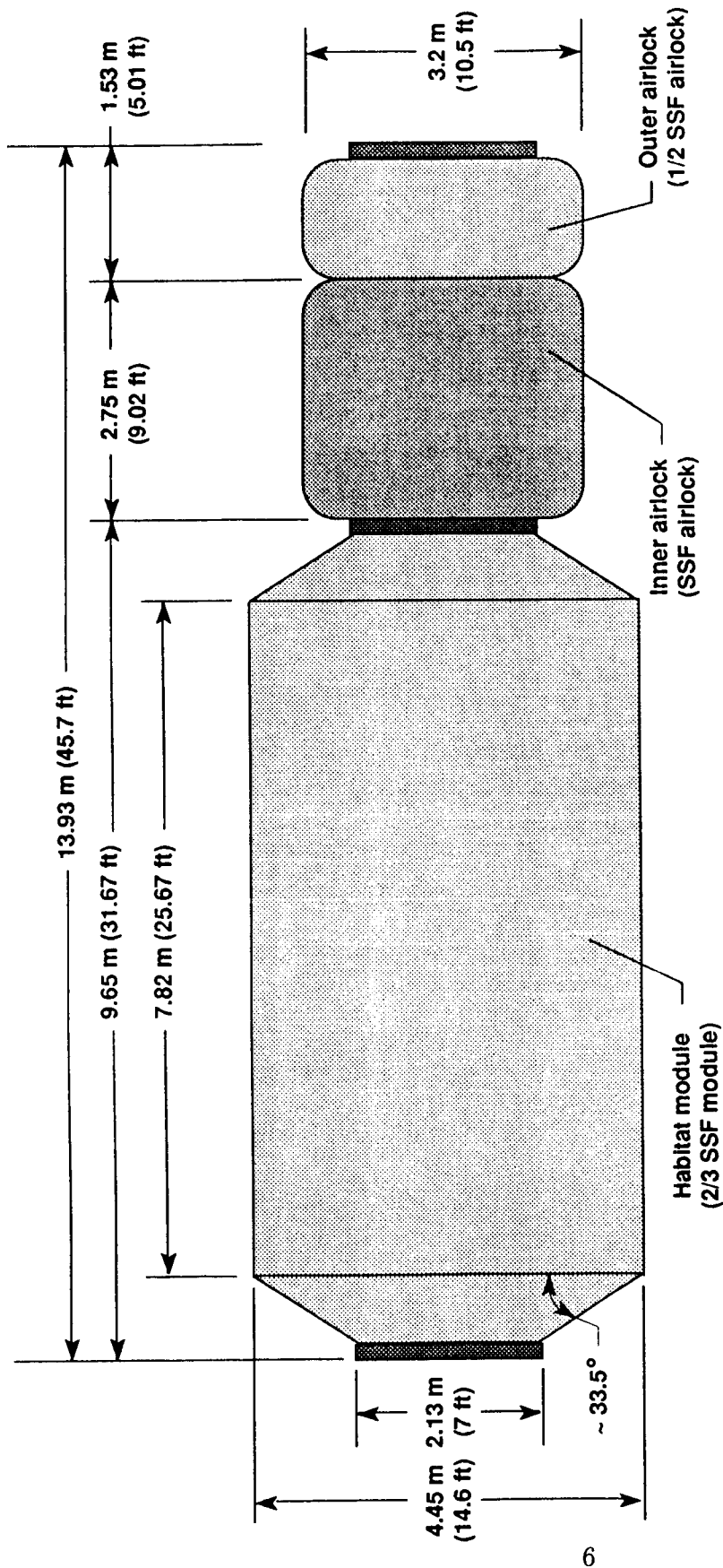
A sketch of the configuration and the element dimensions are presented on figure 1. The dimensions of the habitat module and the inner airlock were obtained from the Preliminary Design Review (PDR) Baseline Space Station Freedom documentation. Dimensions of the outer airlock were established during the study.

The mass empty estimates are volume scaled from the masses of the appropriate SSF element. The mass outfitted estimates are also volume scaled from SSF element data with an adjustment due to the fact that the module cannot be utilized as efficiently in lunar-gravity as it can in zero-gravity because the ceiling area is not as accessible. Volumes are calculated based on the geometry of the configuration.

Lander Configuration and Operational Sequence:

One of the initial goals guiding the development of the Concept 1 habitat was to produce a lander that could serve as the regolith support frame once the habitat had been set down. This goal was one of the drivers in keeping the habitat length, mass, and volume as small as possible while retaining the ability to support the four person crew. A lander of this type has been conceptualized with sufficient supporting detail to suggest that it is feasible. The lander descriptions which follow address transfer requirements, concept features and steps in the flight sequence. All of the concepts and descriptions focus upon use of existing capabilities.

The lander concept for delivery of a Concept 1 habitat to the lunar surface begins with joining of major spacecraft elements in LEO. An assembled spacecraft then moves to the lunar surface by a series of pre-programmed, remotely controllable steps such that regolith fill for shielding is the only crew-tended operation required on the lunar surface. Transfer of an unmanned habitat from LEO to the lunar surface requires a spacecraft-lander assembly that can accommodate the habitat, employ an adequate propulsion technique, and carry the required quantity of propellant. Since all three elements interact, the principal assumptions incorporated are summarized as follows:



HABITAT ELEMENT	APPROXIMATE MASSES		APPROXIMATE INSIDE VOLUME
	EMPTY	OUTFITTED	
Habitat module	7,940 kg (17,504 lb)	10,578 kg (23,322 lb)	121.15 m ³ (4,278 ft ³)
Inner airlock	6,124 kg (13,500 lb)	6,482 kg (14,293 lb)	33.59 m ³ (1,186 ft ³)
Outer airlock			7.33 m ³ (259 ft ³)
TOTAL	14,064 kg (31,004 lb)	17,060 kg (37,615 lb)	162.07 m³ (5,723 ft³)

Figure 1. Concept 1 Habitat

- Spacecraft-lander masses are based upon aluminum materials having a density of $2,700 \text{ kg/m}^3$ (168.56 lbs/ft^3) and operating within the working stress ranges established for the heat treated 2024 alloys. To the extent practical, configurations utilize simply supported beams and hoop tensions to establish the principal structural dimensions at conditions for maximum loading.
- Transfer trajectories for an unmanned spacecraft offer a range of options in moving from LEO to the lunar surface. Previous studies have also identified a number of velocity increment requirements (refs. 5, 6); however, the Apollo mission values are well established and contain sufficient conservatism for use. The velocity increments adopted are:

Earth escape from LEO	3,150 m/sec	(10,345 ft/sec)
Mid-course correction	66 m/sec	(216 ft/sec)
Achieve lunar orbit at 100 km	970 m/sec	(3,183 ft/sec)
Descent from lunar orbit	2,100 m/sec	(6,890 ft/sec)

- Propulsion utilizes uprated Orbital Maneuvering System (OMS) engines operating at the thrust levels defined, e.g., 26,688 N (6,000 lb). Uprating consists of increasing the tank pressure to 1.38 MPa (200 psi) plus employing the alternate hypergolic combination of nitrogen tetroxide (N_2O_4) and unsymmetric dimethyl hydrazine (UDMH, $\text{N}_2\text{H}_2(\text{CH}_3)_2$) to achieve a specific impulse of 3,533 N-sec/kg (360 sec). These engines have a specified burn-life of 15 hours in their present application to the shuttle, and appear to have adequate life margin for an expendable unit in lunar transfer operation.
- Landing on the lunar surface takes advantage of the reduced gravitational acceleration to utilize a free-fall into pneumatic attenuators. In the lunar field, a free-fall from 15 m (49.2 ft) attains a velocity of 6.9 m/sec (22.6 ft/sec) in 4.4 seconds. Attenuators that imposed a deceleration of 20 m/sec^2 (65.6 ft/sec^2) need strokes of 1.2 m (3.9 ft) accomplished in 350 milliseconds. This acceleration profile is considered an inherent capability in all equipment designed for launch by the shuttle or any derivatives.

The overall features and dimensions of the spacecraft-lander are illustrated on figure 2 which presents the "as landed" configuration. A bridge-like strong back provides the principal support element within the spacecraft-lander that transports the habitat from LEO to the lunar surface. A grid of aluminum "I" beams form the strong back. Web dimensions accommodate propellant tanks and flange dimensions are sized to accept landing deceleration loads in bending. Four telescoping cylindrical columns provide support; foot pads distribute spacecraft weight loads at levels compatible with lunar regolith bearing capacities. Each column contains an inflatable bag that accommodates the landing deceleration in a 1.5 m (4.9 ft) stroke against a constant pressure. Residual ullage gases inflate the bags at descent engine stop. These columns also provide mounting for the OMS engines. Engine separation also occurs at descent engine stop. The habitat and airlock unit is carried in a cradle and suspended from the strong back. Cradle side rails engage the trunions which are the normal support points for use during STS launches. Circumferential bands stabilize the assembly during powered flights and landing decelerations. Propellents for the OMS engines are carried in cylindrical aluminum tanks with internal diameters of 0.69 m (2.26 ft). Hoop stress at an operating pressure of 1.38 MPa (200 psi) became the defining limit for a minimum practical wall thickness. A manifold for each propellant constituent (N_2O_4 - UDMH) connect each tank to all engines. Control valve operation selects tanks in a manner that assures adequate flows while minimizing the number of active tanks. Within each phase of the flight, groups

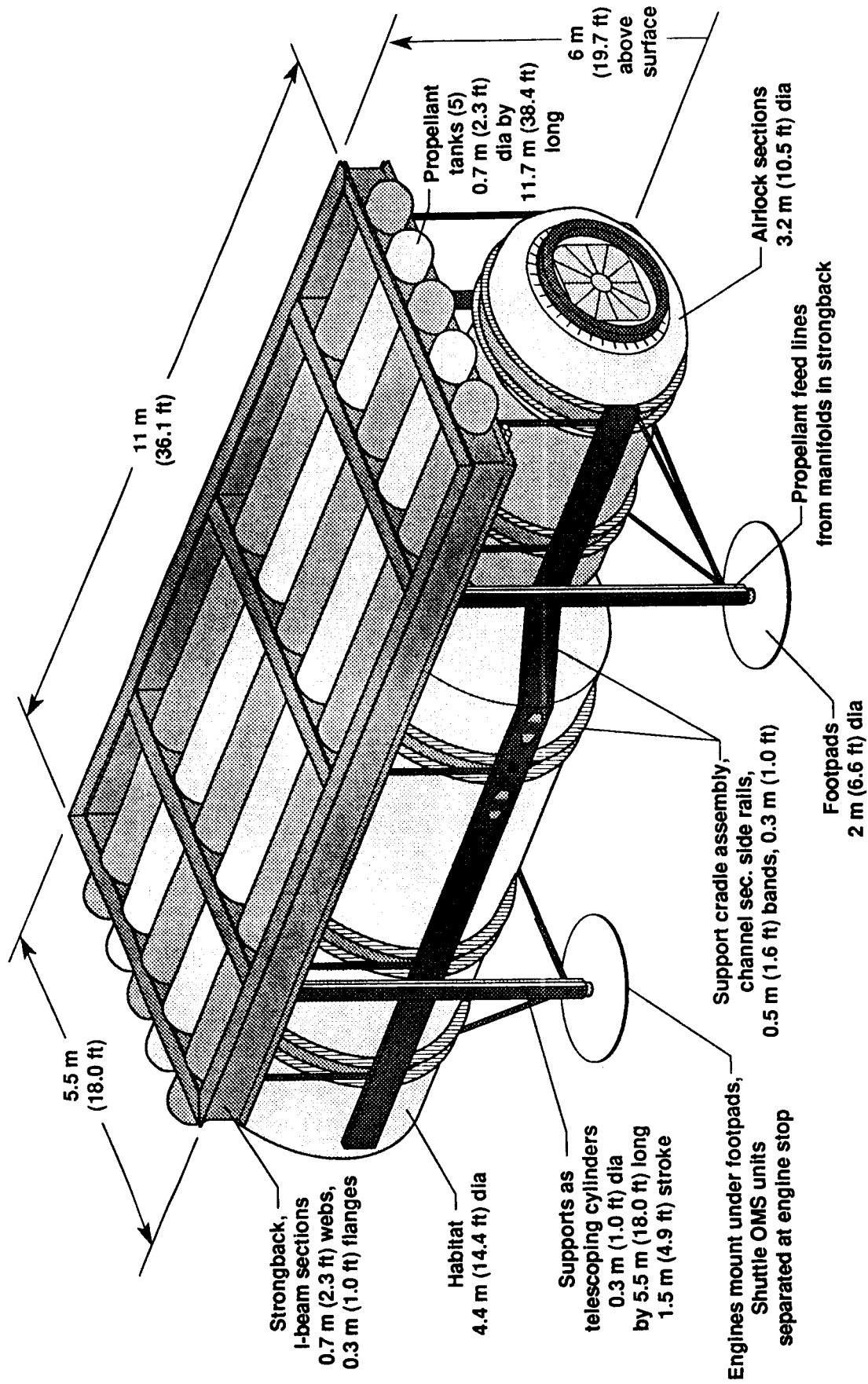


Figure 2. The "As-Landed" Configuration of the Concept 1 Habitat

of tanks separate such that only five tanks remain at touchdown and contain either reserve propellant or ullage gases which inflate the bags used for landing deceleration.

The flight operations sequence for the Concept 1 spacecraft-lander begins in LEO. The final configuration for departure from LEO consists of the landed section augmented by 8 STS, OMS engines and their auxiliary propellant tanks. This configuration is illustrated on figure 3. Steps leading to this configuration in preparation for Earth departure include:

- The habitat and airlock assembly is transported to LEO and docked to an assembly facility which engages the habitat end ring. Space Station Freedom or any other orbital vehicle with remote handling capability can become an assembly facility.
- The cradle then fits to the habitat and airlock, cradle side rails engage and lock to the trunion pins.
- The spacecraft-lander section then engages the cradle. Launch configurations for the lander sections assumes some folding to fit the transporter. A preferred configuration carries all eight engines and their manifold leads connected. The five descent propellant tanks in the bridge structure are full when launched. At completion of this phase, operating verification tests are performed (power, communication, command, guidance and control).
- Expendable propellant tanks are then installed and final electrical verification tests performed. Propellant tanks transport to orbit in separable groups (figure 3 indicates 3 such units). Departure occurs at completion of the assembly and verification testing. Transfer for trajectories and burn sequences for escape from Earth gravity are configuration specific. An unmanned spacecraft with storable, non-cryogenic propellents will utilize an appropriately optimized transfer trajectory. Acceleration levels for transfer appear in the range 1 to 3 m/sec² (3.3 to 9.8 ft/sec²), and do not impose any critical dynamic conditions. Total burn times for the eight engines ranges 30 to 40 minutes, which is less than five percent of their rated life.

Before entry into the lunar gravity field, the spacecraft-lander separates four of the OMS engines and the tanks that contained the escape propellents. Figure 4 shows the configuration just prior to any mid-course corrections. Some type of mid-course correction must be assumed, and will require one or more relatively short engine operations. A direct descent to the surface can be utilized, however, the propellant quantities provide for an orbiting dwell such that the final descent can occur at a time of convenience. Operation of engines during descent and orbital dwell first consumes the propellents contained in the five auxiliary tanks. Final operations before engine stop draw from the three tanks which are carried to the surface. Figure 5 shows the configuration at descent engine stop. Lunar descent utilizing four engines imposes decelerations ranging from 1.3 to 3.6 m/sec² (4.3 to 11.8 ft/sec²) which are not severe. Burn times range from 27 to 30 minutes, such that the total burn time for any engine is less than 10 percent of rated capability. At completion of descent, the engine thrust is more than two times lunar gravity force and appears adequate for control.

At descent engine stop, the spacecraft-lander has become motionless 10 to 15 m (32.8 to 49.2 ft) above a designated landing site. Local attitude for the spacecraft has the engines pointed nadir, the strong back parallel to the lunar surface, and roll rates less than a degree per second. At this time, descent engines separate and clear themselves away from the spacecraft. Ullage gases (or an alternate supply) extend the landing legs. At touchdown the spacecraft-lander has the configuration shown on figure 6. Telescoping struts then absorb the

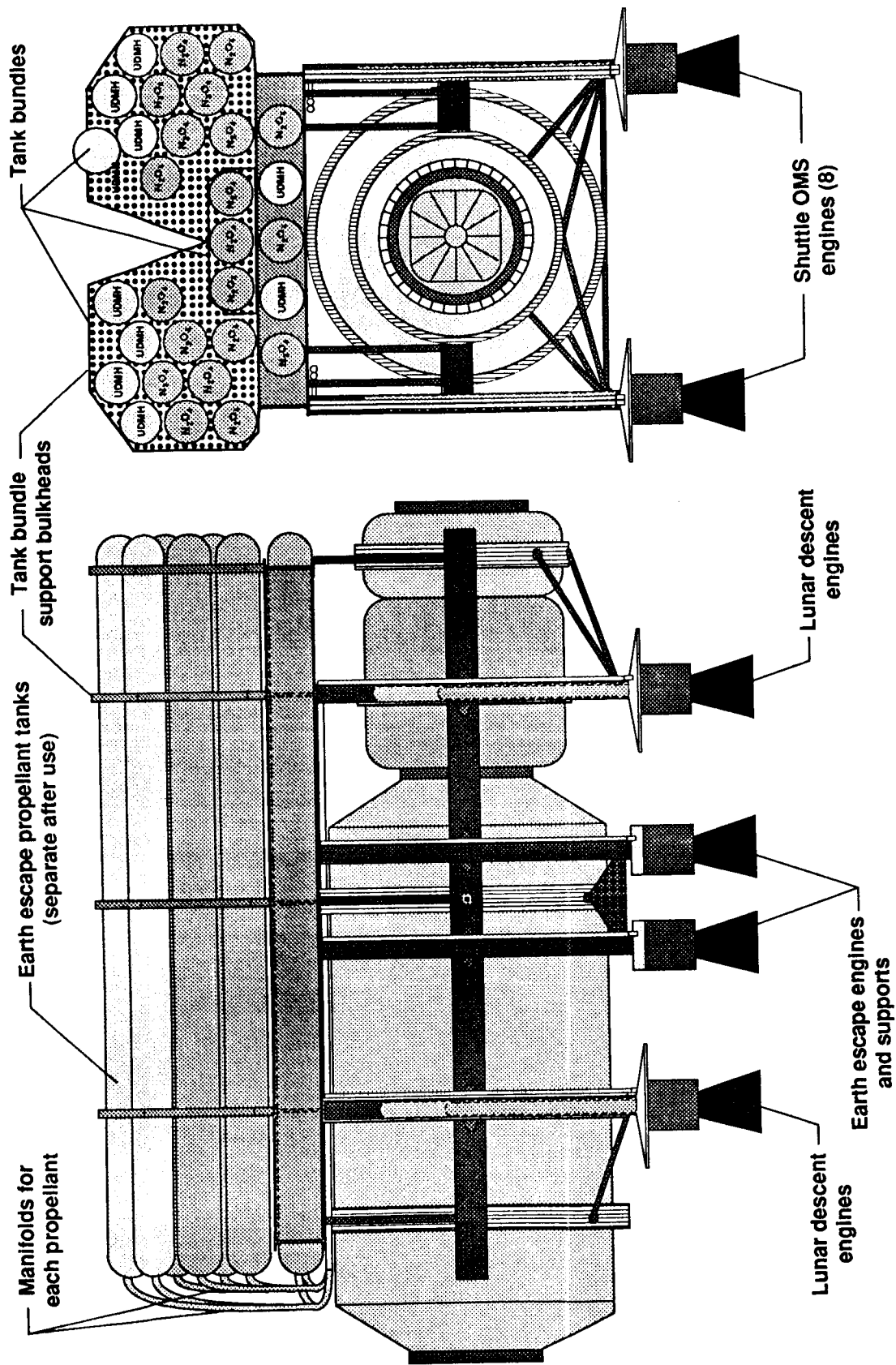


Figure 3. Concept 1 Habitat and Spacecraft-Lander Configuration at LEO Departure

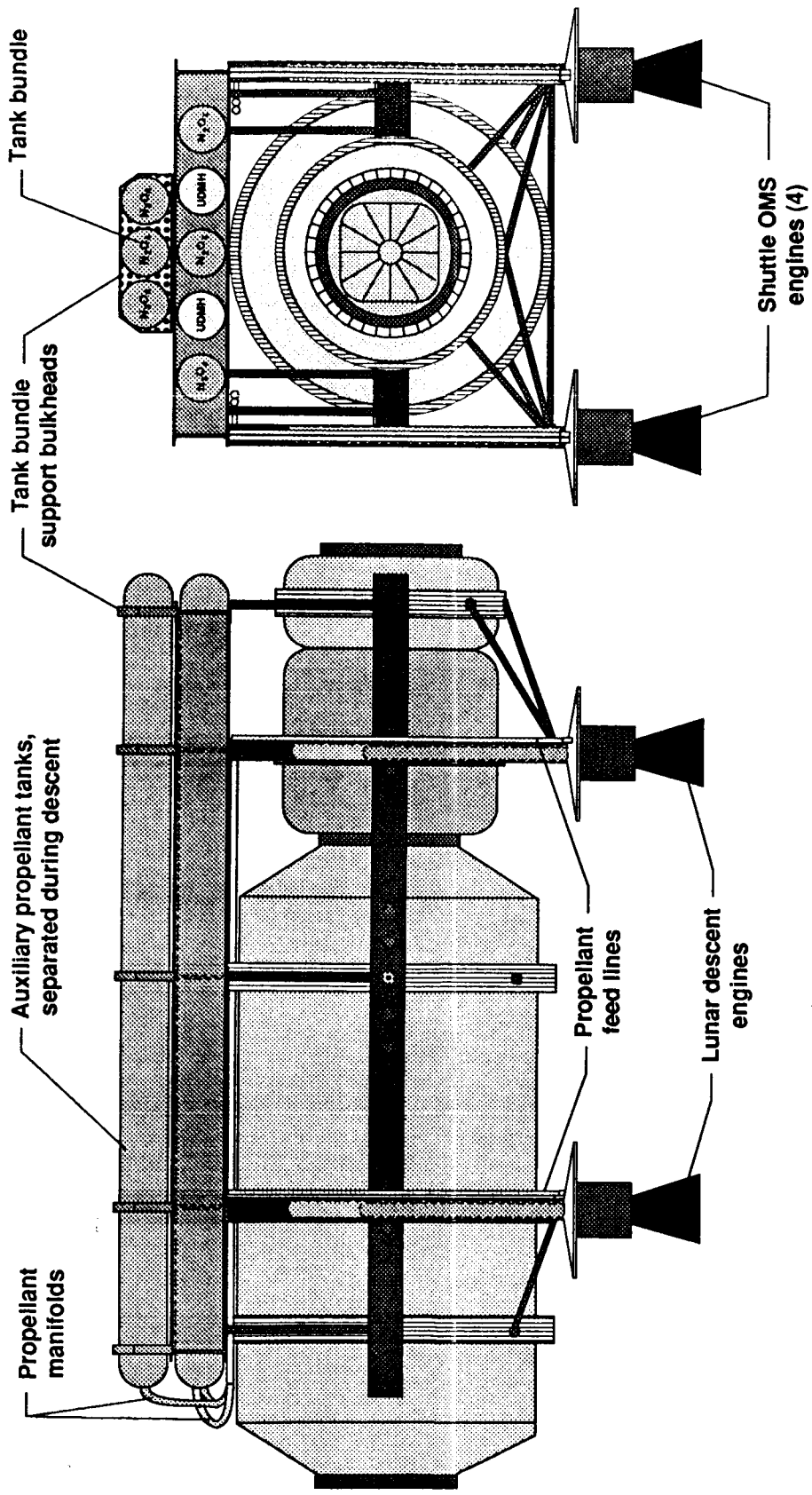
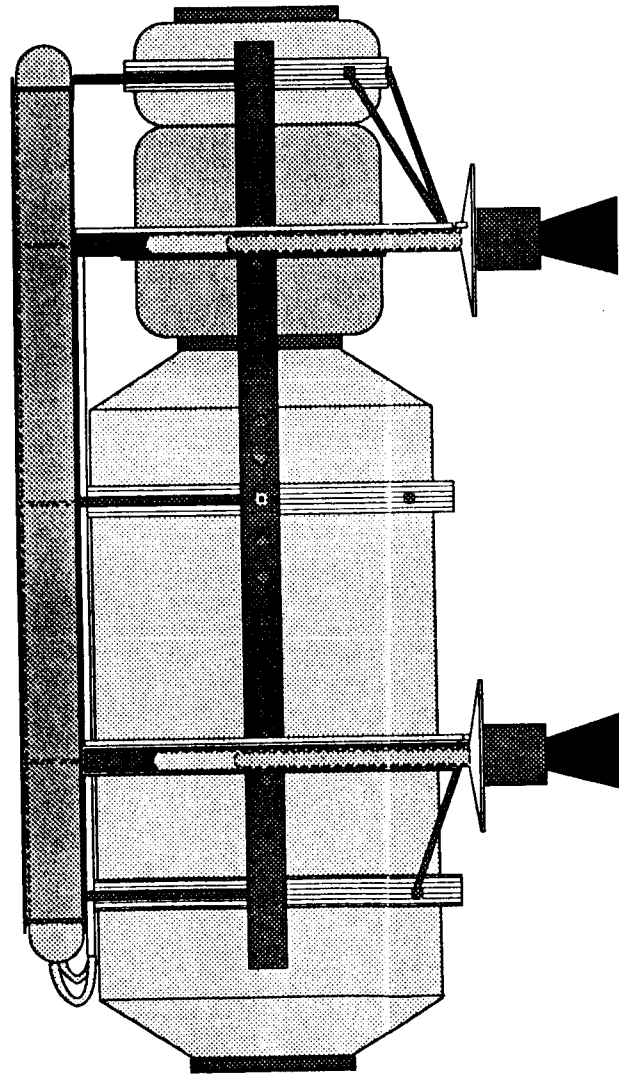


Figure 4. Concept 1 Habitat and Spacecraft-Lander Configuration at Entry into Lunar Gravity Field

Auxiliary tanks separated



- Descent engine separation initiated
- Propellant valves closed

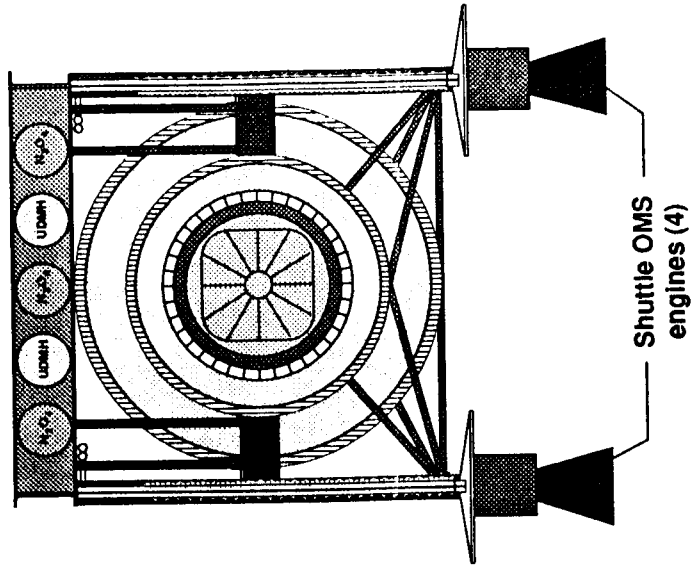


Figure 5. Concept 1 Habitat and Spacecraft-Lander Configuration at Descent Engine Stop

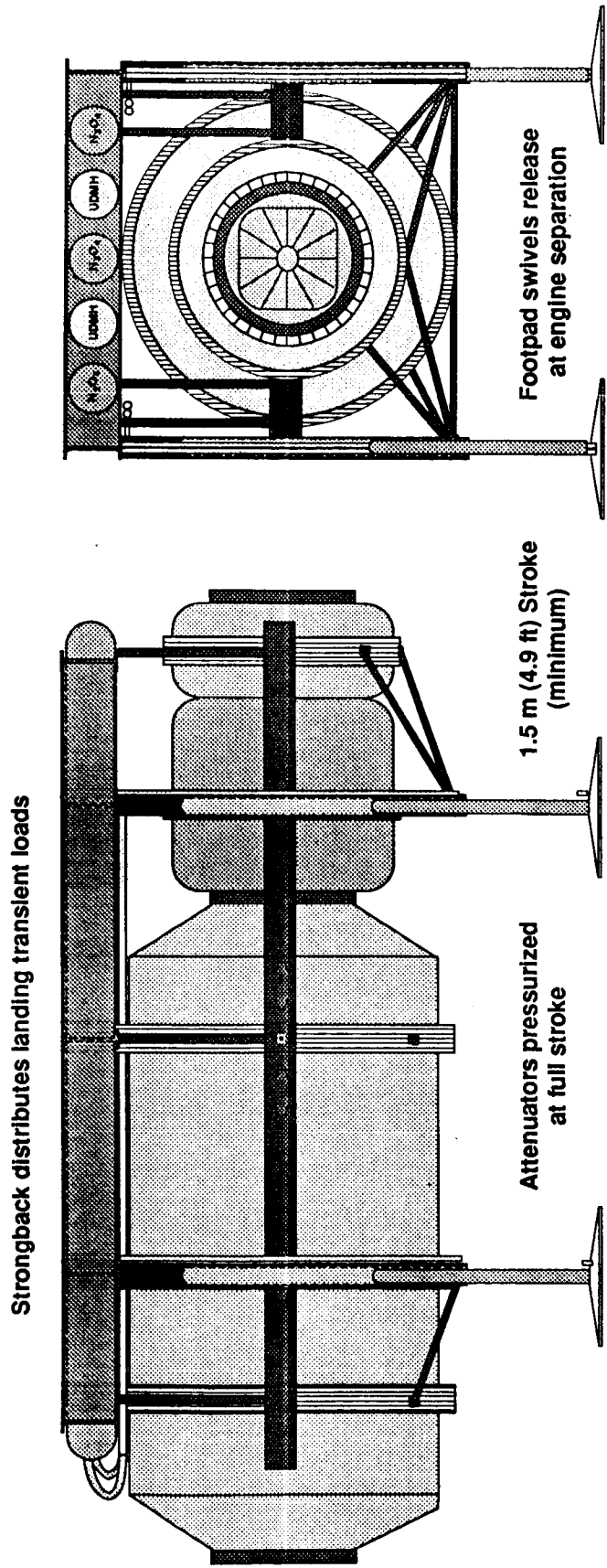


Figure 6. Concept 1 Habitat and Spacecraft-Lander Configuration at Touchdown

landing forces and the entire system comes to rest with the lunar surface weight borne by foot pads. The element masses at the transit stages illustrated on figures 3-6 and the propellents consumed during the transit are summarized in Table 1(a). Table 1(b) presents the mass utilization summary and concludes with a calculation of delivery efficiency expressed as the habitat mass as a percentage of the total mass at LEO departure.

Environmental Shielding:

Some type of shielding placed over the habitat will greatly reduce the stresses imposed by the lunar environment. Most any type of cover could be used to keep the habitat "in-the-shade" thus reducing the thermal cycle stress experienced with the day-night cycle. The most imposing environmental problem, however, is the one due to direct solar and galactic cosmic ray radiation. The 28- to 30-day mission for the initial habitat is sufficiently short in length that the galactic cosmic radiation is not a significant hazard. Direct solar radiation is a hazard only if the mission overlapped a solar flare event. If an event occurred, a safe haven shelter would be necessary. Since some type of environmental shield would help to smooth out thermal extremes and since a habitat will need a flare shelter to combat unpredictable flares, the Concept 1 habitat includes an environmental shield. Another driver in this study that lead to the decision to include an environmental shield on initial habitats is the conclusion that an initial habitat should remain useful in the permanent habitat phase. That conclusion suggests that design concepts should include environmental shields. The most often proposed technique for providing shielding from radiation is to cover the habitat with lunar regolith. At first consideration the concept of coverage with regolith appears to be a simple task but as more thought is given to the question of how to accomplish the task, the more it becomes a design driver to the total design of the habitat concept. Studies at NASA Langley Research Center by Nealy, et al. (ref. 7), have proposed a regolith thickness of 50 cm (19.7 in) or its equivalent areal density in grams/cm² to provide protection. From the standpoint of the overall scenario of habitat design, delivery, implantation, and subsequent operations of the lunar base, the technique chosen to apply the regolith shield is a significant design driver. The technique impacts:

- Design of Habitat Structure - The most immediate impact of the regolith coverage technique is on the design of the structure. If the regolith is to be applied over a separate stand-off structure, the habitat can be designed independent of regolith. However, if regolith is to be placed directly on the structure, a new set of structural requirements emerge.
- Surface Operations - Some method of digging or scrapping with subsequent lifting and dumping large amounts of regolith would be required. This will also require several pieces of heavy equipment. The need for large amounts of regolith will also alter the habitat site and may create intensive trade studies between choosing a single large habitat with regolith obtained from a wide radius vs. separate locations of smaller habitat elements with regolith obtained from a more local area.
- Base Operations - Regolith applied directly to the surface of the habitat will reduce or eliminate access to the wall thus complicating maintenance and/or modifications which require access to the exterior of the habitat. In contrast, regolith applied on a separate stand-off structure provides a convenient (beside the habitat) place for a shaded cold storage of cryogenics and any other material for which the heat and intensive ultraviolet of the lunar day would be destructive.

The baseline environmental shielding technique for the Concept 1 habitat is to use the lander as a stand-off regolith support frame. The first step in the process is to adjust

TABLE 1. SUMMARY OF MASSES FOR CONCEPT 1 HABITAT AND SPACECRAFT-LANDER

(a) AT TRANSIT STAGES

Element	Element Mass kg	Total Mass kg (lb)
Habitat - Airlock Assy		17,060 (37,615)
Spacecraft-Lander		6,035 (13,307)
Cradle	1,217	
Beams	1,762	
Legs/Feet	906	
Tanks, Manifold, Valves	1,400	
Regolith Containment Bags	750	
Residual Propellant		1,905 (4,200)
N ₂ O ₄ (0.8 m ³)		
UDMH (0.5 m ³)		
TOTAL LANDED		<u>25,000</u> (55,125)
Engines Separated		1,000 (2,205)
4 Engines	480	
4 Controls and Auxiliaries	520	
TOTAL AT ENGINE STOP		<u>26,000</u> (57,330)
Descent Tanks, Separated (3 Tanks with Manifolds, Valves)		840 (1,852)
Descent Propellant Consumed		38,480 (84,848)
N ₂ O ₄	28,994	
UDMH	9,486	
TOTAL AT LUNAR FIELD ENTRY		<u>65,320</u> (144,030)
Post-Burn Separations		10,000 (22,050)
4 Engines and Supports	1,600	
22 Tanks + Valves, Manifolds	6,500	
Stabilizing Structure	1,900	
TOTAL AT EARTH ESCAPE VELOCITY		<u>75,320</u> (166,080)
Propellant Consumed		111,852 (246,634)
N ₂ O ₄	85,201	
UDMH	26,651	
TOTAL AT LEO DEPARTURE		<u>187,172</u> (412,714)

(b) MASS UTILIZATION SUMMARY

Lunar Surface Delivered	25,000 (55,125)
Jettisoned En Route	11,840 (26,107)
Propellants Consumed	150,322 (331,482)
TOTAL	<u>187,172 (415,714)</u>
Delivery Efficiency (Habitat Mass as a Percent of Total)	13.3%

the length of the main support legs using jack screws. A modest adjustment up to 0.5 m (1.6 ft) will result in level floors within the habitat. After leveling the lander, the regolith containment bags are released to fall into place for filling operations. The regolith containment bags for the sides mount against the webs of the I beams; upon release they fall into place with the bottom surfaces of the bags in contact with the lunar surface. Regolith bags that cover the front face can also mount against the I beams and rotate into place or mount under the strongback above the airlock and deploy. Bag construction maintains regolith shield thickness by means of stabilizers at locations down the bags. These stabilizers are meshes with openings that permit the flow of particles but retain the required dimensions for effective shielding. Bags are constructed of a flexible fiber-reinforced polymeric sheet. Totally shielding the habitat involves covering the exposed aft end with a free standing pile with an equilibrium slope (36° slump) surface. The volume formed corresponds to a wedge-shaped segment and approximately two thirds of a right circular cone. The height of the cone and wedge has been estimated at 6 m (19.7 ft), the radius of the cone and base of the wedge is 8.3 m (27.2 ft). The length of the wedge segment equals the diameter of the habitat.

The Concept 1 habitat in the regolith covered configuration is shown on figure 7. This configuration requires 50.05 m^3 (65.5 yds^3) for the top, 92.40 m^3 (120.8 yds^3) for the two sides, 14.87 m^3 (19.4 yd^3) for the front face, and 398.80 m^3 (521.6 yds^3) for the aft pile. The total amount of regolith required is 556.12 m^3 (727.4 yds^3) of which the aft pile is 72 percent of the total. The requirement for the large quantity to cover the aft end suggests looking at an alternate technique for shielding this portion of the habitat. Lunar surface loadings for the configuration show a maximum internal pressure within the regolith bags of 14,864 N (2.13 psi) and footpad loadings of 13,482 N (2.0 psi). Each support column carries a load of 42,355 N (9522 lb) which is 30 percent of the landing dynamic load.

Alternate Approach:

The habitat elements of Concept 1 were selected specifically to result in a minimum dimension, volume, and mass envelope to be compatible with a lander that can suspend the habitat beneath the lander and can serve as a stand-off regolith support stand. The habitat elements, however, are not limited to use with the lander concept presented. The habitat could easily be carried to the lunar surface as cargo on top of a lander of the type described as the Lunar Module in the JSC 90-day study (ref. 8), or the three-legged lander described in the Eagle Engineering Study (ref. 9). If used with either of these two landers, the habitat would need to be off-loaded and be placed on a support base. One approach to supporting the habitat would be to use the trunion support pins used for supporting SSF modules in the Orbiter cargo bay as support points. Six single tube columns of "floor jack" style located as illustrated on figure 8 could easily support the static load. An analysis of this configuration determined that the maximum static load at any one of the six supports would be approximately 4,341 kg (9,571 lbs). Applying a safety factor of 1.5 produces a static load of 6,512 kg (14,357 lbs). Tubular aluminum columns of aluminum 6061-T6 alloy with an allowable stress of $9.65 \times 10^4 \text{ kPa}$ (14,000 psi) could be applied in a wide selection of cross sections to form the column supports. The supports would include an undefined type of threaded rod/drive nut arrangement similar to floor jacks to provide height adjustment for levelling.

Although the single tube column would have sufficient strength for supporting the habitat, tip over stability would be questionable. As an alternate, aluminum tripods folded during

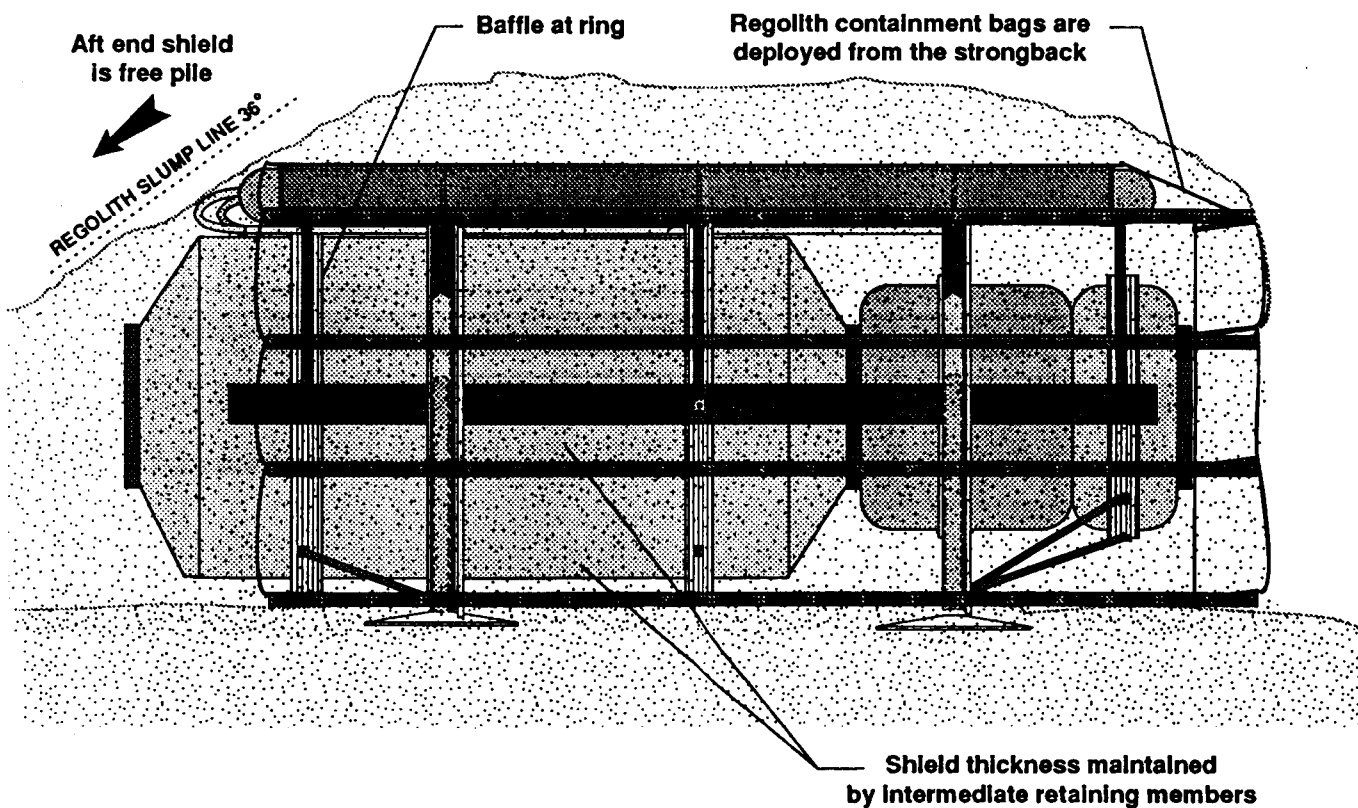
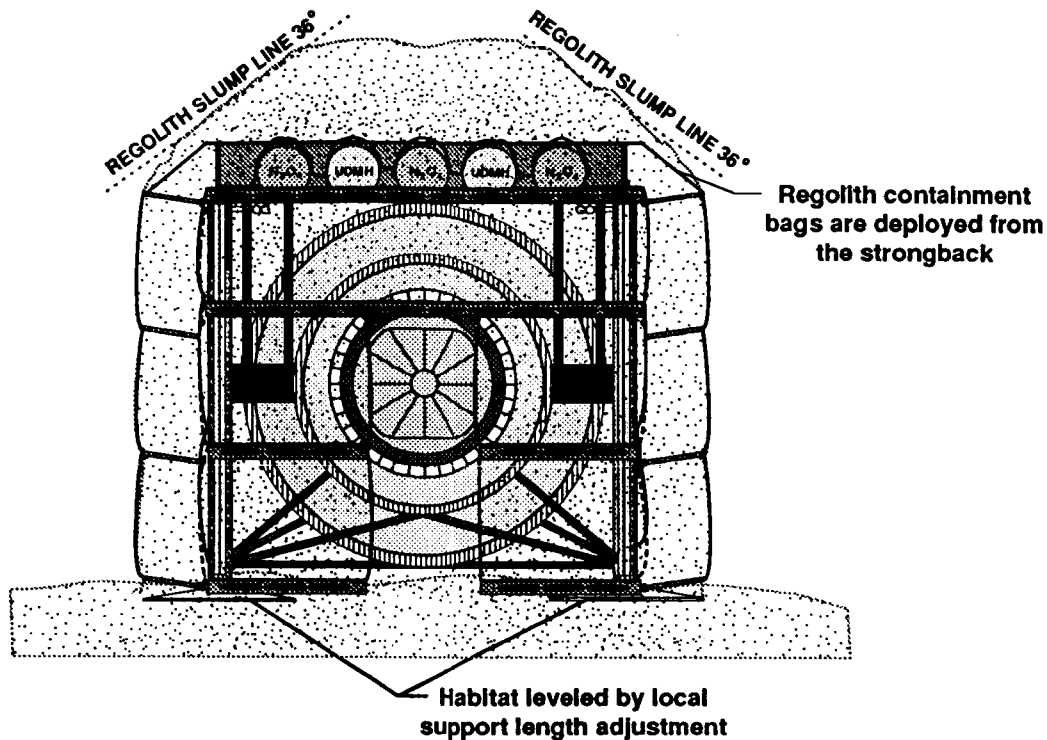


Figure 7. Concept 1 Habitat with Regolith Shield

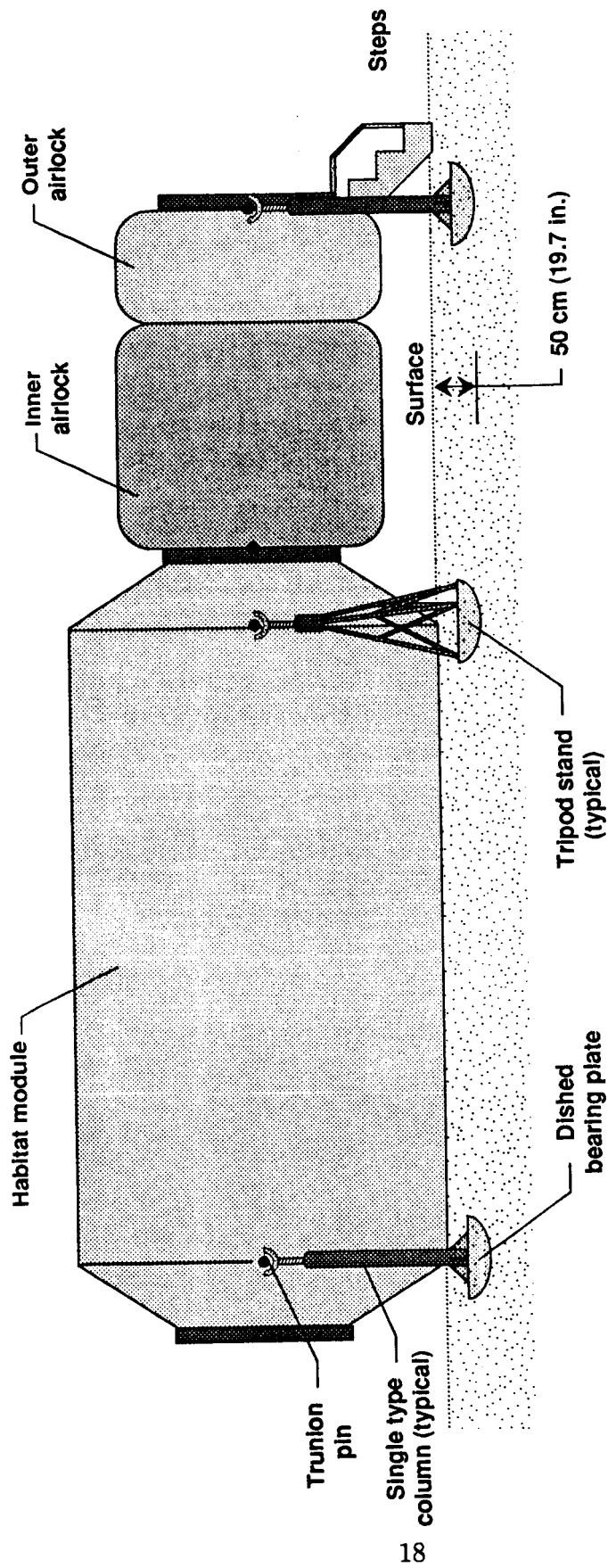


Figure 8. Alternate Column Supports for a Concept 1 Habitat

transit could also be used to support the habitat at the trunion pin locations. A sketch of a typical configuration is included on figure 8. Design details have not been developed.

The bearing surface area of foot pads for either type of column discussed above has been defined using the lunar soil bearing capacity equation presented and discussed in reference 10. The equation states:

$$Q_{\text{all}} = k d_{\text{acc}}$$

where:

Q_{all} = allowable bearing capacity

k = modulus of subgrade reaction

d_{acc} = acceptable settlement

The reference suggests using a value of 2 kPa/cm for the value of k and a value of between 30–100 cm for d . A settlement depth of 50 cm was selected. Thus, the bearing capacity of 100 kPa (2,089 lbs/ft²) results. This bearing capacity and a safety factor of 1.5 defines a foot pad bearing surface area of (0.64 m²) (6.87 ft²). A dished footpad with a diameter of (0.90 m) (2.96 ft) would be required.

Technology Assessment:

One of the major advantages of a Concept 1 habitat is that little new technology would be needed. The habitability module and the double airlock elements are assembled from SSF modules and airlock components, and the assumption is made that the space station will be operational when the implantation of a lunar base begins. Some of the supporting systems, such as a regenerative life support system, would require at least one design and test iteration to modify some of the phase separation devices from zero-gravity to lunar-gravity functional components. In general, the switch from zero-gravity function to lunar-gravity function would be a simplification of process. If the habitat were to be used only for the 28 to 30-day mission of the initial habitat, many of the regenerative subsystems would not be required. For a mission of that duration the only regenerative components applicable would be a regenerable carbon dioxide concentrator and a water reclamation unit probably limited to the recycling of hygiene waters. The current SSF baseline carbon dioxide concentration unit, the artificial zeolite molecular sieve, is not a gravity sensitive unit. The SSF baseline hygiene water reclamation unit, the uni-bed multifiltration unit, will inherently work better in a gravity field with the exception of the phase separations discussed above.

The element of the Concept 1 habitat needing the most technology development is the spacecraft-lander configuration that also serves as a regolith stand-off. To our knowledge a lander of this type with a large load suspended within the lander frame has never been designed and studied in detail.

Delivery and emplacement of a habitat-airlock assembly as a lunar base principally requires adaptations of existing concepts to a new application. Therefore, technology assessments can address the degree of readiness within present capabilities toward applications to lunar base concepts. Technology readiness criteria have been developed for assessing NASA sponsored developments (ref. 11), and these appear adaptable to lunar base habitats. Table 2 lists the seven established technology readiness levels and, using the same type of evolutionary logic, makes a corresponding level assessment for lunar habitats. Technology development needs are summarized in Table 3. The listing identifies needs, indicates the action or response required, and estimates present technology readiness. The technology

TABLE 2. TECHNOLOGY READINESS LEVELS

	<u>Technology Forecast Criteria</u>	<u>Corresponding Lunar Habitat Criteria</u>
Level 1	Basic Principles Observed and Reported	Concept with no Previous Application
Level 2	Conceptual Design Formulated	Related Concept Proposed for Application
Level 3	Conceptual Design Tested Analytically or Experimentally	Related Concept with Limited Application
Level 4	Critical Function/Characteristic Demonstrated	Concept with Established Operation in Previous Flights
Level 5	Component/Breadboard Tested in Relevant Environment	Concept in Active Update for New Application
Level 6	Prototype/Engineering Model Tested in Relevant Environment	Presently Operational in Reduced Scale or Complexity
Level 7	Engineering Model Tested in Space	Existing Capability in Present Use

developments show significant interactions. The following discussions address the developments and their interacting relationships to spacecraft configuration, propulsion, trajectories, landing and emplacements.

Spacecraft Related Technology Needs (1,2,3)

The final configuration of the spacecraft-lander elements that transport the habitat must simultaneously optimize mass, be transportable to orbit in shuttle dimensioned boosters, and be capable of being assembled in orbit using remote handling equipment to the maximum extent practical. Previous studies have indicated mass savings ranging from 15 to 45 percent by use of existing advanced composite materials. Velocity increments and specific impulse establish the propellant requirements associated with any delivered mass; however, the mass summary shown in Table 1 indicates a 5 metric ton reduction in propellant to LEO for each metric ton eliminated from the mass of the spacecraft-lander section. Assembly in space emphasizes the need for self-deploying or self-erecting configurations. Such concepts have received extended studies in support of existing flight projects and Space Station Freedom (refs. 12, 13). Equipment to support and service such deployables have also been addressed and such items are considered part of the SSF project activity. Finally, pyroactuated devices have an established capability as an effective technique for operating latches and releases, and they are considered available for this application. The trade and definition studies to define a flight configuration appear within the capabilities of an experienced technical team.

TABLE 3. SUMMARY OF TECHNOLOGY DEVELOPMENT NEEDS FOR CONCEPT 1

	Technology Need	Action or Response Required	Technology Readiness Level
1	Spacecraft-Lander Optimized for Mass Efficiency in a Configuration Compatible with Launch Vehicle Dimensions	Interactive Trade Studies for Selection of Materials and Structural Analysis Leading to a Proposed Configuration	6
2	In Orbit Assembly Sequence Defined for Accomplishment by Remote Manipulators	Define and Implement End Effectors and Control Techniques for Shuttle RMS and SSF Remote Units	5
3	Remotely Operated and Pyroactuated Joints or Release Mechanisms	Definition Studies and Verification Tests	4
4	Shuttle OMS Engines Operate at a Specific Impulse of 3,533 N-sec/kg and any achievable increase in thrust	Design Refinements, such as Increased Operating Pressure, Higher Energy Propellants	6
5	Control Technique for Multi-Engine Operation	Develop Techniques for Thrust Trim Control and Control Algorithms Compatible with 4 and 8 Engine Operations	6
6	Propellant Delivery from Storage that Accommodates Multiple Restarts and Jetting of Empty Tanks	Trade and Design Definition Study Addressing Pressurization and Flow Control Techniques	4
7	Transfer Trajectory and Time Line for Remote Operation Delivery to the Lunar Surface	Transfer Trajectory and Descent Analysis to Define Optimum Sequences and Mission Timing	7
8	Landing Deceleration Technique Compatible with the Combined Mass of the Habitat, Airlocks and Lander	Technical Trade and Design Study to Define the System, Verification Testing to Confirm Operation	4
9	Regolith containment bags or packets that will fold and nest during transit and be routinely deployed after landing	Detailed Requirement Studies Followed by Design Studies Relative to Specific Configuration	1-2
10	Materials Transfer Technique Capable of Moving Regolith to the Height Identified (~ 6 m) and in the Quantities Estimated	Trade and Design Study for Definition of Candidate Systems - Verification of Candidates for Selection	3

Propulsion System Technology Needs (4,5,6)

For any velocity increment, the specific impulse of the propellant determines the quantities required. Of the available propellents $H_2 - O_2$ carries the highest range for specific impulse and has been the propellant of choice for most of the lunar exploration studies (refs. 14, 15). Hyperbolic propellents offer the next lower alternative range with $N_2 O_4 - UDMH$ showing the highest value. Uprating the shuttle OMS engines appear as a near-term achievement particularly since the present configuration has shown nearly a decade of successful flight operations. Uprating of the present engines could easily result in an increased thrust. The present engines operate at a specific impulse of 3,067 N-sec/kg and show a propellant flow of 8.70 kg/sec distributed as 3.28 kg/sec fuel and 5.42 kg/sec oxidizer. An uprated engine with the same fuel flow for UDMH would require 7.84 kg/sec of N_2O_4 and produce a thrust of 46,352 N (10,420 lb); an adequate margin for all phases of flight. Hypergolics with their lower specific impulse values carry the disadvantage of additional propellant mass delivered to orbit. On the the other hand, multiple restart is an inherent capability for pressure fed hypergolic systems, and they avoid the complexities associated with long-term storage of cryogenic liquids. Multi-engine operation is a well established technique as shown by the major boosters and shuttle operations. Extension of multi-engine control to eight, pressure fed hypergolics is a recognized advancement and introduces a particular requirement for accommodating transients at start or stop plus trimming of thrusts among the eight engines. Propellant flow and ullage management differ from shuttle operations in two principal areas. Tanks jettison after use, and maintaining a spacecraft center of mass position is an anticipated requirement imposed upon propellant flow. Ullage pressure generated by controlled combustion of the propellents has been addressed and appears to offer some advantage for this application.

An effort that accomplishes the developments outlined will require an experienced propulsion design and test team. Equipment modifications and flow control elements need to move through design into a comprehensive verification testing before commitment to flight. In a similar manner an algorithm that provides thrust vector and thrust trimming control has to be defined, generated, and verified by operation.

Transfer Trajectory and Timing Technology Need (7)

Transfer trajectories for lunar exploration have considered propulsion options ranging from solar sails to high thrust boosters; however, all lunar bound flights to-date have involved departure and deceleration forces in excess of Earth gravitational. Transfer trajectories and descent profiles utilizing relatively low accelerations do fall within the range of previous work. A principal difference in this application appears to be the use of fixed thrust engines with no limit on restarts. The only assumption carried into trajectory definition is characterization of the lunar surface to the degree that a landing site can be selected compatible with a remote touchdown for a unit of the size indicated.

Definition of the transfer and descent profiles is considered within present capabilities of an experienced technical team and would be a short-term effort beginning with establishment of spacecraft masses, thrust levels and selection of a landing site.

Landing Deceleration Technology Need (8)

A free fall into a long stroke energy absorber appears as a readily available technique for landing a massive assembly on the lunar surface. Crushable absorbers have been used on Surveyor, Viking, and the Lunar Excursion Module, and they are candidates for this application. Vented air bags were developed by the LaRC and have been used commercially.

Their advantage in this application appears in the capacity to inflate when needed and utilize gases carried for other purposes (ullage) and thereby introduce an element of synergy. The attenuator system is considered a design exercise within capabilities of existing technical teams. A test facility to evaluate lunar landing has been developed at the LaRC. That facility has been adapted for evaluation of aircraft impacts; however, it can be restored to the lunar simulation capability.

Regolith Containment Need (9)

One of the more universal needs among most concepts of lunar habitats is the need for materials selection and design concepts for regolith containment devices. Many concepts including Concept 1 and 3 in this study require bags or pockets that are folded for transit and are deployed only when regolith fill is initiated. It is easy in a conceptual design study to state their presence and assume the capability to produce them. It is believed, however, that defining a specific suitable design will be a challenging technology development problem. There appears to be at least five issues related to this technology item: (1) the selection of a suitable fabric mat type of material; (2) definition and fabrication of a specific design; (3) a technique for folding and securing the item during transit; (4) a technique for deploying it when needed; and (5) the integration of the container design with the design of the regolith application device; a type of dumping or blowing device. When the entire regolith shield provision is viewed collectively, it may be the pacing technology development for most design concepts.

Regolith Transfer, Technology Need (10)

A number of techniques have been proposed for emplacing lunar regolith as radiation shielding. This study has not attempted to select a specific design of a regolith application device although conceptual designs did evolve during the study. It is recognized that the selected design will be defined after consideration of many factors including transportability, functionality on the surface, regolith properties, amount of regolith to be moved and the resulting area to be dug or dredged, lift height involved, and delicacy of the dump and/or fill operation. The Concept 1 habitat requires both dump and fill operations with a vertical lift of approximately 6 m (20 ft). It is believed that an appropriate piece of equipment can be adapted from terrestrial Earth equipment design. Regardless of the applicability of Earth analogs, the unique characteristic of the total lunar base scenario will require a new development and extensive analytical and experimental testing.

Concept 2

Habitat Elements:

The basic concept is a habitat that uses full size Space Station Freedom elements to produce a habitat similar to the habitat of the space station. There are two variations from the SSF configuration. The Node used for the inner airlock would have the lateral hatches removed and replace with a continuous wall. The outer airlock would be fabricated from Node components but be reduced to approximately half length to reduce volume and, therefore, reduce gas loss during EVA activity. Two other features are prominent with the Concept 2 habitat. Due to size and mass, it is expected that the module and the double airlock would be delivered by two separate landers. The module and airlock would need to be joined after being removed from the landers. The other prominent feature is the regolith support technique. Panels are attached to the module and double airlock and folded

for transport and are unfolded after landing and used for regolith support. Note that the double airlock arrangement is present; however, each section of the airlock is larger and provides more volume than the double airlock of Concept 1.

A sketch of the configuration and its element dimensions are presented on figure 9. The dimensions of the habitat module and inner airlock were obtained from Space Station Freedom documentation. Dimensions of the outer airlock were established during the study.

The mass empty estimates are the reported masses of the appropriate SSF element. The mass outfitted are those of SSF elements with an adjustment due to the fact that the module cannot be utilized as efficiently in lunar-gravity as it can in zero-gravity because the ceiling area is not as accessible.

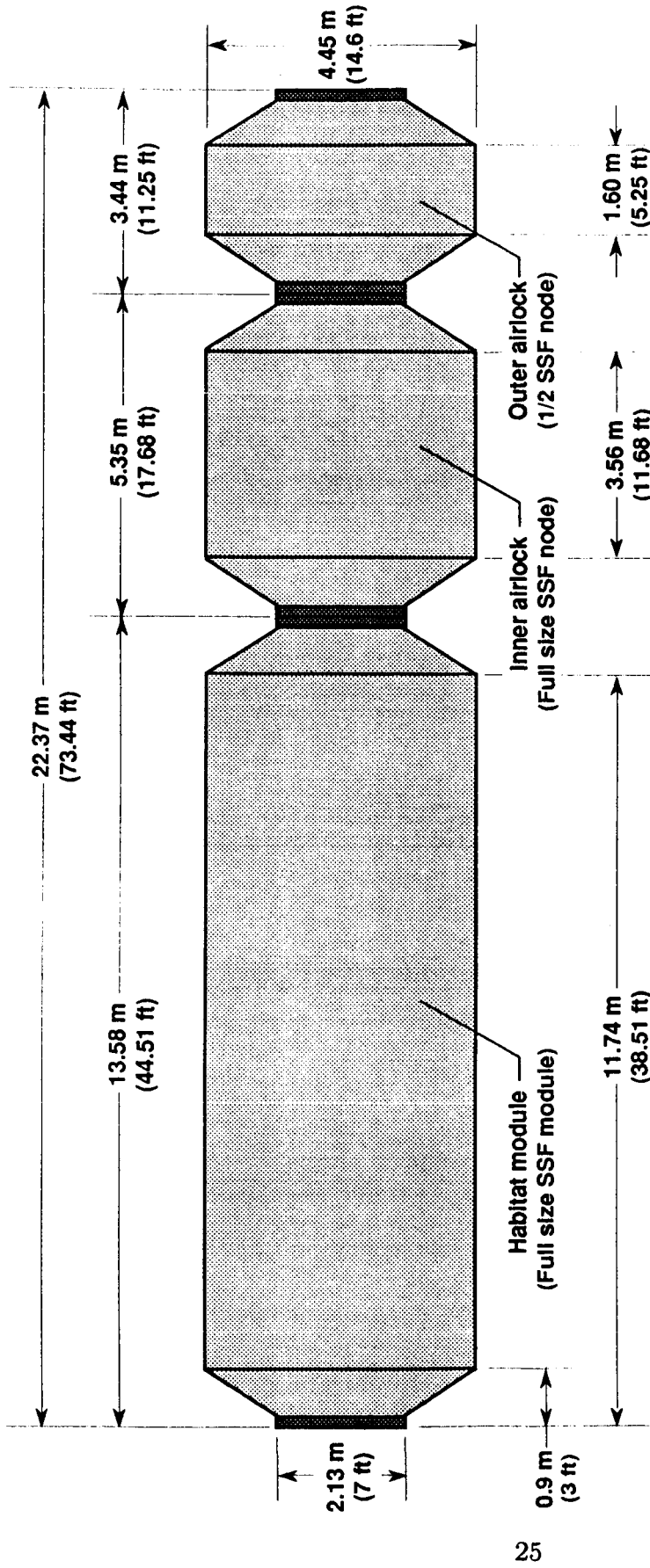
The double airlock arrangement and operation is the same as that of the Concept 1 habitat and the total pressure of 68.95 kPa (10.0 psi) is also the same.

Lander Configuration and Operational Sequence:

The landers which deliver separate habitat and airlock sections to the lunar surface also begin with joining of major spacecraft elements in low Earth orbit and utilize the same general approach previously described. The habitat module spacecraft and the airlock section spacecraft move independently to the lunar surface by a series of pre-programmed, remotely controllable steps. The same transfer requirements and assumptions previously defined apply to the delivery of the two-part system. A separate flight for each portion does introduce additional constraints relative to trajectory definition and landing site selection which include:

- The flight profiles for each of the two elements will achieve lunar touchdowns within a reasonable distance of each other; perhaps within one kilometer.
- Knowledge of the landing site terrain will assure a barrier-free surface between the two landed units.

The spacecraft-lander for the Concept 2 habitat includes design features that function as habitat support (base and cradle) and regolith support components. The overall features of the spacecraft-lander in the "as landed" configuration can be seen in figure 10. The cradle assemblies shown provide the principal spacecraft-lander elements which support the airlock and habitat sections throughout the transfer flight, landing, and lunar surface operation. Cradle side rails provide the load distribution during powered flight and landing; attachments to the habitat and airlock section utilize the trunion pins employed for launch. Circumferential bands stabilize the sections and provide mounting points for tanks and engines. The lower segments of each cradle band fair into gusset brackets that provide mountings for propellant tanks, propellant manifolds, and OMS engines. Upper segments of the bands also accommodate propellant tanks which can be separated when emptied. The cradle also supports the regolith containment panels which are discussed under Environmental Shielding. The flight operations sequence for the Concept 2 spacecraft-lander begin in LEO. Each of the two habitat/spacecraft-lander units become separate spacecraft at departure. Each carries auxiliary OMS engines during the boost phase away from Earth gravity; auxiliary engines and propellant tanks jettison at completion of their use. Figure 11 shows the two units in their LEO departure configuration. Considerations and steps outlined previously also apply to the in-orbit assembly, verification testing, and flight sequence. For these units, the departure acceleration range from 0.7 m/sec^2 to 2.9 m/sec^2 (2.3 ft/sec^2 to 9.5 ft/sec^2) with burn times of 47 and 30 minutes. An uprating of engines that also increases the thrust levels enhances the transfer operations.



HABITAT ELEMENT	APPROXIMATE MASSES		APPROXIMATE INSIDE VOLUME
	EMPTY	OUTFITTED	
Habitat module	12,030 kg (26,521 lb)	15,034 kg (33,151 lb)	174.62 m ³ (6,166 ft ³)
Inner airlock	6,305 kg (13,900 lb)	6,304 kg (13,900 lb)	62.92 m ³ (2,222 ft ³)
Outer airlock	3,152 kg (6,950 lb)	3,172 kg (6,995 lb)	36.14 m ³ (1,276 ft ³)
TOTAL *	21,487 kg (47,371 lb)	24,510 kg (54,046 lb)	273.68 m³ (9,664 ft³)

* These totals do not include the additional items required for flight. See Table 5.

Figure 9. Concept 2 Habitat

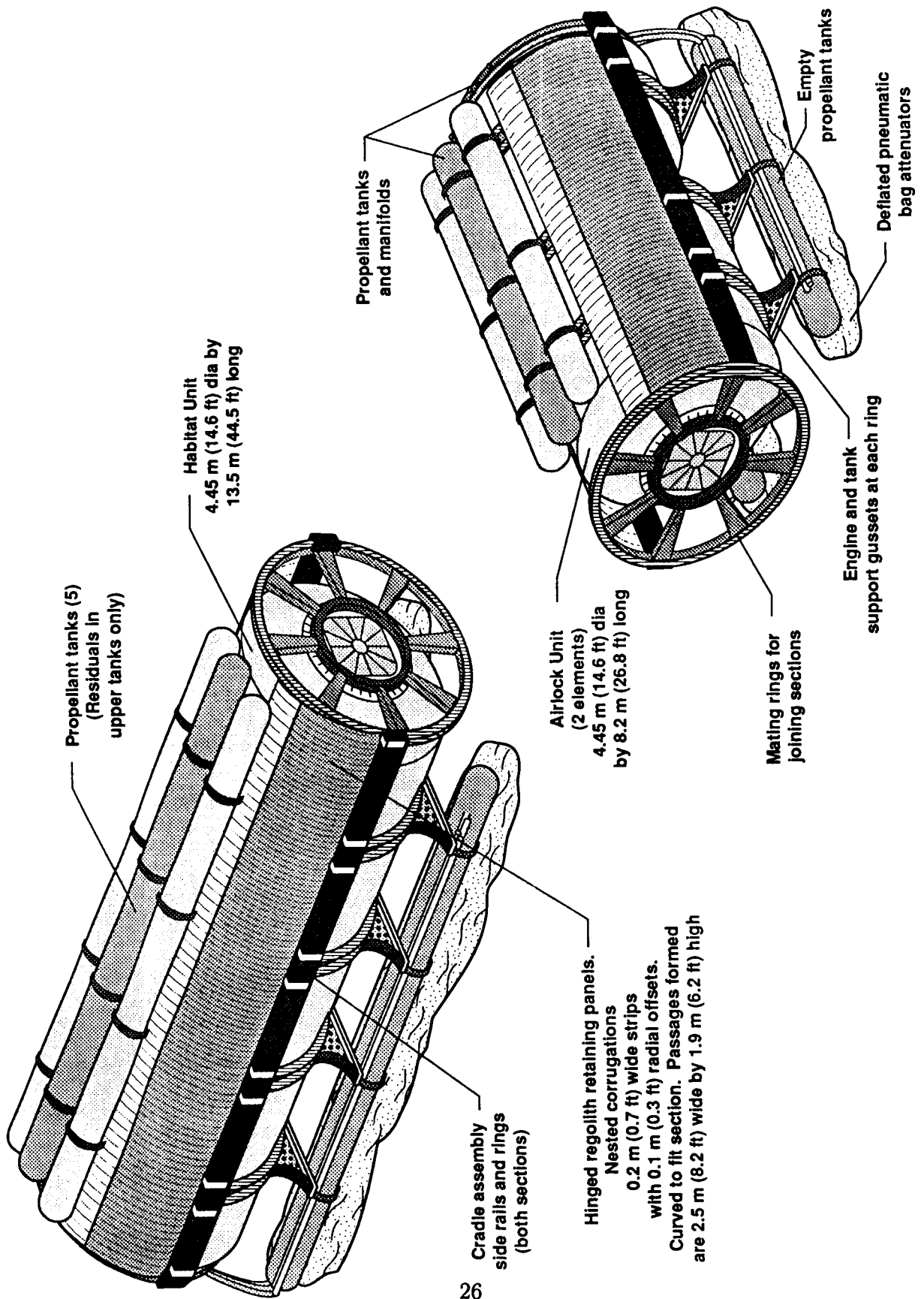


Figure 10. The "As-Landed" Configuration Features for the Concept 2 Habitat

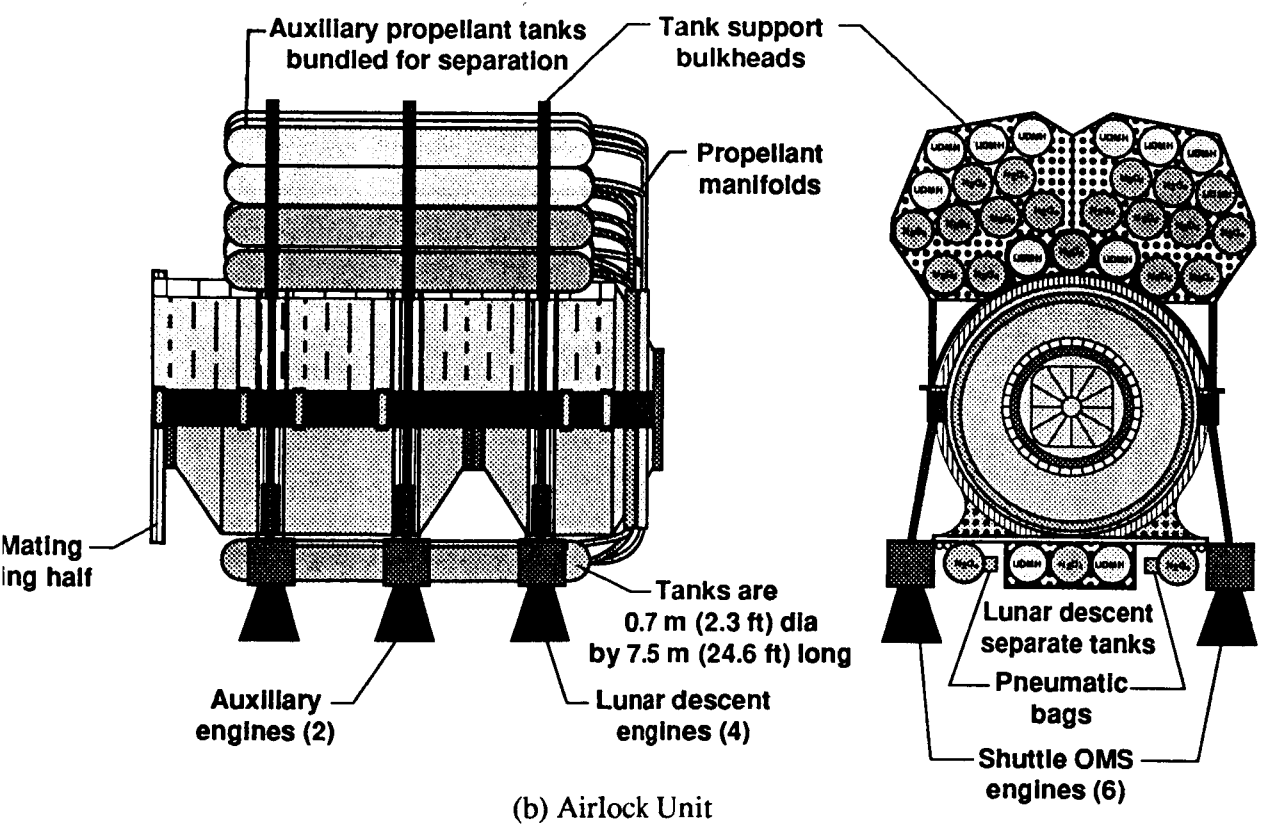
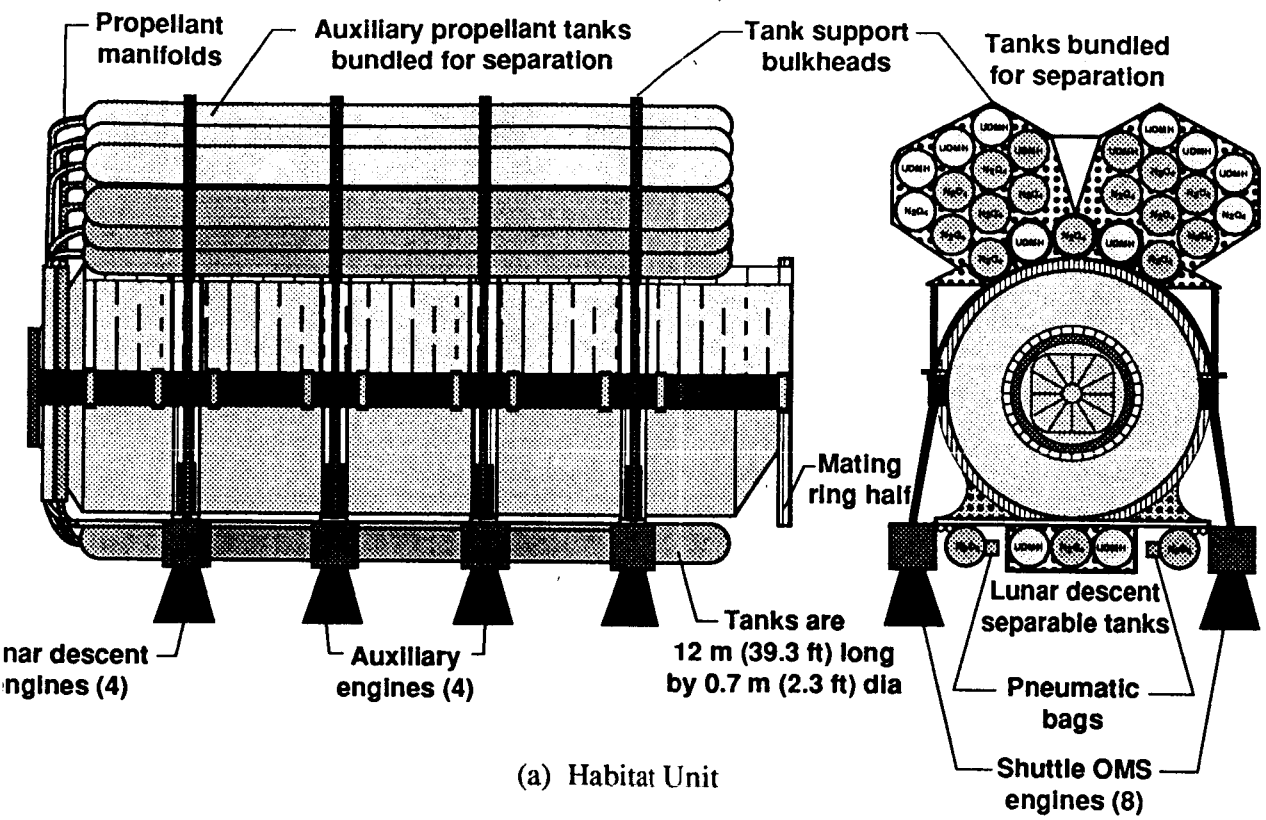


Figure 11. Concept 2 Habitat Spacecraft-Lander at LEO Departure Configuration

The two units both separate the auxiliary engines and tank bundles at the beginning of lunar descent and subsequently achieve the configurations shown on figure 12. Lunar descent profiles are also tailored to each configuration. Decelerations range from 1 m/sec² to 5 m/sec² (3.3 ft/sec² to 16.4 ft/sec²) with nominal burn times of 36 and 15 minutes. At engine stop, the airlock unit would be operating with a thrust-to-gravity ratio of 3.2, and the habitat unit would be operating at a ratio of 1.6. Any increase in engine thrust capability would also enhance these operations. The configurations at engine stop are shown on figure 13. Only five tanks remain, the two lower tanks have been emptied of propellant but remain fully pressurized with ullage gas. Descent engine stop and engine separation also occurs at a position 10 to 15 m (32.8 ft to 49.2 ft) above the landing site with the lower plane of the spacecraft parallel with the lunar surface. Engine separation triggers inflation of the pneumatic bag attenuators using the ullage gases from the tanks on the lower surface. Table 4 summarizes the fill parameters to achieve the touchdown configurations shown on figure 14. After touchdown, the pneumatic bags vent and release from the landed units. The flight plan envisioned for delivery places the habitat unit on the lunar surface first such that it can provide a homing reference for the airlock unit that follows.

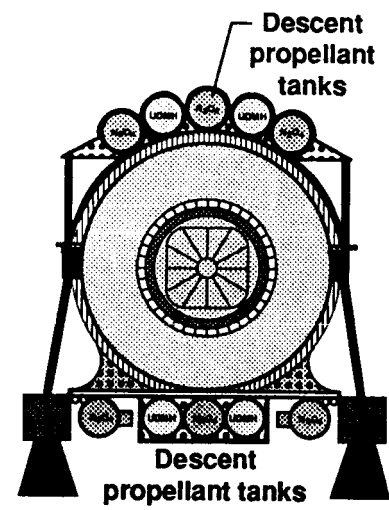
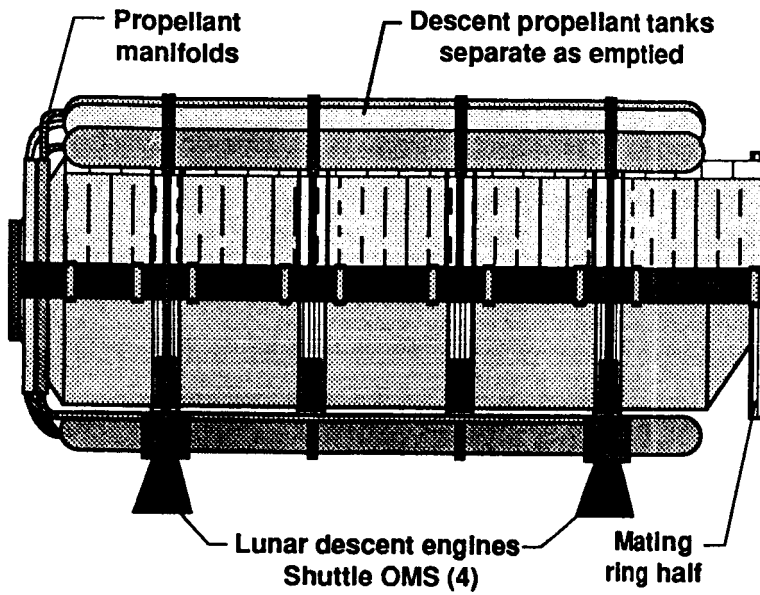
The element masses at the transit stages illustrated in figures 11-14 and the propellents consumed during the transit are summarized on Table 5(a). Table 5(b) presents the mass utilization summary and concludes with a calculation of delivery efficiency expressed as the habitat mass as a percentage of the total mass at LEO departure.

Once the two units are on the surface some distance apart, they must be moved and joined. Heavy equipment for moving either or both of the two elements to a common location is required, but concepts for the equipment have not been developed in this study. In general, it is assumed that the less massive unit, the airlock unit, would be moved to the habitat unit for mating. Alignment and joining to provide a habitable assembly proceeds crewtended. Each unit carries a mating ring supported by the side rails of the cradle and radial struts to the pressure flanges around the airlock-habitat doors. In operation the mating ring provides both an alignment fixture and hard points for making final position adjustments. The side rails of the cradle have the capability to temporarily support the lunar weight of the airlock section in cantilever bending during the alignment joining process. Alignment and joining operations can utilize side rails, gusset brackets and circumferential bands as hard points during the final alignment and joining sequence. Figure 15 shows the assembly as joined on the lunar surface.

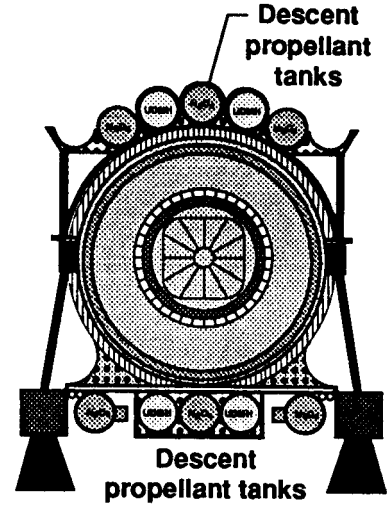
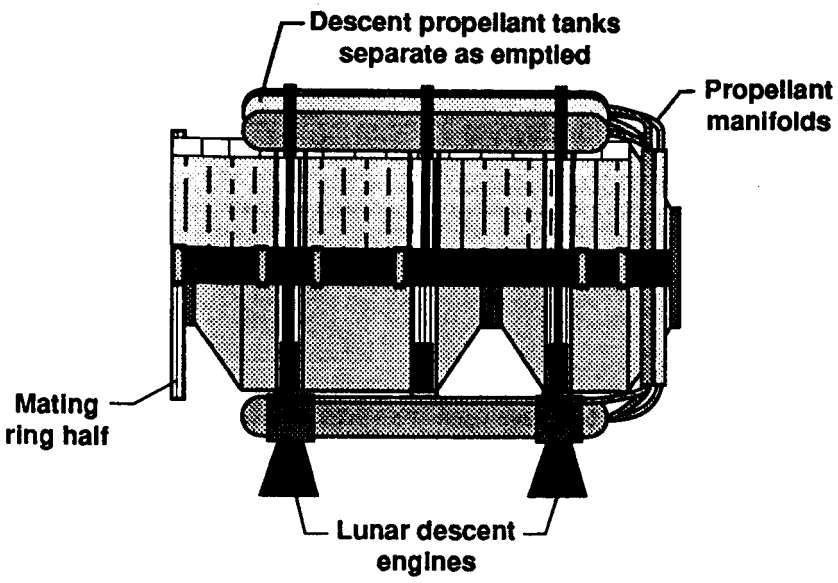
Environmental Shielding:

A general discussion of the need for regolith shield, the mass of regolith needed to give the required density of the shield, and the impact of the technique selected on habitat design and base operations was presented under the Concept 1 discussion. That discussion is also applicable to the Concept 2 habitat. The previously stated guideline that the implantation and preparation for operations phases should be as simple as possible and not require specialized equipment and tools remains applicable and, in the Concept 2 habitat, became the principal design driver.

The baseline environmental shielding technique for the Concept 2 habitat is to utilize fold-out panels as regolith support devices. The panels would be attached to and folded against the module and double airlock elements. After joining of the two units and leveling by partial emplacement of the supporting spent fuel tanks, the folded panels are deployed in an automated or man-tended mode as more detailed design studies dictate. Although details of this operational sequence have not been defined, it is acknowledged that the practicality,

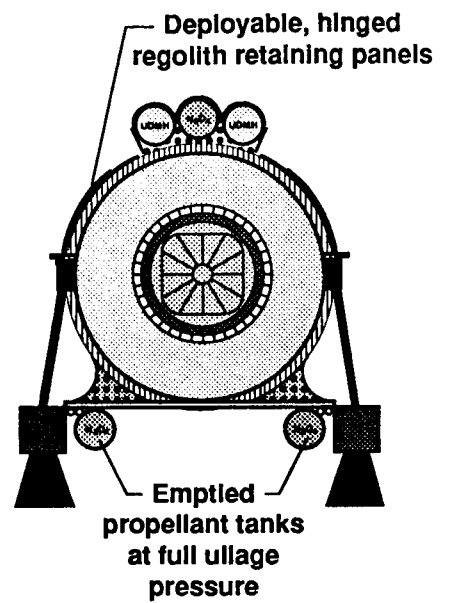
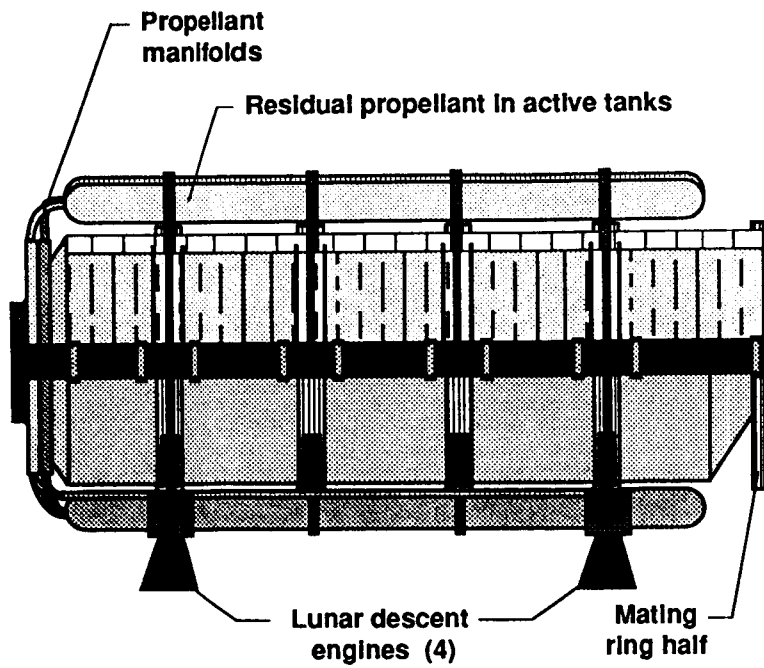


(a) Habitat Unit

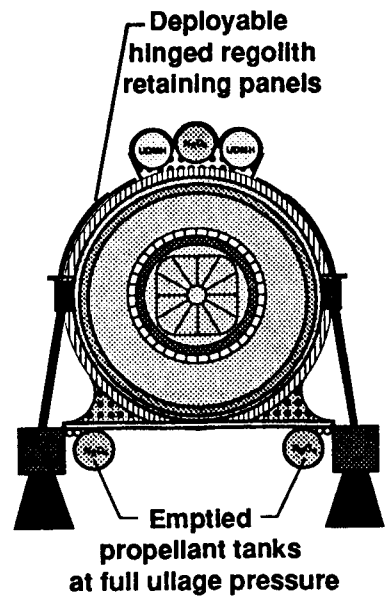
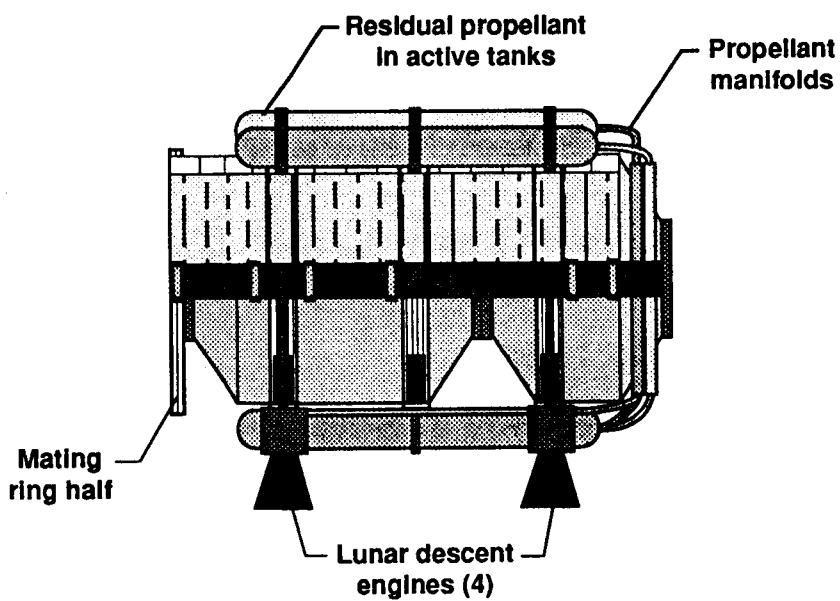


(b) Airlock Unit

Figure 12. Concept 2 Habitat and Spacecraft-Lander Configuration at Entry into Lunar Gravity Field

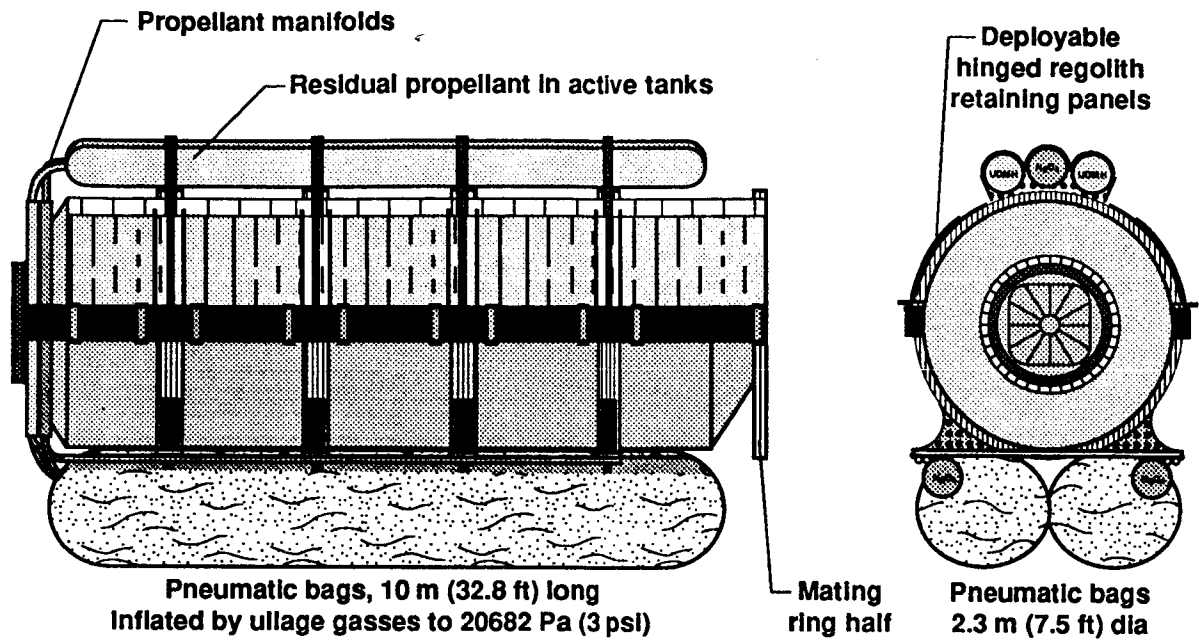


(a) Habitat Unit

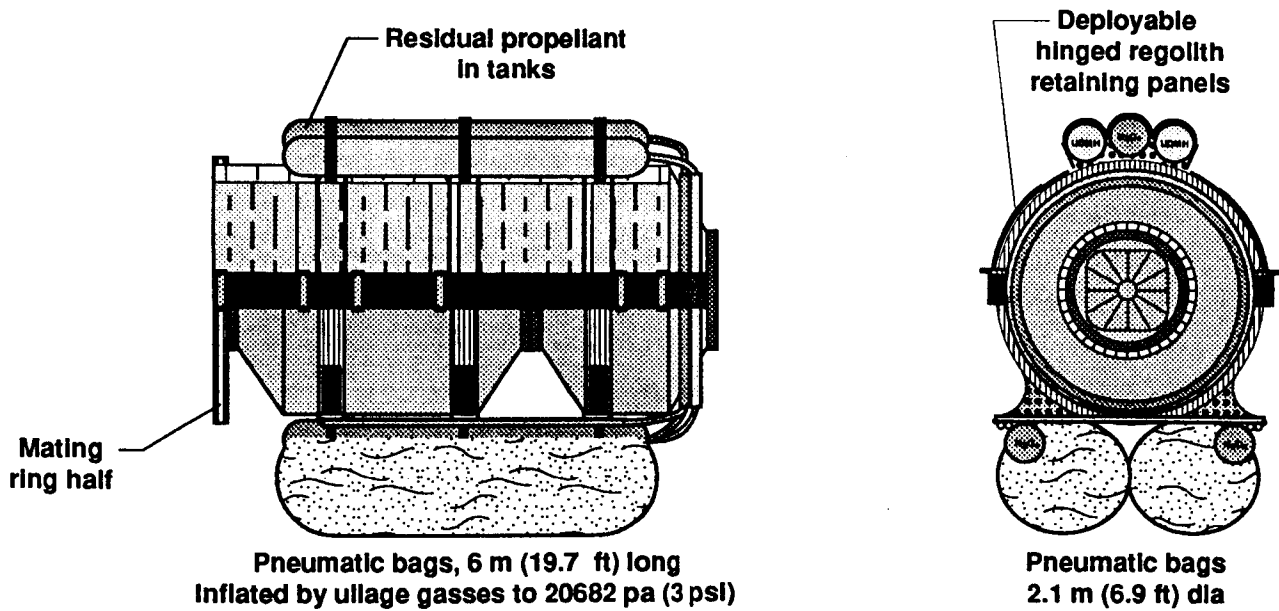


(b) Airlock Unit

Figure 13. Concept 2 Habitat and Spacecraft-Lander Configuration at Descent Engine Stop



(a) Habitat Unit



(b) Airlock Unit

Figure 14. Concept 2 Habitat and Spacecraft-Lander Configuration at Touchdown

TABLE 4. SUMMARY OF PNEUMATIC BAG
OPERATIONAL PARAMETERS

<u>Parameter</u>	<u>Habitat Unit</u>	<u>Airlock Unit</u>
Landing Force (20 m/sec ²)	480,000 N	294,000 N
Bag Footprint for 3 psi (20,682 Pa)	23.21 m ² (10 × 2.3)	14.2 m ² (6 × 2.3)
Bag Diameter	2.3 m	2.3 m
Bag Volume	54 m ³	28.2 m ³
Tank Content (N ₂ Ullage 68° F)	68.2 kg	38.5 kg
Bag Content (At 159 R)*	42.7 kg	22.26 kg
Jet Velocity (Minimum)	258 m/sec	263 m/sec
Jet Density (Minimum)	4.9 kg/m ³	5.3 kg/m ³
Flow Area for 2 Sec. Fill Time	0.0167 m ²	0.00798 m ²
Number of Ports 7.5 cm Diameter	4	2

or lack of practicality, of deployment of the panels is critical to the overall value of the Concept 2 configuration. The design goal of "building-on" the regolith support device before lunar landing and of being able to deploy it quickly without special equipment is a major feature of the Concept 2 configuration.

The assembled habitat with the habitat section and airlock section joined with regolith support panels deployed is illustrated on figure 16. Regolith is then placed on top until the habitat is covered providing at least 50 cm (19.7 in) of regolith at the thinnest location on the shield. The covered habitat is presented on figure 17. Since this configuration is a "dumped pile" it is difficult to assign sub-totals of volume to specific components. Suffice it to say that a total of 693 m³ (795 yds³) of regolith are needed.

The Concept 2 habitat/regolith shield configuration offers two major advantages. As stated, the regolith is essentially dumped. Reasonable care must be exercised during the dump operations, but tedious steps such as folding out bags and holding them open are not present. Once the panels are unfolded, operation of the dump device is the only operation

TABLE 5. SUMMARY OF MASSES FOR CONCEPT 2
HABITAT AND SPACECRAFT-LANDER

(a) AT TRANSIT STAGES

Element	Habitat Unit, kg (lb)		Airlock Unit, kg (lb)	
	Element Mass	Total Mass	Element Mass	Total Mass
Pressurized Sections		15,034 kg (33,151)		9,476 (20,895)
Spacecraft-Lander		5,666 (12,493)		3,974 (8,761)
Cradle Assy.	2,114		1,626	
Tanks (5)	1,100		753	
Propellant Controls	616		505	
Landing Bags	620		340	
Regolith Panels	1,216		750	
Residual Propellants		3,300 (7,276)		2,550 (5,623)
N ₂ O ₄	2,488		1,923	
UDMH	812		627	
TOTAL LANDED		24,000 (52,920)		16,000 (35,280)
Engines Separated		1,000 (2,205)		1,000 (2,205)
4 Engines	480		480	
4 Controls and Aux.	520		520	
TOTAL AT ENGINE STOP		25,000 (55,215)		17,000 (37,485)
Descent Tanks Separated		1,000 (2,205)		750 (1,654)
Descent Propellant Use		36,300 (80,041)		24,900 (54,905)
N ₂ O ₄	27,374		18,777	
UDMH	8,926		6,123	
TOTAL AT LUNAR FIELD ENTRY		62,300 (137,372)		42,650 (94,044)
Post Burn Separations		10,000 (22,050)		6,000 (13,320)
Engines and Control	1,000		500	
Tanks	6,600		3,360	
Structure	2,400		2,140	
TOTAL AT EARTH ESCAPE VELOCITY		72,300 (159,421)		48,650 (107,274)

TABLE 5. SUMMARY OF MASSES FOR CONCEPT 2
HABITAT AND SPACECRAFT-LANDER

(a) AT TRANSIT STAGES
(concluded)

Element	Habitat Unit, kg (lb)		Airlock Unit, kf (lb)	
	Element Mass	Total Mass	Element Mass	Total Mass
Propellant Consumed		104,040 (229,408)		70,008 (154,367)
N ₂ O ₄	78,456		52,793	
UDMH	25,584		17,215	
TOTAL AT LEO DEPARTURE		<u>176,340</u> (388,831)		<u>118,658</u> (261,641)

(b) MASS UTILIZATION SUMMARY

Lunar Surface Delivered	24,000 (52,920)	16,000 (35,280)
Jettisoned En Route	12,000 (26,400)	7,750 (17,089)
Propellants Consumed	140,340 (309,450)	94,908 (209,272)
TOTAL	<u>176,340</u> (388,830)	<u>118,658</u> (261,641)
Delivery Efficiency (Habitat Mass as a Percent of Total)	13.6%	13.5%

required. Perhaps it could be automated thus making the entire deployment of a regolith shield an astronaut free operation. The other major advantage is that the configuration provides a shielded area along both sides of the habitat with 1.9 m (6.2 ft) minimum overhead clearance. This area can be used to store cryogenics for habitat operation or store any component that needs shielding from direct sunlight and radiation. In addition, it provides access to the outside surfaces of the modules for routine operations and maintenance.

Radiation isodose contours were calculated for the Concept 2 habitat. Calculations used the BRYNTRN and heavy ion code discussed in references 16-19. The solar flare event of August 1972 was used in the flare calculations. Isodose contours are presented at five cross sections along the length of the habitat which was assumed to be one long cylinder. The regolith shield thickness is constrained to be no smaller than 50 cm (19.7 in) with greater thickness determined by the 36-degree slump angle as shown on figure 17. The outer airlock is estimated to provide the equivalent of 20 cm (7.9 in). With the cross section at the center position designated cross section 0, cross sections +500 cm and +1000 cm are 500 and 1000 cm from the center position toward the front of the habitat, respectively. Cross sections -500 cm and -1000 cm are 500 and 1000 cm from the center position toward the aft end of the habitat, respectively. Figure 18 shows the calculated isodose contours for the blood forming organs (5 cm depth) in rem/yr due to galactic cosmic radiation at solar minimum.

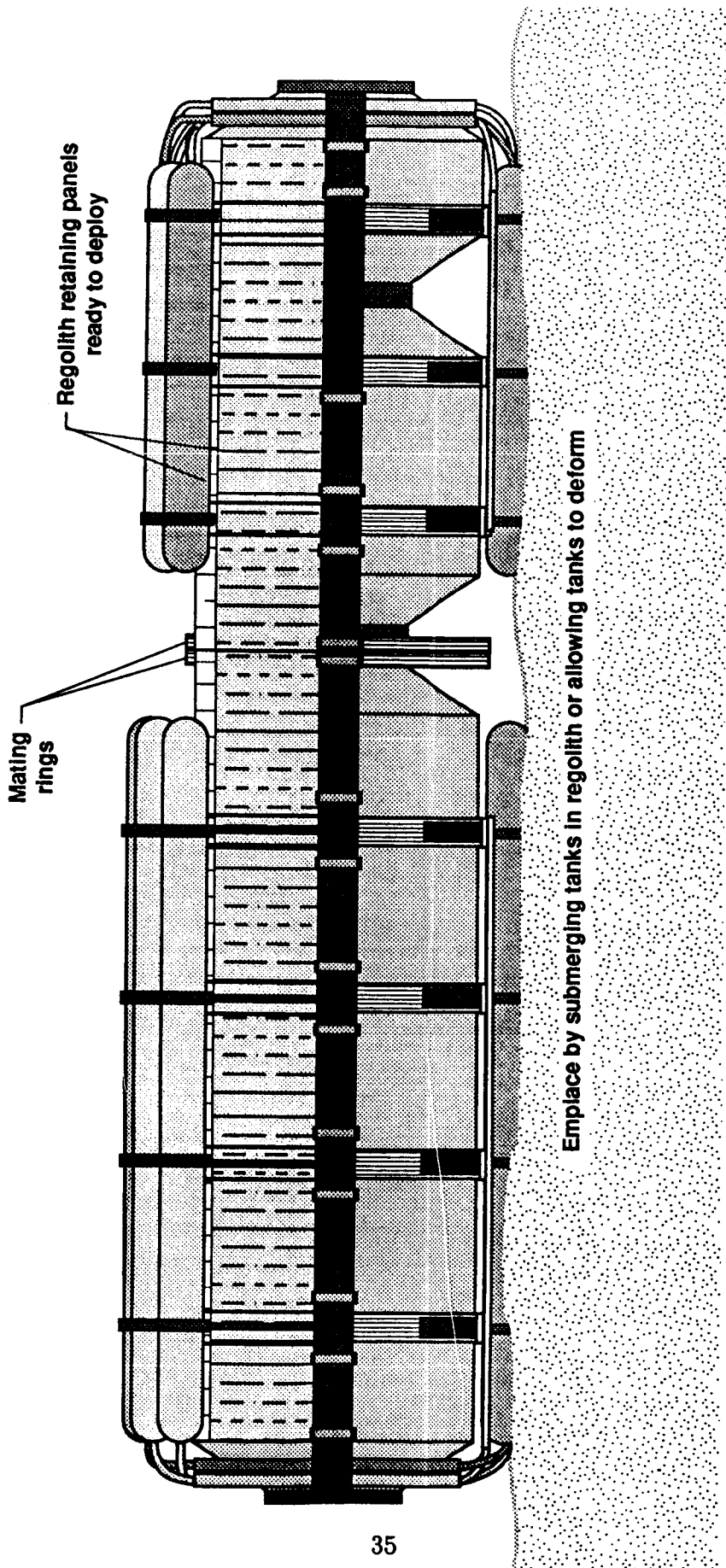


Figure 15. Concept 2 Habitat and Airlock Units Joined on Lunar Surface

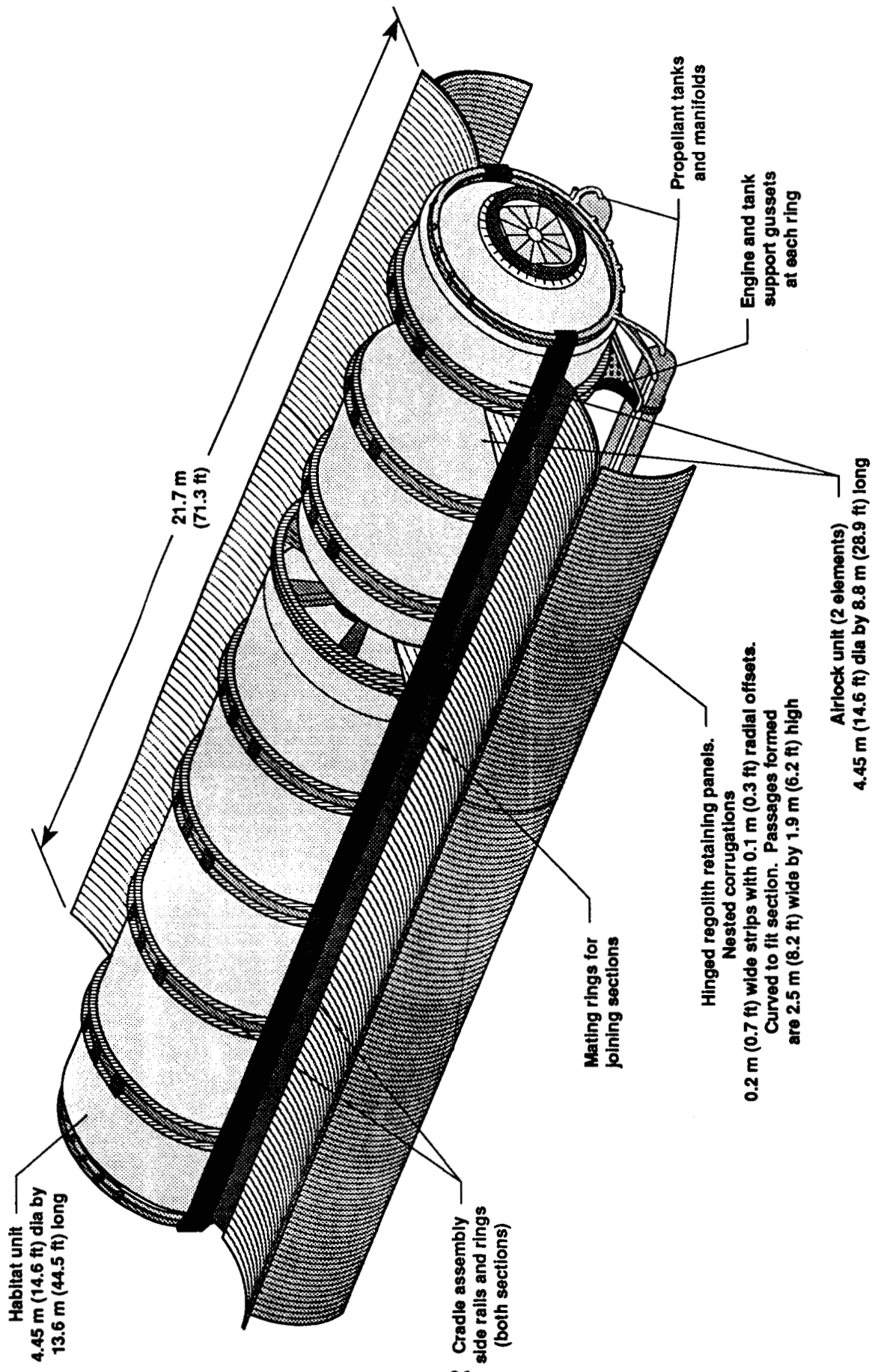


Figure 16. Concept 2 Habitat and Airlock Units, Joined on Lunar Surface Ready for Regolith Fill

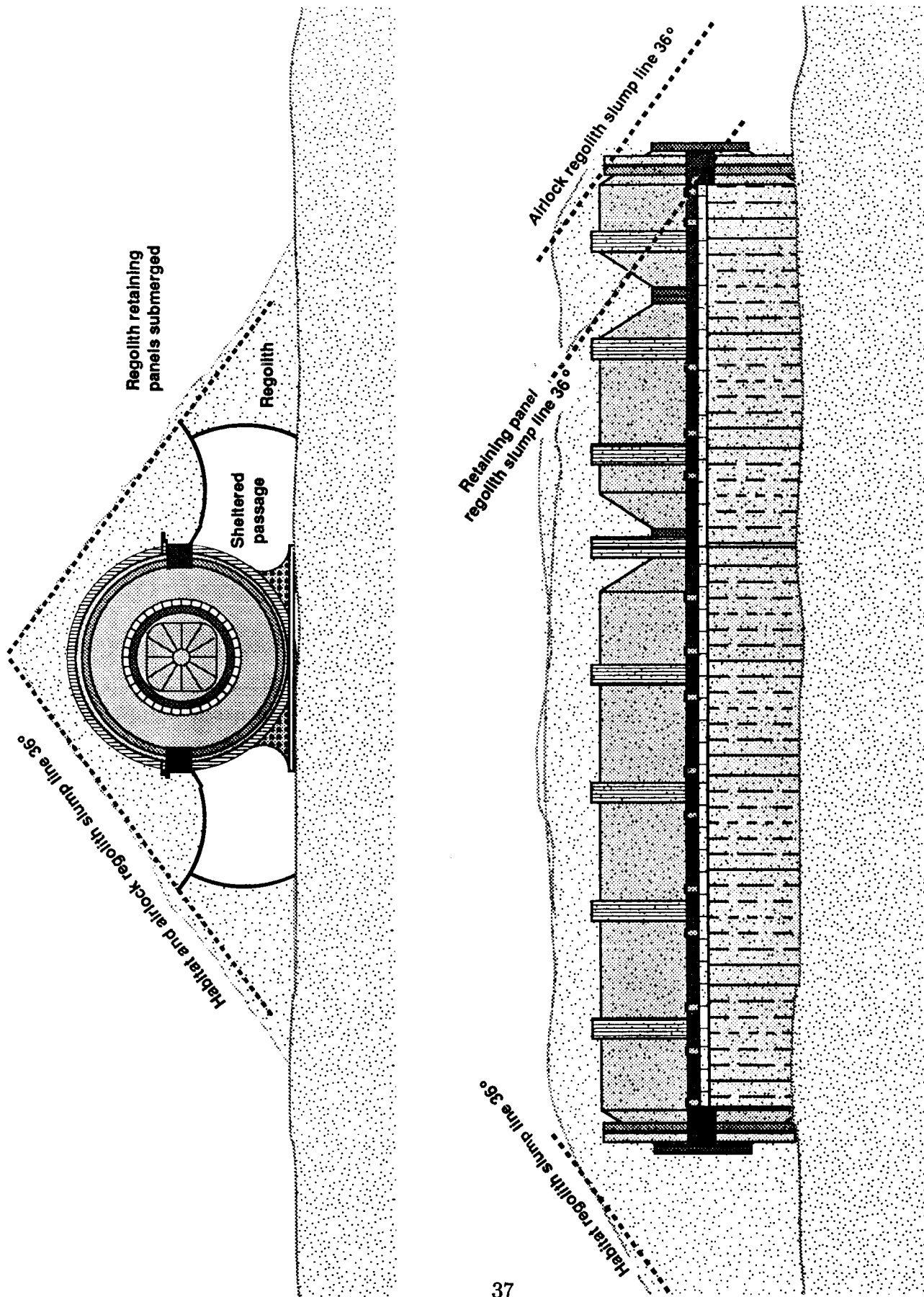
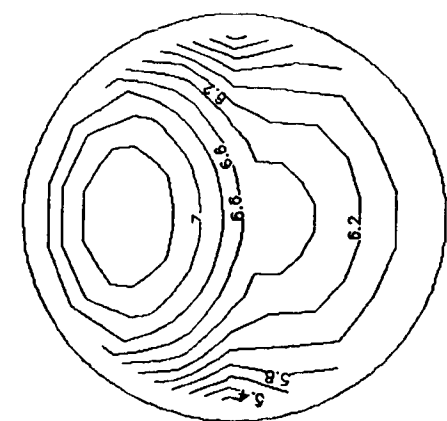
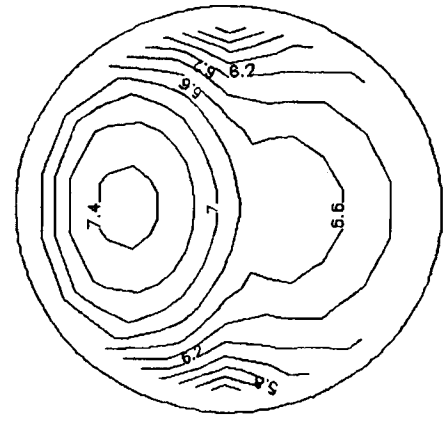


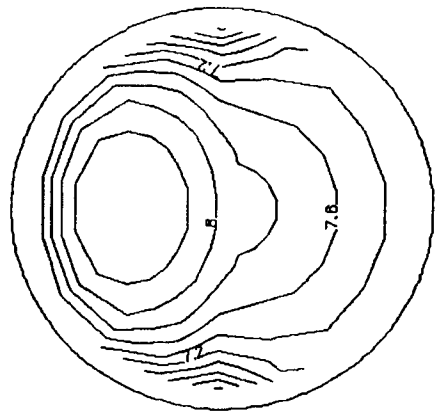
Figure 17. Concept 2 Configuration with Regolith in Place



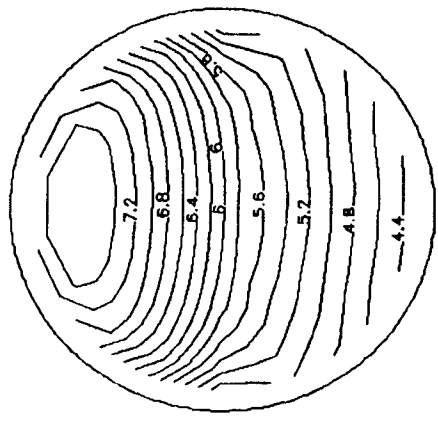
**(c) Cross section
0 cm**



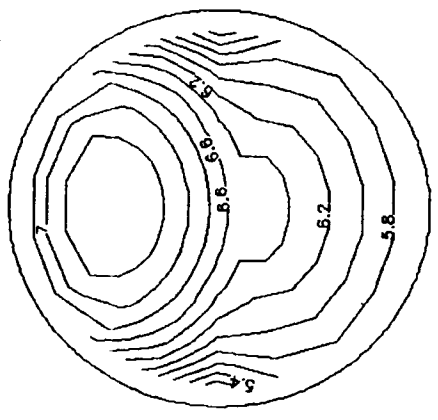
**(b) Cross section
+ 500 cm**



**(a) Cross section
+ 1000 cm**



**(e) Cross section
- 1000 cm**



**(d) Cross section
- 500 cm**

Dose in rem

Figure 18. Radiation dose contours for galactic radiation, habitat concept 2.

Likewise, figure 19 shows the calculated dose to the blood forming organs for the August 1972 flare event. The calculated doses are well below current acceptable limits, thus, the regolith shield is assumed to provide adequate protection.

Alternate Approach:

The alternate approach to the Concept 2 habitat is a variation in the technique of applying the regolith shield. It is referred to as the spill through technique. After joining of the sections as previously described, single foldout panels are deployed and held in position by tension cables spanning the module and airlock sections and resting on a load distribution longeron. The regolith support panels are limited to one on each side compared to two foldout used on the baseline Concept 2 configuration. The configuration is shown on figure 20. When deployed the single panels leave a void space between the habitat section and the regolith support panels. The void space is a uniform 61 cm (24 in) wide. This dimension is based on the requirement to provide at least a 50 cm (19.7 in) thickness of regolith shield plus allow sufficient space for the regolith spill through.

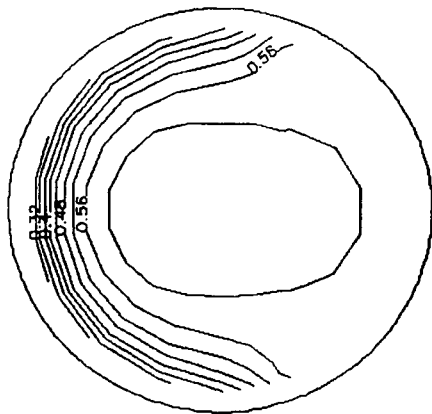
Regolith is carefully dumped on top of the support panels and allowed to spill through the void. After the pile of regolith under the panels reaches the void, further dumping on the panels will cover the panels and accumulate up the sides of the module and airlock. The volume of regolith required is determined by the height of the habitat structure and the slump angle formed by the accumulating regolith and the need for a regolith thickness of 50 cm (19.7 in). Calculation of the volume of regolith required for this configuration determined that 481 m³ (629 yds³) are needed of which 46 percent is required for the aft cover pile. Its large diameter, height, and 36-degree slump angle leads to the large volume. Further study is needed to trade-off this simple piling technique that requires moving a large volume of regolith against a more complex regolith containment device that means carrying additional structure but greatly reduces the volume of regolith to be moved.

There are three major advantages of this regolith coverage technique: (1) the total volume of regolith required is much less than would be required if the habitat were to be covered in an as delivered, unmodified configuration; (2) assuming a structure is needed to support regolith in an attempt to reduce volume, the structure is simple, relatively light in weight compared to other approaches, and it is built into the habitat before launch; and (3) the regolith deposition is simple. It does not require the filling of bags, tubes, hollow structures, etc. The only requirements are to dump gently and permit the regolith to seek its own gravity dependent configuration.

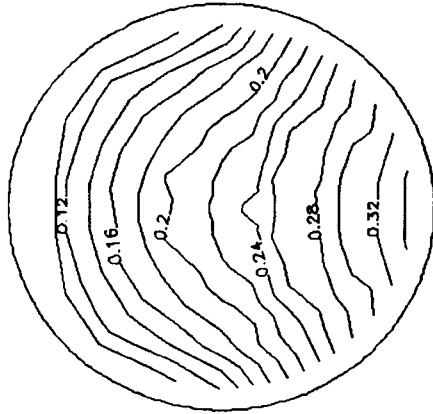
One disadvantage of this regolith coverage technique is that the outside of the habitat becomes difficult to access. It may not be necessary to access the outer shell after the habitat has been implanted but intuition suggests that accessibility would provide some flexibility for maintenance and modification.

One issue that needs at least one iteration of consideration but has not been addressed in this study is the question of dumping regolith directly on the outer skin of the habitat. Is it permissible? Will it damage the pressure vessel? Does the direct dump technique require setting some specific operational limits such as dump height, maximum size of rock, etc. If regolith is dumped on the module, is there a need for a protective pad to be placed on the module prior to dumping? These issues need to be addressed if the direct dump technique is carried into future studies.

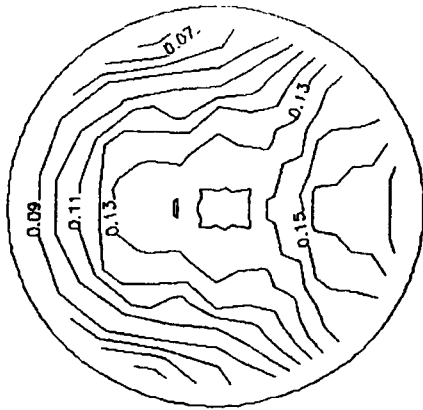
No specific base support has been developed for this alternate configuration. The concept appears to be independent of the type of base used.



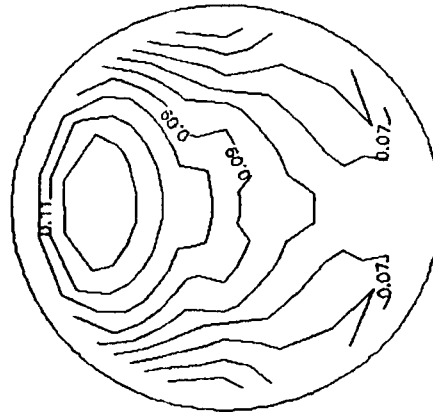
**(a) Cross section
+ 1000 cm**



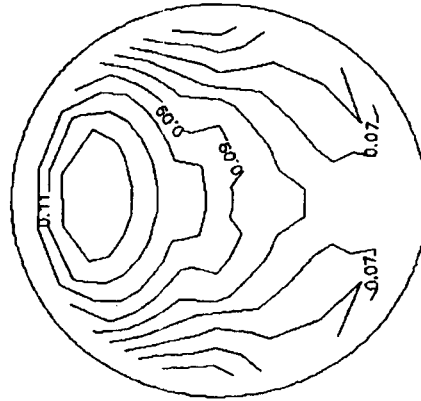
**(b) Cross section
+ 500 cm**



**(c) Cross section
0 cm**



**(d) Cross section
- 500 cm**



**(e) Cross section
- 1000 cm**

Dose in rem

Figure 19. Radiation dose contours for solar flare radiation, August 1972 event, habitat concept 2.

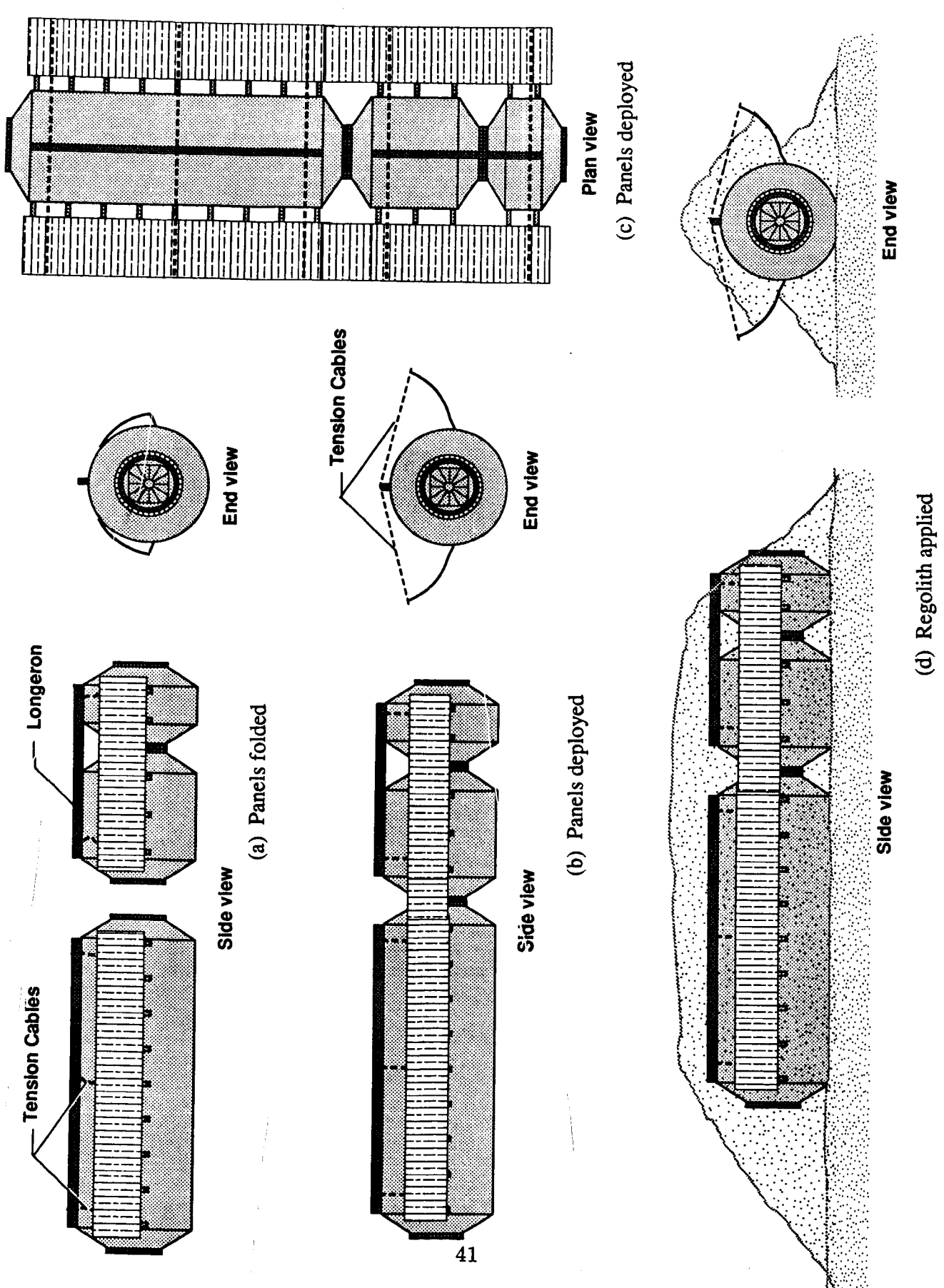


Figure 20. Regolith Spill-Through Configuration for Concept 2 Habitat

Technology Assessment:

Most of the technology needs related to the Concept 1 configuration and outlined in Table 3 apply to the Concept 2 configuration. Delivery and emplacement of the two unit assembly does, however, bring focus on additional technology needs. These needs are outlined in Table 6 and are discussed briefly in the following paragraphs.

Trajectory and Landing Site (Need 1)

Lunar base implementation scenarios involve the landing of unmanned spacecraft in close proximity to the inhabited areas (ref. 14). The principal difference implied in those landings relates to the degree of pioneering; first landings carry equipment to prepare the surface for later landings. This scenario assumes no opportunity for surface preparation; the units land under remote control.

Landing Decelerators (Need 2)

The utilization of large lightly inflated pneumatic attenuators for the landing decelerations is a synergistic extension of an existing technology. Bags of comparable size have been constructed for terrestrial applications. Pyroactuated bags are standard automotive items. Operation in vacuum using an ullage gas appears as a synergy of opportunity. Verification testing in this case appears more complex than for high-pressure strut-enclosed units. On the other hand large vacuum chambers do exist, and an acceptable simulation of lunar gravity can be achieved by counterweights. Operational verification consistent with an unmanned touchdown appears within the capabilities of existing facilities.

On-Surface Operations (Need 3)

The movement that brings the two units together and the technique for performing the alignment of the units for joining represent the areas of least knowledge. Alignment for joining will require techniques for exerting considerable force, the lunar gravity weight for the airlock section stands at 23,050 N (5,180 lbs). Availability of hydraulic or pneumatic actuators as jacks or struts is an assumed requirement. In addition, emplacement leveling of the final assembly can involve some type of mechanism. In the conduct of such a study, the residual propellents offer an energy source as hot gases or pressurants; such a synergy is proposed for this application. At one time combustion generated hot gas jets were considered as an aid for terrestrial Earth moving techniques and an application to bulldozers proved useful in working some types of soil. Residual hyperbolic propellents offer a means for considering such a technique applied to lunar surface emplacement operations and regolith transport.

Concept 3

Habitat Elements:

The Concept 3 habitat is entirely different from the others. It is a concept that is based on expandable structure technology that was developed in the 1960's but shelved because of the absence of a mission for its application. The concept features a hybrid rigid-expandable habitat that utilizes the most favorable features of each while avoiding the design weaknesses of the earlier expandable designs.

The most advantageous feature of the Concept 3 design is the low packaged volume to deployed volume ratio achievable with the expandable module. The size and mass of the

TABLE 6. SUMMARY OF TECHNOLOGY DEVELOPMENT NEEDS FOR CONCEPT 2

Technology Need	Action or Response Required	Technology Readiness Level*
1 Transfer trajectories and timeline for remote operation delivery of two units to the lunar surface within 1 km of each other and landed upon an obstacle free site.	Transfer trajectory and descent analysis to define sequences, timing and techniques for final landing. Lunar surface detail characterization sufficient for landing site definition.	6
2 Landing deceleration technique compatible with spacecraft masses and landing site proximity.	Technical trade and design study to define the system. Verification testing for confirmation.	4
3 Alignment and joining technique for habitat and airlock compatible with man-tended operations on the lunar surface.	Trade and design study to define the techniques. Verification testing for confirmation.	4

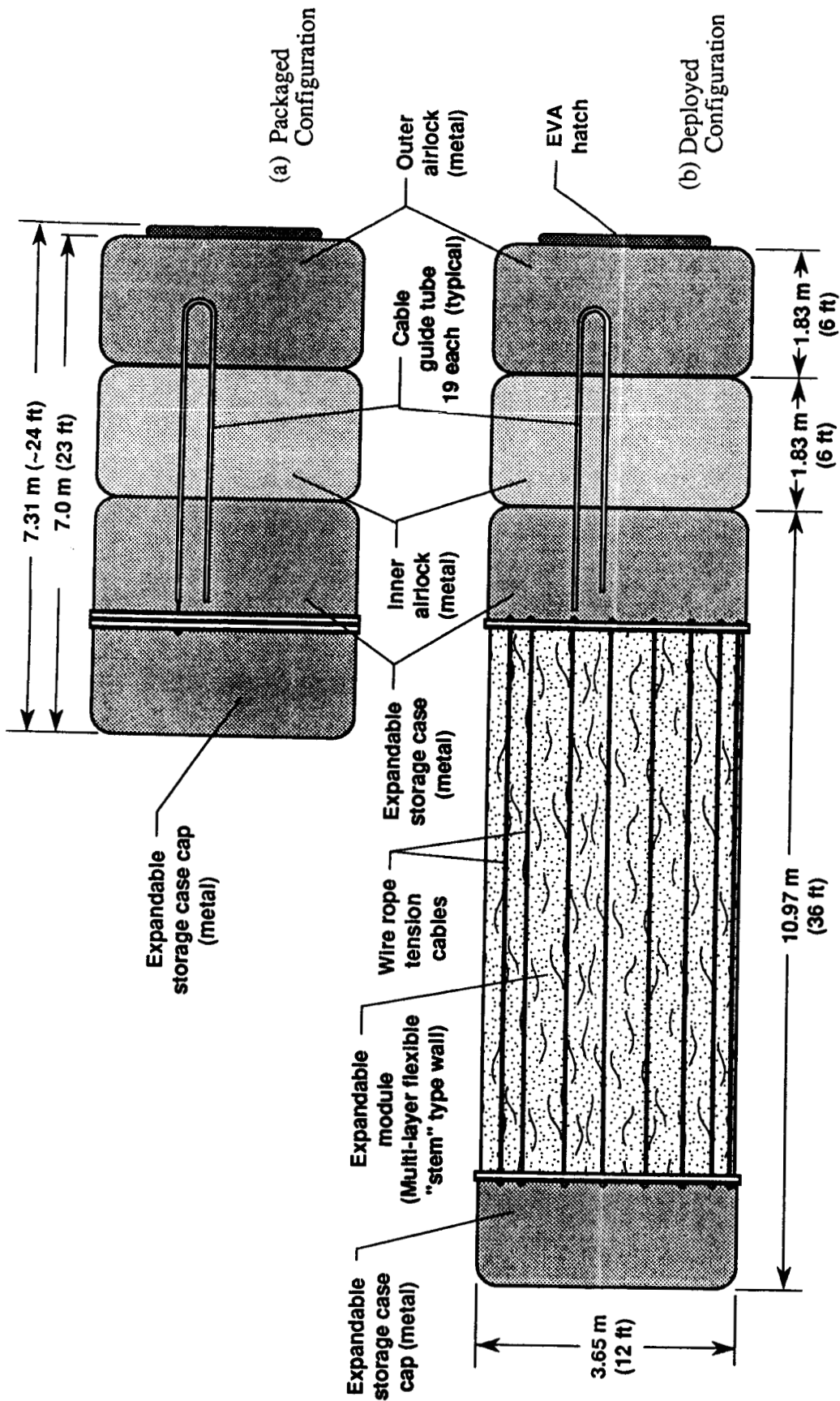
*Level 1	Concept with no Previous Application
Level 2	Related Concept Proposed for Application
Level 3	Related Concept with Limited Application
Level 4	Concept with Established Operation in Previous Flights
Level 5	Concept in Active Update for New Application
Level 6	Presently Operational in Reduced Scale or Complexity
Level 7	Existing Capability in Present Use

Concept 3 habitat and the alternate that is presented is compatible with current launch systems such as the STS orbiter. This feature alone makes the concept an attractive one. The design retains the double airlock arrangement utilizing metal pressure vessels which are most appropriate for the pressure cycling of a personnel airlock. The metallic, double airlock elements are also coupled with a regolith coverage technique to provide a safe haven should failure of the expandable occur and as a special safe haven in the event of a solar flare.

A sketch of the configuration and the element dimensions are presented on figure 21. The overall dimensions of the concept were selected after integration of several factors. The diameter of 3.65 m (12 ft) is a balance of the need for minimum but adequate internal volume and dimensions vs. a packaged diameter that will fit easily into the STS cargo bay and possibly into a Titan shroud. The deployed length of 10.97 m (36 ft) is a balance of the desire to obtain as much usable internal volume as possible while not exceeding a deployed to packaged ratio that appears achievable based on the previous work with expandables. The Concept 3 habitat exhibits a deployed to packaged ratio of 3:1 (36ft:12ft). The ratios achieved in the earlier work ranged from 8:1 with the STEM to 28:1 with the MOBY DICK. The more conservative 3:1 packaging ratio for the Concept 3 habitat is based on an assumption that the wall designed for 68.95 kPa (10.0 psi) will be more difficult to fold and package than the wall designed for the 34.47 kPa (5.0 psi) of STEM and MOBY DICK. The multi-layer flexible wall used in the STEM design is thought to be typical of the type of wall that would be used in Concept 3. The composition of a typical wall is shown on figure 22. Note on figure 22 that the four element construction of the typical wall has many subelements. The flame/gas barrier subcomposite shown on figure 22(a) contains the subelements shown on figure 22(b). The overall wall construction design is a complex material selection and fabrication issue. After consideration of the packaged to deployed ratios achieved with the earlier work on expandables and the factors related to the higher internal atmospheric pressure, a conservative packaged to deployed ratio of 6:1 appeared achievable. Thus, the resultant 10.97 m (36 ft) long habitat expandable packaged in the storage case and cap 3.66 m (12 ft) overall provides an additional margin of conservatism with a packaging ratio of 3:1.

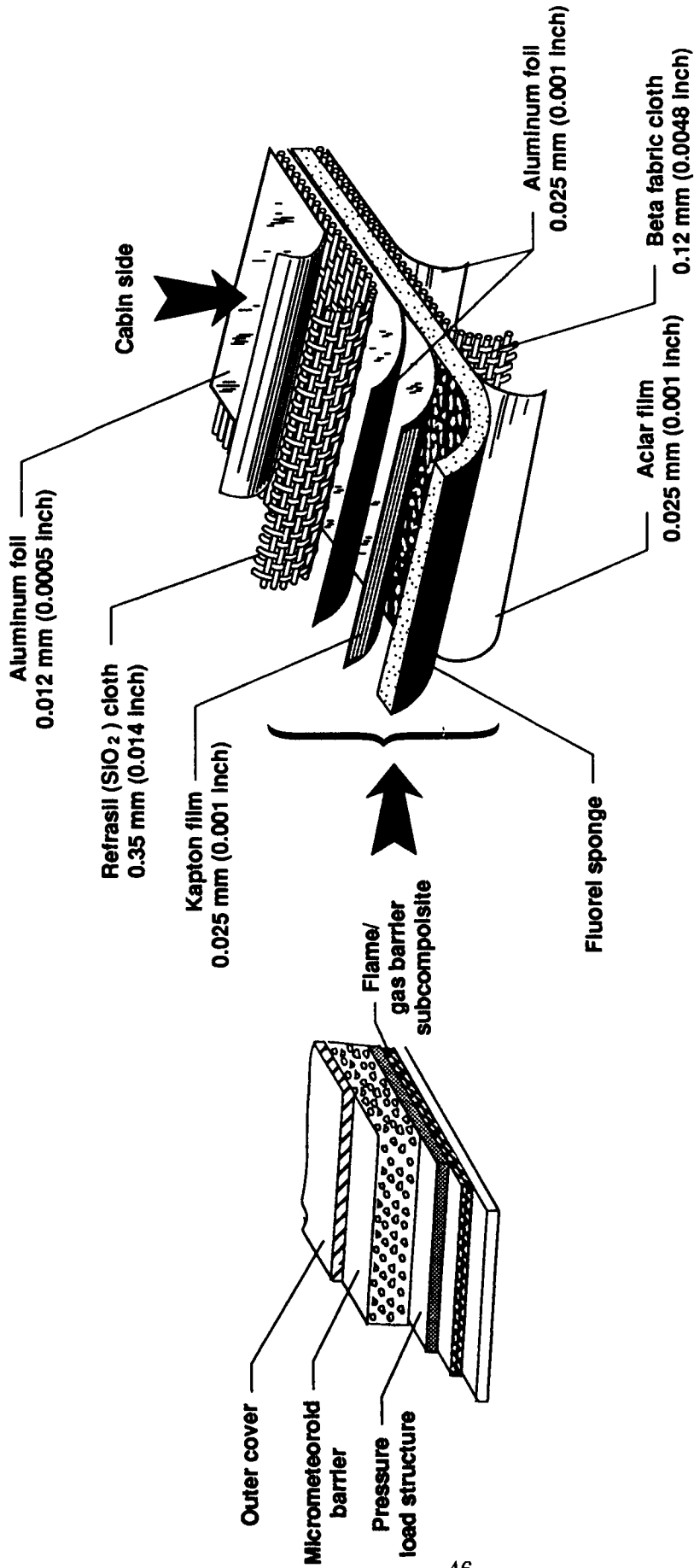
Another result of the earlier work on expandables that had significant impact on the Concept 3 design is the difficulty that was encountered at the joining interfaces between the flexible wall and rigid components. A typical example is the interface where a flexible wall joins the metal frame of a metal hatch. Most of the problems experienced during folding, deployment, and leak testing of the STEM and MOBY DICK occurred at these interfaces. This potential problem area was minimized in the Concept 3 design by limiting the flexible to rigid interfaces to areas of low stress of the types that can easily be controlled and that do not enter significantly into the folded packaging scenario. The interface with the storage cap case is a non-stress interface relative to stresses acting to separate the expandable from the rigid component. The end cap is only a retainer acting with the tension cables to carry axial tension load when the expandable is pressurized. The tension cable system shown on figure 21 utilizes nineteen, 3/8-inch diameter, 19 wire galvanized steel strand wire rope spaced approximately 0.6 m (2.0 ft) apart around the circumference of the storage case and storage case cap. The wire rope approach is only a baseline concept; alternate approaches are presented as part of the Technology Assessment Section for Concept 3.

With an internal pressure of 68.95 kPa (10.0 psi), use of nineteen cables will result in approximately 38.1 kN (8,567 lbs) of tensile stress each. Breaking strength for the cable shown is rated at 76.2 kN (17,135 lbs), and thereby presenting a safety factor of two. The actual safety factor is larger since no axial stress has been assigned to the expandable,



HABITAT ELEMENT	APPROXIMATE MASSES EMPTY	OUTFITTED	APPROXIMATE DEPLOYED
Habitat module	3,701 kg (8,160 lb)	4,354 kg (9,600 lb)	100.79 m ³ (3,559 ft ³)
Inner airlock	2,082 kg (4,589 lb)	2,127 kg (4,691 lb)	15.26 m ³ (539 ft ³)
Outer airlock	2,082 kg (4,589 lb)	2,127 kg (4,691 lb)	15.26 m ³ (539 ft ³)
TOTAL	7,865 kg (17,338 lb)	8,608 kg (18,982 lb)	131.31 m³ (4,637 ft³)

Figure 21. Concept 3 Habitat



(a) Typical wall construction

(b) Flame/gas barrier subcomposite

Figure 22. Typical Multi-Layer Flexible Wall, Concept 3 Habitat

although in the STEM and MOBY DICK systems, wall structure carried all the tension loads for a 34.47 kPa (5.0 psi) atmosphere. In the packaged configuration, the cables are stored inside tubular cable guides. Upon expansion of the module on the lunar surface, the cables slide inside the guides until restrained at maximum extension by the beveled flange/tapered slug design illustrated on figure 23. Utilization of cables to support the axial loads eliminates shearing force at the expandable to metal interface. The inflation related hoop stresses are controlled by the interface design discussed below and illustrated on figure 24.

The storage case wall is shown on figure 24(a) with an integral flange machined on the inside diameter and the flange has equally spaced threaded holes for joining to a mating flange of an inner attachment ring. The expandable wall is shown with a nominal 6.2 cm (2.5 in) thickness and a tapered region over the inner attachment ring. The lay-up of the expandable wall would begin by winding or fabricating the inner layers and bonding to the inner attachment ring using an elastomeric synthetic resin adhesive. The expandable wall core is then built up with a density gradient that increases axially toward the flange of the inner attachment ring. The gradient provides the most uniform stress distribution throughout the skin and core of the flexible structure. The outer skin or windings of the expandable wall are then applied and cured. The outer skin has a taper that matches an outer attachment ring but with a dimensional gap between the outer skin and the outer attachment ring. After cure of the structure, the outer attachment ring is positioned and fastened with securing screws. An elastomeric adhesive is then pressure injected to completely fill the gap between the outer attachment ring and the outer skin of the expandable wall. The elastomer extends past the edge of the outer attachment ring and establishes a true cylindrical shape faired into the expandable wall. Two O-ring glands are machined in the flanges of the inner attachment ring to provide a double O-ring seal. The seal prevents the habitat's atmosphere from escaping through a mechanical joint assembly with the storage case integral flange. The integral flange is located approximately 0.76 m (2.5 ft) from the storage case separation plane and across a portion of this distance, the inside diameters of both halves of the storage case are tapered outward to the separation plane. The taper allows the flexible wall to expand slightly such that at full pressure the separation between the storage case and the inflatable wall occurs within the tapered region without causing a stress concentration along the rounded edge of the rigid metal storage case. The corner radius of the separation flange should eliminate local damage to the expandable wall during folding and unfolding transients. The double shear elastomeric bond offers two advantages. When inflated, the double shear bond lines provide a more uniform distribution of the resulting inflation stresses. In the folded configuration the combination of elastomeric bond lines and the flared edge of the inner attachment ring minimize the peel stresses introduced by the folding process.

The potential problems associated with penetrations of services and utilities (heat transfer fluids, atmospheric gases, electrical leads, etc.) entering through the multi-layer flexible wall component have been eliminated in the Concept 3 configuration by incorporating a Utility Feed-through Ring that is positioned between the expandable storage case and the inner airlock. The ring is illustrated on figure 25. In this configuration the flexible wall of the expandable module becomes a long horizontal cylinder (open on one end) without penetrations. All of the service penetrations enter the habitat or inner airlock through the Utility Feed-through Ring. Radially drilled holes receive threaded fittings having O-ring glands in their mounting flange to prevent gas leakage past the threaded fittings. An example is shown of tubing furnace brazed into a threaded fitting to assure a vacuum tight assembly. Intersecting holes are drilled and threaded in the utility feed-through ring to receive O-ring sealed fittings for utilities to the habitat and/or the inner airlock. The ring

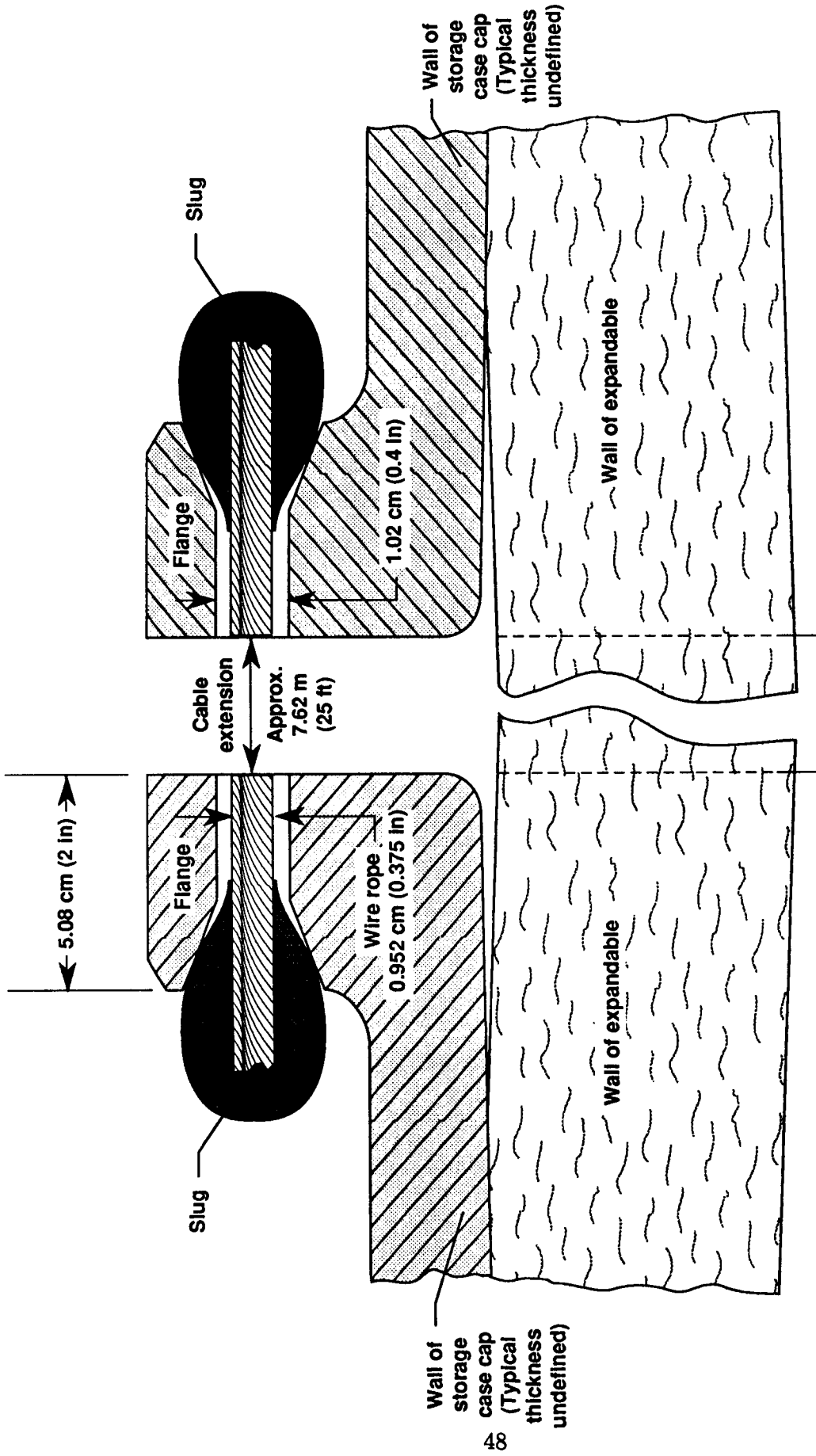


Figure 23. Concept 3 Habitat Expansion Control Flange and Cable Details

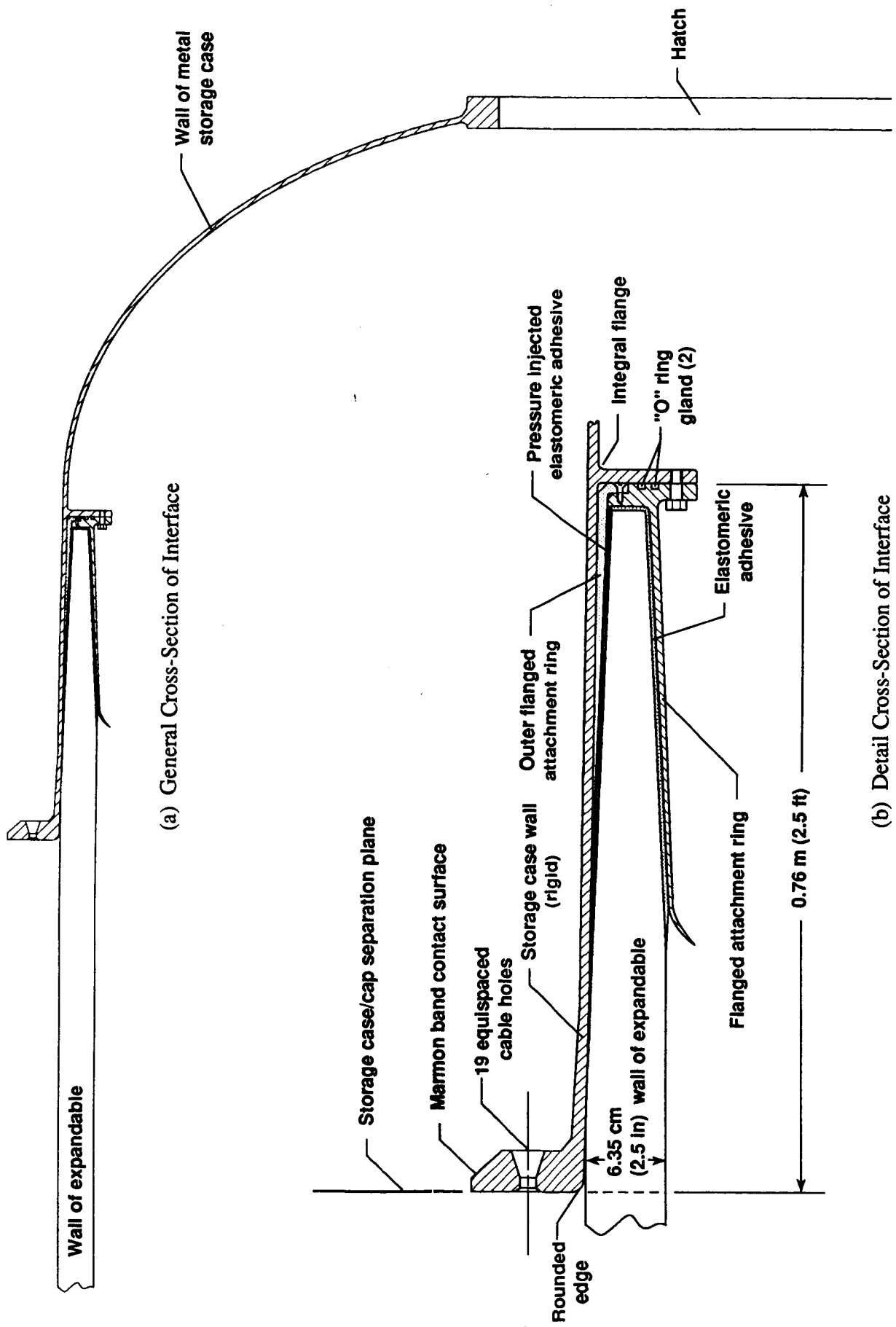
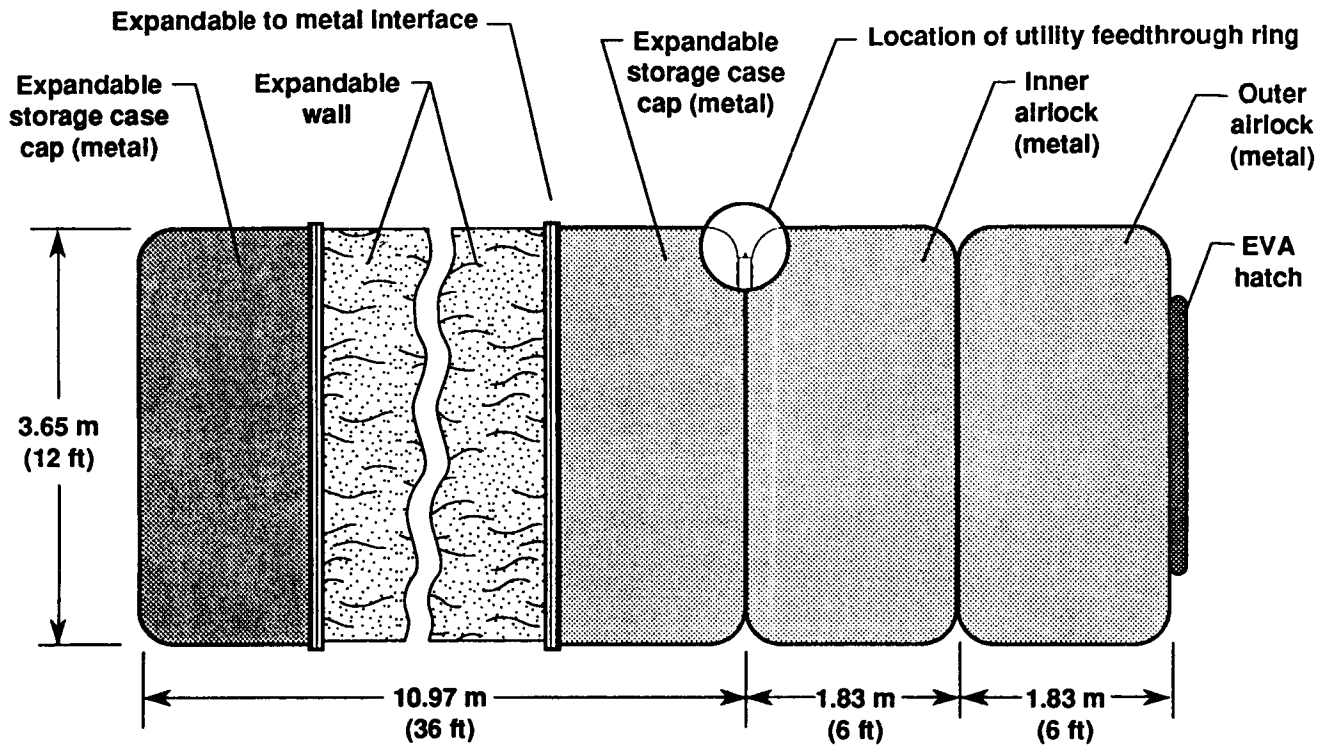
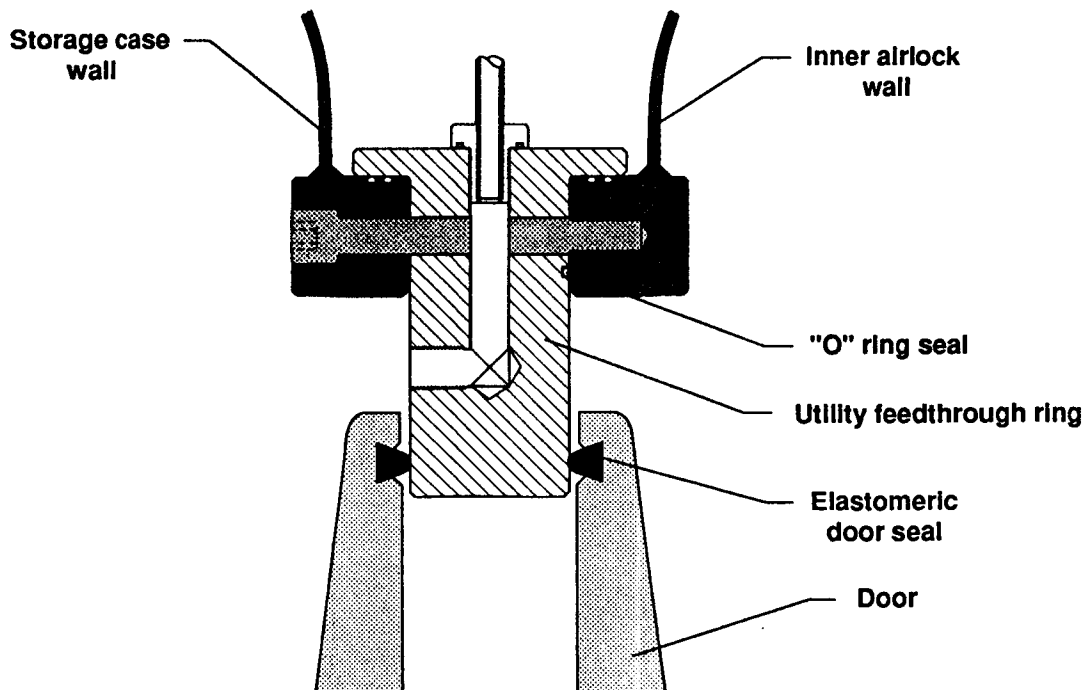


Figure 24. Expandable Wall to Metal Interface (Storage Case) Design



(a) General Location of Utility Feedthrough Ring



(b) Cross-Section Detail of Utility Feedthrough Ring

Figure 25. Utility Feedthrough Ring Concept

performs additional functions as follows:

- The flanges on the ring provide a means of centering the expandable module and the inner airlock at assembly.
- O-ring glands in the pressure vessel's attachment rings prevent loss of the internal pressurant gas of the habitat. The feed-through ring is drilled to receive through fasteners which join the storage case metal structure inner airlock, and the ring.
- An O-ring gland prevents gas leakage from the expandable module through the fastener opening into the inner airlock when a pressure differential exists.
- The utility feed-through ring has an opening and door which could be rectangular or oval to permit the astronaut to walk erect through the door opening.
- The feed-through ring is equipped with two doors, each door having an elastomeric seal retained in a dove-tailed groove about its perimeter. One door is positioned to swing into the habitat and a second door is positioned to swing into the inner airlock. The habitat door is normally used since the habitat's pressure is maintained at 68.95 kPa (10.0 psi) under normal operating conditions whereby the inner airlock would vary in internal pressure during astronaut egress-ingress operations. The effectiveness of the rigid door with elastomeric seal design relies on a positive pressure differential forcing the door/seal against the sealing face of the utility feed-through ring. For normal astronaut egress-ingress operations the habitat door would be closed and the astronaut suit up in the inner airlock. The outer airlock is pressurized by sharing the atmosphere with the inner airlock at approximately 34.47 kPa (5.0 psi). The inner airlock door is closed to the outer airlock and the outer airlock's atmosphere is pumped back to the inner airlock to conserve atmospheric gases. The outer airlock is then ported to lunar surface vacuum and the astronaut performs EVA. For ingress the astronaut enters the outer airlock, closes the outer airlock door. Then the airlock is pressurized by sharing the atmosphere with the inner airlock. The astronaut then enters the inner airlock and closes the door to the outer airlock. The inner airlock is then pressurized to match the pressure of the habitat.

In the event of pressurant gas leakage from the expandable habitat, the crew can take refuge within the inner airlock by closing its door so that the airlock's pressure may be maintained at 68.95 kPa (10.0 psi). Also, under conditions such as a solar flare, the crew would take refuge in the inner airlock which would serve as a safe haven if the expandable habitat did not have adequate regolith radiation shielding to protect the crew.

Any concept featuring an expandable or inflatable module requires a specially designed floor that can be conveniently packaged for transportation and that will integrate smoothly into the expandable without need for wall penetrations.

A proposed concept uses 18 honeycomb sandwich panels carried upon a longeron/rib substructure. The substructure elements have openings which reduce mass and permit cabling or plumbing to be placed beneath the floor's surface. Figure 26 illustrates the principal features and the assembly sequence. A cutaway section of the flooring assembly identifies ribs which are hinged to longeron members for folding and minimum volume storage of the structure during transit. The longeron/rib construction consists of a low density foam core with structural composite skins to form a lightweight sandwich panel. The floor panels have aluminum alloy metal facing sheets with an aluminum foil honeycomb core. The edges of the individual floor panels overlap using a shiplap edge design. A spring-like clip is shown as attached to the honeycomb sandwich floor panel to assure proper edge location and load

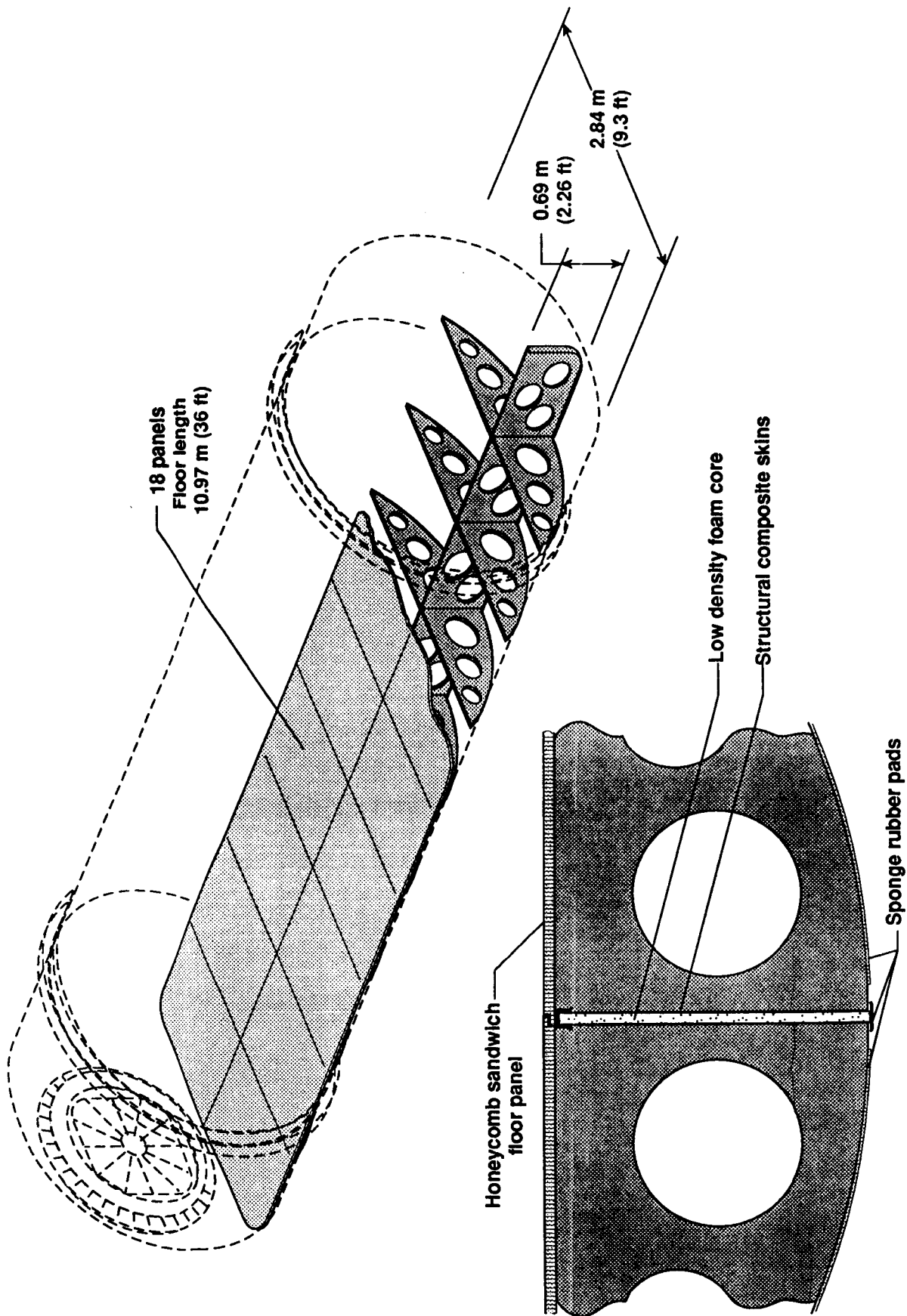


Figure 26. Floor Construction Concept

distribution into the longeron/rib construction. The edges of longerons and ribs that contact the inflated expandable wall construction are covered with thin sponge rubber to prevent damage to the inflatable wall. The floor assembly sequence is shown on figure 27. View (a) shows the outline of the cylindrical radius floor and an outline of the airlock opening as a standard hatch 1.22 m (50 in) square with radiused inside corners. The longeron/rib subassembly is introduced in a folded configuration through the airlock opening and the longeron placed parallel to the axis of the inflated cylinder. The ribs are then extended outward as shown in View (b). The first floor panel is positioned and aligned with clips as shown in View (c). View (d) shows a second floor panel with an overlapping edge being placed in position and a second longeron rib subassembly introduced through the airlock opening. The sequence is repeated as shown in Views (e) and (f) until the entire floor construction is complete. During cislunar transport the floor panels and flooring substructure can be folded, stacked and nested such that all of the flooring can be packaged within the rectangular dimensions as shown on figure 28(a). The package would be approximately 9.1 m (3.0 ft) in height, 1.2 m (4.0 ft) in width and 1.4 m (4.6 ft) long. The entire package will pass through a 1.27 m (50 in) square airlock opening as shown. The package of flooring could be carried in the inner airlock as shown on figure 28(b). It may be advantageous to divide the floor assembly panels and substructure elements such that they can be stowed in more than one location within the inner airlock during cislunar transport.

The mass empty estimates presented on figure 21 were calculated by a combination of techniques. The mass of the expandable module was calculated using weight data from the STEM adjusted for the greater internal atmospheric pressure. The mass of the metallic airlocks and storage case were volume scaled from SSF Node data. Other components such as metal flanges, tension cables, cable guides, and flooring were calculated from engineering handbook data. The outfitted module mass value was calculated using the same algorithm used for the other concepts using the SSF analog, i.e., the empty mass of the module is 75 percent of the outfitted mass at zero-gravity. An additional 10 percent is added because the interior space cannot be used as efficiently in lunar-gravity. At the level of design included in this study, these total mass values are, at best, calculated estimates. An error of 20 percent could easily be present and, if present, it is likely to be an error of underestimation because in-depth preliminary and detail design usually adds mass rather than reducing it.

Note that the double airlock arrangement presented in the earlier concepts is retained. In addition to the advantages relative to crew convenience and minimizing loss of gases as presented in the Concept 1 discussion, there is a safe haven feature provided by the double metal airlock when coupled with the lander concept. This feature will be described in the following sections.

Lander Configuration and Operational Sequence:

The Concept 3 habitat shared a design goal with the Concept 1 habitat, i.e., the habitat would be sufficiently small (dimension and volume) such that a single lander can set the complete habitat on the surface and then become a stand-off regolith support frame. Of the three concepts presented, the Concept 3 design is most amenable to this design goal because of its packaged dimension and volume. The lander is significantly smaller than landers for the other concepts.

The spacecraft-lander which delivers the expandable habitat to the lunar surface is a variation of the concept developed for the assembled module-airlock configuration of Concepts 1 and 2. Assembly for delivery also begins with joining of major elements. The smaller diameter of the habitat allows transport to orbit mounted in its cradle assembly

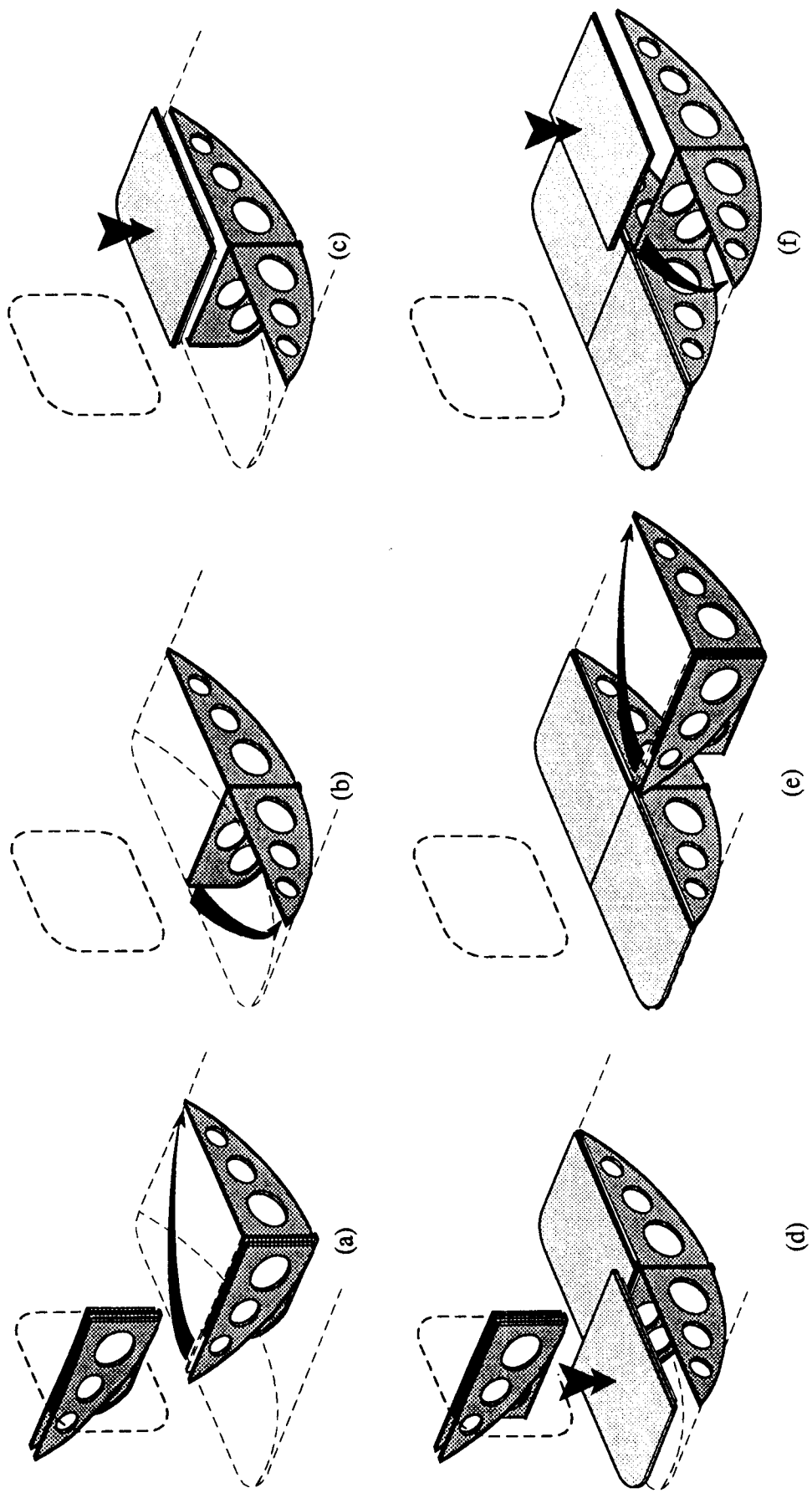
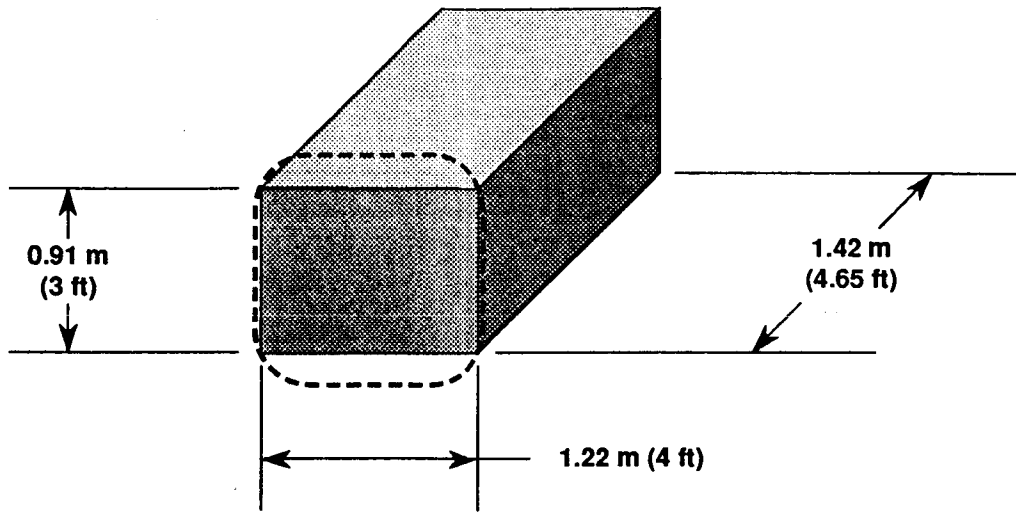
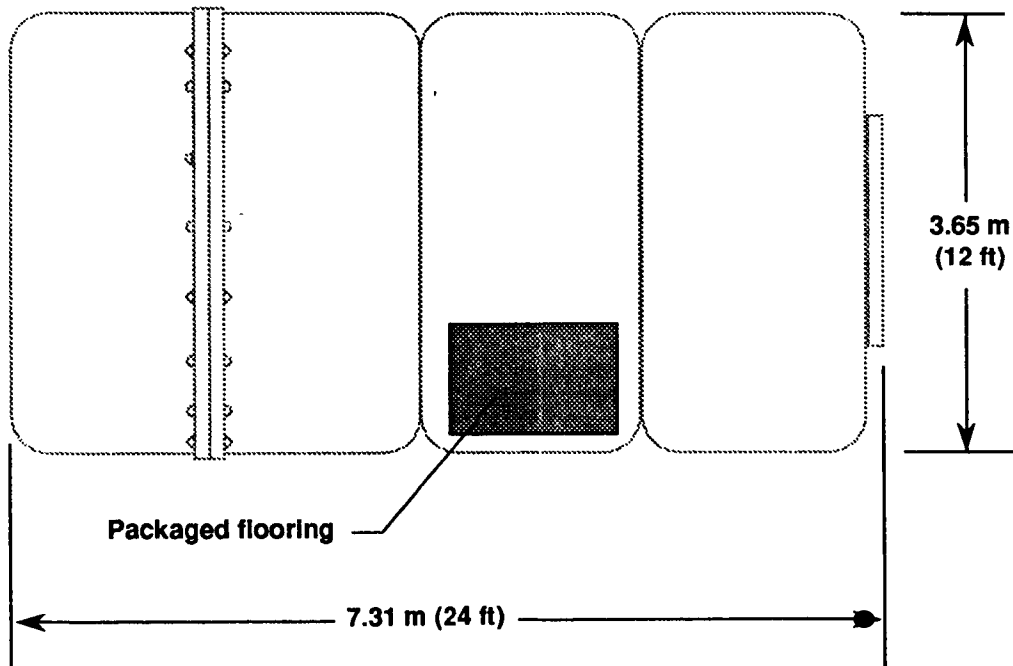


Figure 27. Floor Assembly Sequence



(a) Packaged Flooring Through Airlock Opening



(b) Flooring Transported in Inner Airlock

Figure 28. Packaged Flooring Transport
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and thereby reduces the number of on orbit assembly steps. Transport to the lunar surface proceeds in a series of pre-programmed remotely controllable steps. The propulsion techniques and propellents used for the Concept 3 configuration spacecraft-lander are the same as those used for the other two concepts. In addition, the assumptions relative to transfer of an unmanned habitat from LEO to the lunar surface presented in the Concept 1 lander discussion still apply. The overall features and dimensions of the spacecraft-lander are illustrated on figure 29 which presents the "as landed" configuration.

The spacecraft-lander for transporting the expandable habitat to the lunar surface also uses a grid of aluminum I beams as the principal structural elements. Within the strongback, I-beam webs accommodate the outside diameters of the propellant tanks so that the flanges accept landing deceleration loads in bending. Four telescoping cylindrical columns provide the support, and foot pads distribute lunar mass loads at levels compatible with regolith bearing capabilities. The landing decelerations will emplace the foot pad at depths sufficient to support the combined masses of the lander, habitat, and subsequent regolith shield. This configuration also carries a shuttle OMS engine at the end of each column throughout the boosted phases of transfer flight. In this concept the habitat unit together with the cradle and expansion control elements are integrated and validated during ground testing prior to launch.

At departure from LEO, the spacecraft lander configuration consists of the landed configuration augmented by six OMS engines and their auxiliary propellant tanks. The departure configuration is illustrated on figure 30; Table 7(a) presents mass summary for transfer from LEO to the lunar surface and Table 7(b) summarizes the utilization of masses delivered to orbit. The dimensions shown and masses listed suggest that in orbit preparation can be accomplished by remote handling techniques and can use a single shuttle flight supplemented by propellant delivery and transfer from shuttle C or its equivalent. A shuttle flight can carry the habitat-cradle assembly plus a folded spacecraft section within the payload bay. Fixturing within the payload bay would engage the habitat-cradle assembly (e.g., clamp to the outer airlock door frame) and position the habitat for mating to the spacecraft-lander section. A shuttle borne manipulator such as the RMS moves the lander section into a position where it can unfold the legs and perform any other deployments required in preparation for mating to the habitat-cradle section. The manipulator then brings the two sections into contact and completes the mating operations (e.g., latch and lock). At this time operating verifications are performed.

Transfer of propellents will involve either a pre-delivery of filled propellant tanks for rendezvous or rendezvous and berthing to an auxiliary booster such as shuttle C. Transfer of tanks from a shuttle C could require carrying a second RMS unit aboard the shuttle. In such a transfer, the second RMS engages and stabilizes the shuttle C while the primary manipulator moves the propellant tank bundles from the shuttle C cargo bay into flight position on the spacecraft-lander strongback. At completion of a final verification, the spacecraft-lander unit is energized and separated for flight to the lunar surface.

Transfer flight to the lunar surface follows the same general steps as discussed for Concepts 1 and 2. The initial phase of the flight using 6 OMS engines will experience accelerations ranging from 1.8 m/sec^2 (7.2 ft/sec^2) to 4 m/sec^2 (13.1 ft/sec^2) with a total burn-time of 27 minutes. While these values appear adequate, any increase in thrust would offer advantages in less burn-time and more flexibility in transfer trajectories. At completion of the Earth escape burns, two auxiliary engines and the empty propellant tanks jettison; figure 31 shows the configuration after such separation. Operations within the lunar gravity field involve a series of burns that accomplish mid-course corrections and the lunar descent trajectories.

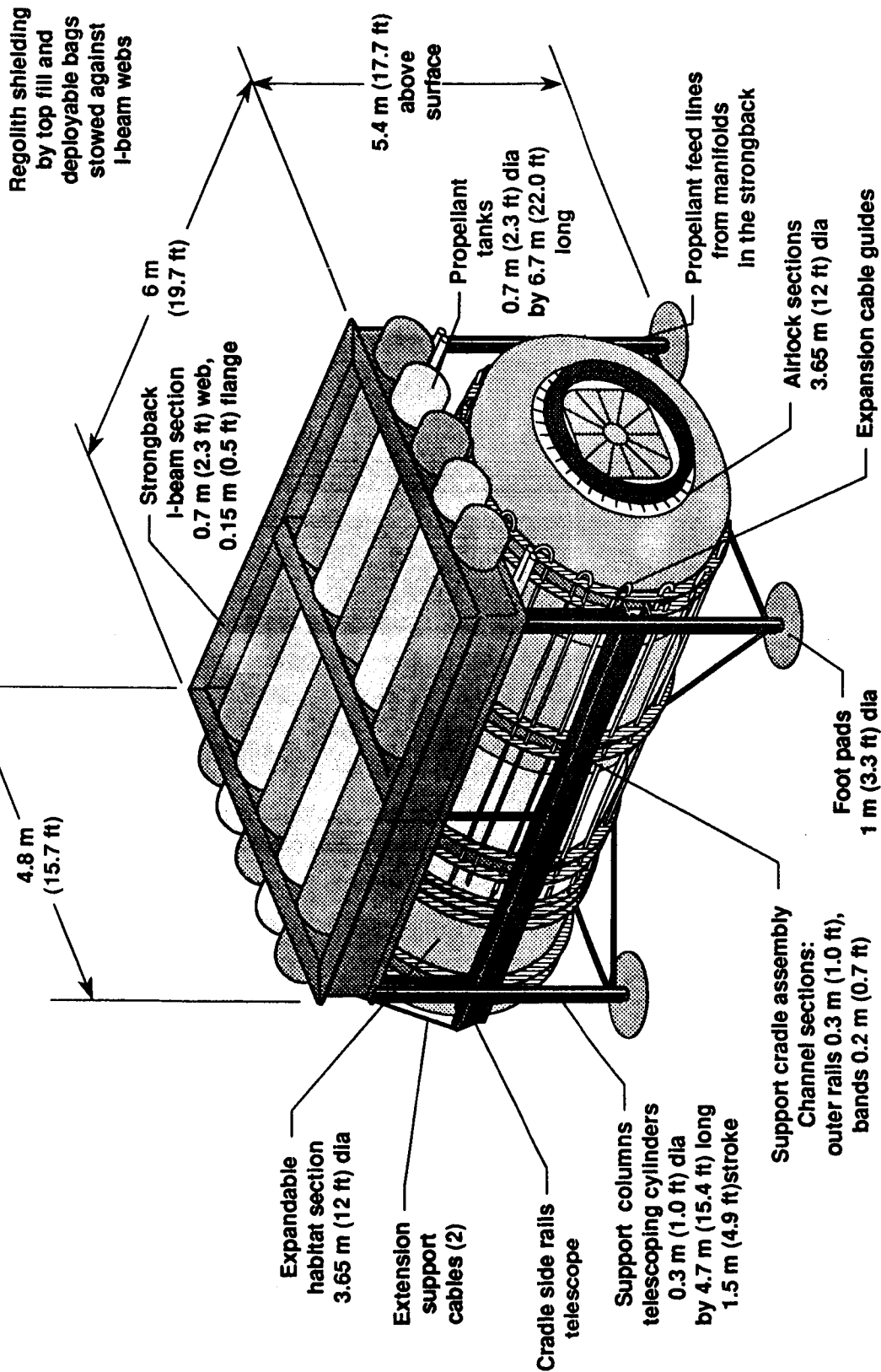


Figure 29. The "As-Landed" Configuration of the Concept 3 Habitat

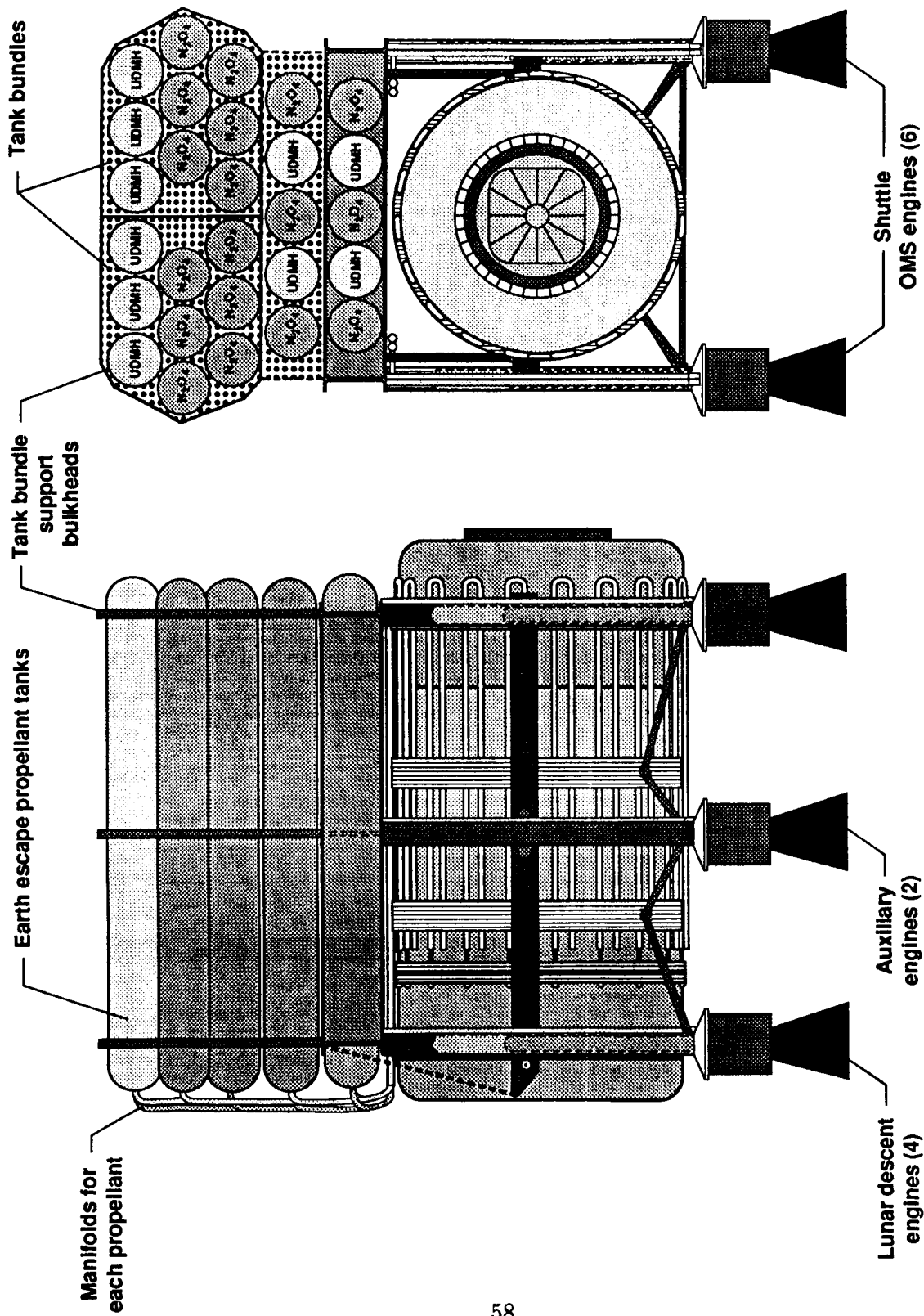


Figure 30. Concept 3 Habitat and Spacecraft-Lander Configuration at LEO Departure

TABLE 7. - SUMMARY OF MASSES FOR CONCEPT 3
HABITAT AND SPACECRAFT LANDER

(a) AT TRANSMIT STAGES

Element	Element Mass kg	Total Mass kg (lb)
Expandable Habitat Assy		8,608 (18,982)
Spacecraft-Lander		3,090 (6,813)
As Cradle	510	
Beams	972	
Legs/Feet	257	
Tanks, Manifold	684	
Valves	157	
Regolith Bags	510	
Residual Propellant		1,802 (3,974)
N ₂ O ₄	1,359	
UDMH	443	
TOTAL LANDED		<u>13,500 (29,767)</u>
Engines Separated		1,000 (2,205)
4 Engines	486	
4 Controls Auxiliary	520	
TOTAL AT ENGINE STOP		<u>14,500 (31,972)</u>
Descent Tanks Separated (5 Tanks, Manifolds Valves)		680 (1,499)
Descent Propellant Consumed		20,820 (45,908)
N ₂ O ₄	15,700	
UDMH	5,120	
TOTAL AT LUNAR FIELD ENTRY		<u>36,000 (79,380)</u>
Post-Burn Separations		4,000 (8,320)
Tanks	2,090	
Engines (2)	800	
Structure	1,110	
TOTAL AT EARTH ESCAPE VELOCITY		<u>40,000 (88,200)</u>
Propellant Consumed		48,800 (107,604)
N ₂ O ₄	36,800	
UDMH	12,000	
TOTAL MASS AT LEO DEPARTURE		<u>88,800 (195,804)</u>

(b) MASS UTILIZATION SUMMARY

Lunar Surface Delivered	13,500 (29,767)
Jettisoned En Route	5,680 (12,524)
Propellants Consumed	69,620 (153,512)
TOTAL	<u>88,000 (195,804)</u>
Delivery Efficiency (Habitat Mass as a Percent of Total)	15.2%

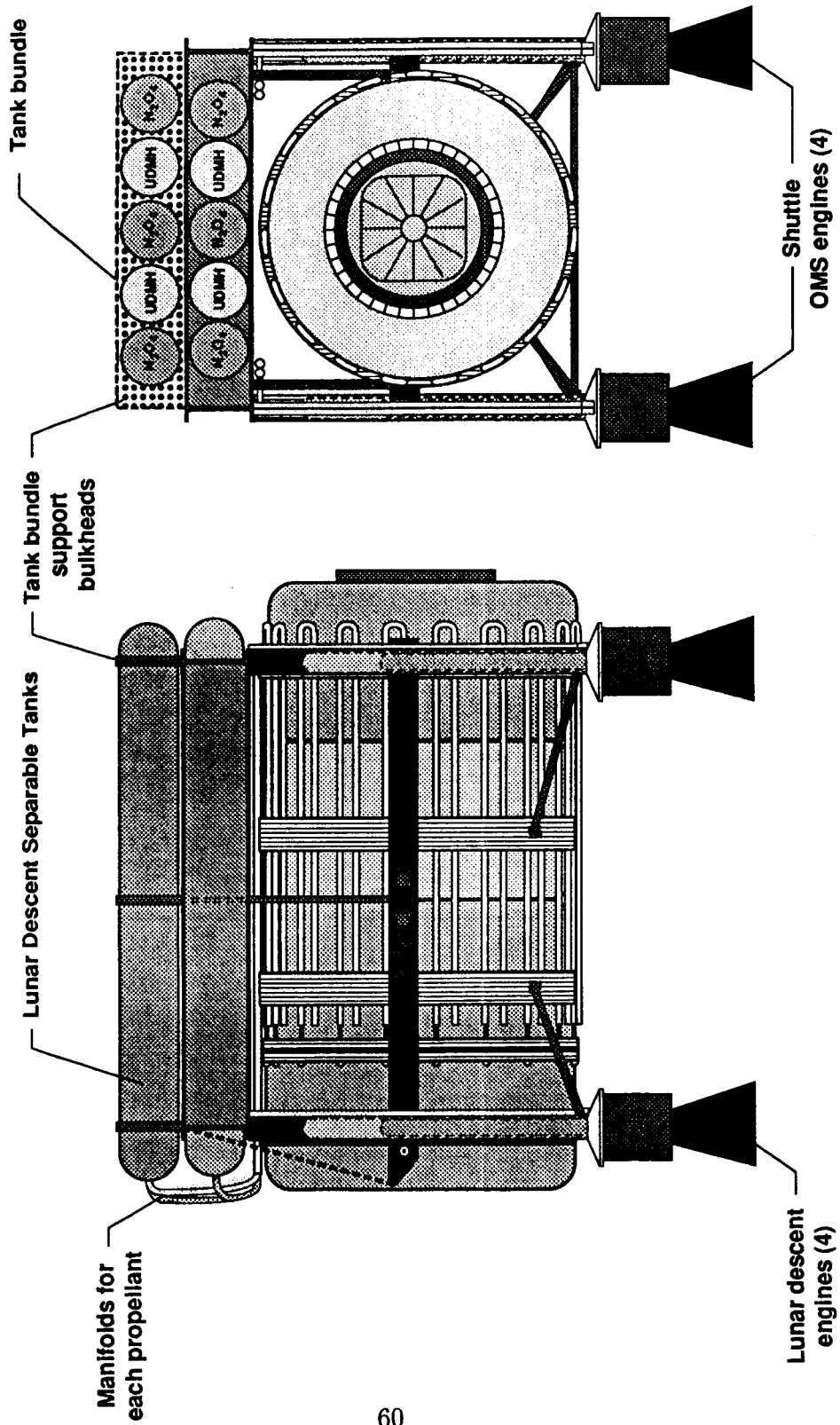


Figure 31. Concept 3 Habitat and Spacecraft-Lander at Entry into the Lunar Gravity Field

In these operations, acceleration levels with OMS engines range from 2.9 to 7.4 m/sec² (4.5 to 24.3 ft/sec²). At engine shutdown as shown on figure 32 the spacecraft-lander will come to zero velocity at a point above the landing site and engine thrust levels would then be approximately 4.7 times the lunar gravity weight. Engine separation follows engine shutdown which initiates inflation of the pneumatic bags in the attenuator struts. At touchdown the spacecraft-lander has the configuration shown on figure 33 and assumes the configuration as shown previously on figure 29 as it awaits the arrival of the lunar exploration crew.

The initial step in the erection of the expandable model is the automatic release of a Marmon style ring clamp holding the storage case and storage case cap together. Upon release of the clamp, the stored energy of the folded expandable will initiate a small extension of the expandable module. Subsequent extension operations proceed crew-tended with controls from inside the airlock. The driving force for extension is a gradual inflation of the expandable section. Pressure forces generated from inflation balance against reacting forces transmitted by the extension support cables and the mechanism which unifies the motion of the cradle elements (rails and rings). A continuing expansion encounters an increasing restraint force component from the extension support cables such that payout of the cables efficiently controls both motion and position. Extension also draws the expansion cables through their guides until the ends seat in the retaining flanges. At completion of extension, the internal pressure increases to the operating level of 68.95 kPa (10.0 psi). At final extension and pressurization the habitat is configured as illustrated on figure 34.

Environmental Shielding:

The environmental shield proposed for the Concept 3 habitat is designed only as a safe haven against a solar flare event. The small mass, volume, and packaged length of the expandable is focused exclusively on use as an initial habitat and, therefore, complete shielding against galactic cosmic radiation is not required. The shield exhibits an additional safe haven nature by the fact that it covers the two metallic pressure vessel elements rather than the expandable portion. In the event of a solar flare, micrometeoroid shower, or other environmental emergency, the two metal pressure vessels covered with regolith provide an excellent safe haven. Although the Concept 3 habitat is not proposed for continued habitation in a permanent base scenario, the safe haven portion of the habitat could be retained for continued use.

During the transfer flight, regolith containment "bags" or "pockets" stow against the webs of the beams which form the strong back. A crew initiated release frees and deploys the bags in preparation for fill. Fill can proceed automated or crew tended as the design of the regolith transfer equipment dictates. Figure 35 illustrates the configuration of the habitat at completion of the regolith fill. To achieve a minimum regolith thickness of 50 cm (19.7 in) the configuration requires 18.9 m³ (24.7 yds³) for the top, 49.0 m³ (64.1 yds³) for the sides, and 13.2 m³ (17.3 yds³) for the front face. The total amount of regolith required is 81.1 m³ (106.1 yds³). Compared to the Concept 1 and Concept 2 regolith volume requirements of 556.1 m³ (727.4 yds³) and 693.0 m³ (906.4 yds³), respectively, the requirements for Concept 3 is relatively small.

Alternate Approach:

The alternate approach to the Concept 3 habitat is one that is independent of the spacecraft-lander and perhaps optimized relative to logistics considerations. In addition, it provides a different level of environmental shielding that may make it more amenable to

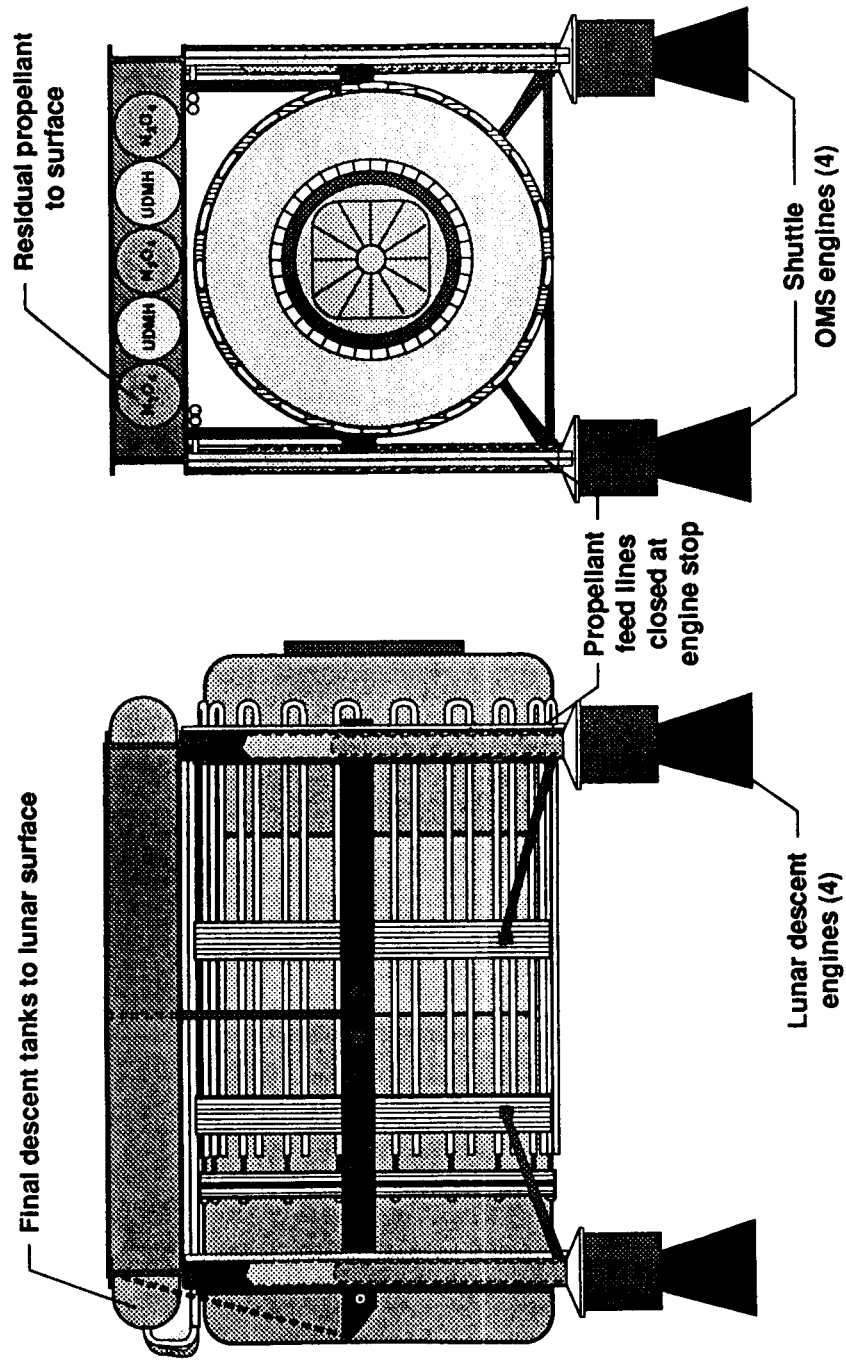


Figure 32. Concept 3 Habitat and Spacecraft-Lander Configuration at Descent Engine Stop

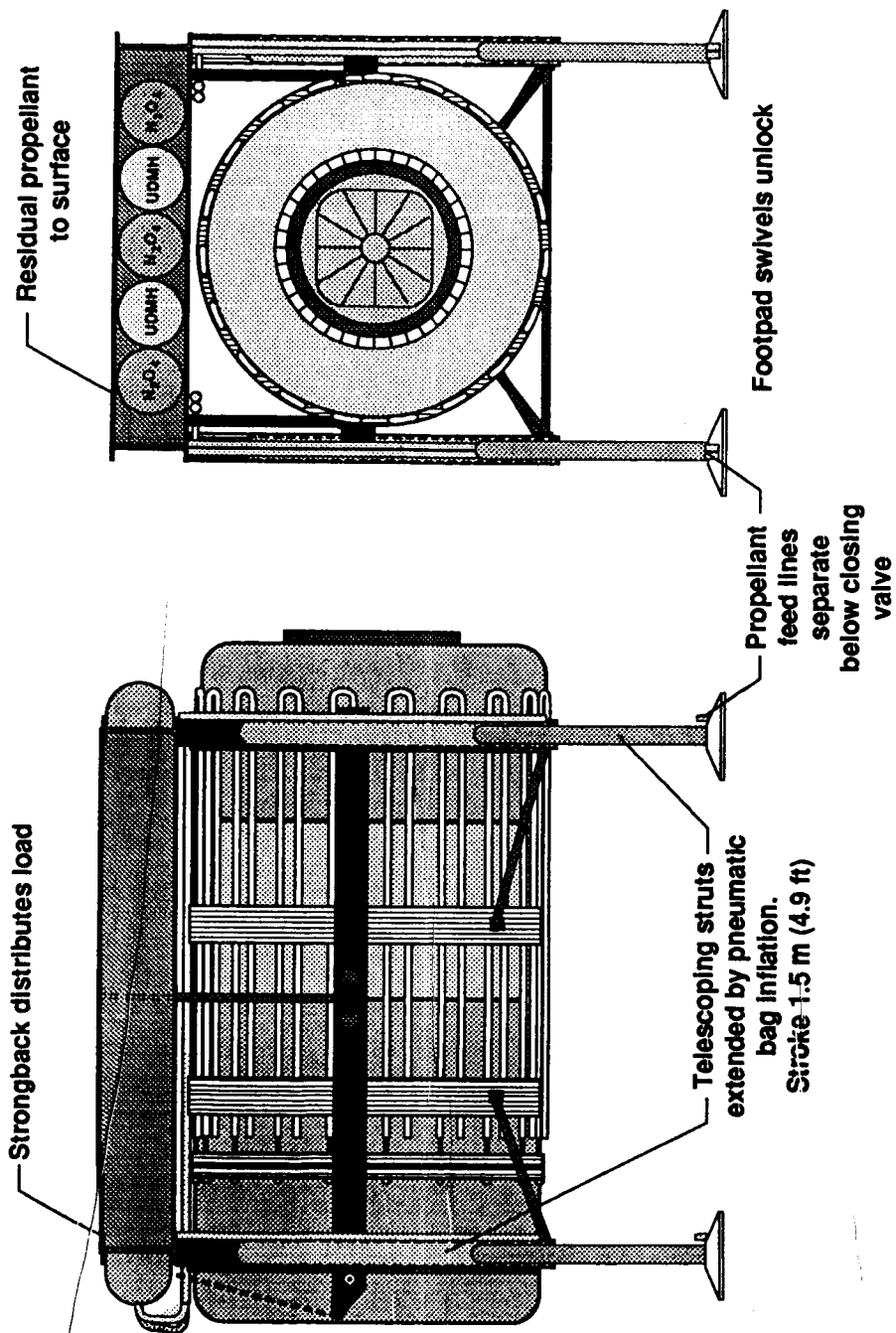
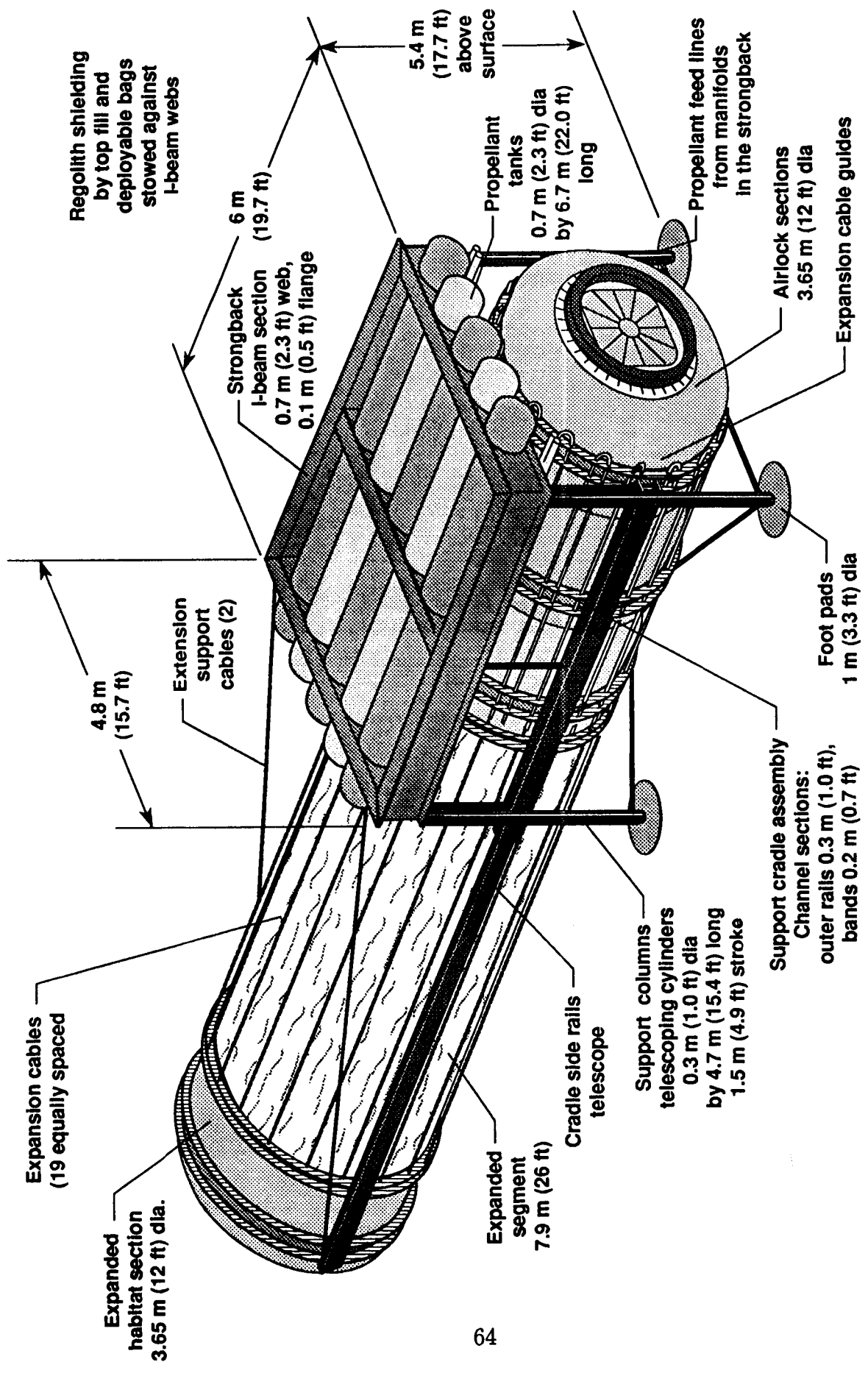


Figure 33. Concept 3 Habitat and Spacecraft-Lander Configuration at Touchdown



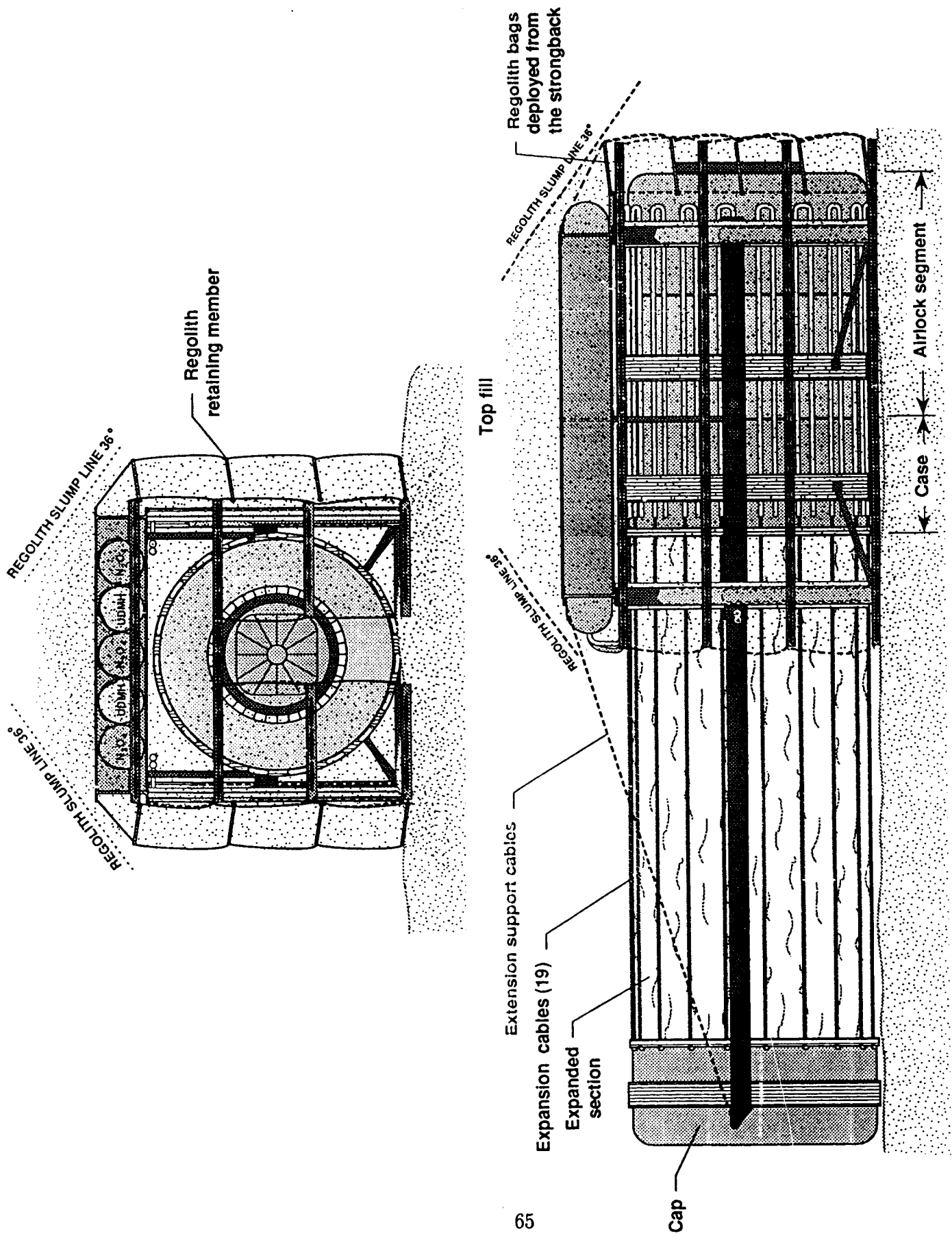


Figure 35. Concept 3 Habitat with Regolith Shield

continue use in a permanent base scenario. The alternate is highly conceptualized and no in-depth engineering studies have been conducted to validate a design.

The concept uses the same expandable habitat presented for the Concept 3 baseline. In the packaged configuration, the habitat is placed on a structural pallet which serves as a base for handling during transit operations and as a base for support on the lunar surface. A second, identical pallet is loaded with subsystems, furnishings, expendables, etc. Both the palletized habitat and the logistics pallet are enclosed in a prefabricated, lenticular cross section ribbed panel whose ribs can be flattened and rolled to a great extent during transit and be unrolled into its structural configuration when released. It is possible that the panels for each pallet cannot be fabricated as single panels. It may require fabrication in multiple sections. A palletized Concept 3 habitat and a palletized hypothetical load of logistical supplies are illustrated on figure 36. The lower edges of the panels would be fitted with some type of structural member that will serve as a support foot when placed on the surface and serve as a fastening mechanism to a lower edge of the pallet during transit. In effect, the habitat or logistics package, support base, and environmental shield all become an integrated palletized payload that can fit easily into the shuttle orbiter bay. In fact, the concept is that a habitat and a logistics pallet would be launched simultaneously and travel as an integrated habitat.

The type of lander visualized for the two palletized units is the configuration illustrated in figure 33. The figure has been extracted without modification from the 90-day study report, ref. 8. The palletized units would be the two cargo units illustrated on figure 37. Once landed the two units would be off-loaded by an undefined lifting device and brought together in the following sequence of events:

- Ends of the two pallets are fastened together producing one long support base.
- The two environmental shield panels are released and deployed to assume a "quonset-hut" configuration.
- The items on the logistics pallet are removed leaving the pallet to serve as a base for the expanded habitat.
- The habitat is expanded as previously discussed except the telescoping cradle side rails will not be present at guide expansion. In its place will be some type of slide device built into the pallet tracks (horizontal I-beam structural members) pallet or perhaps rollers built into the storage cap case which roll with expansion along the inside of the pallet tracks. Prior to total inflation, the tension cables are completely extended providing stability and preventing an overturning moment to occur with the bottom restrained and the top remaining free.
- Logistics materials are then placed under the shield along the habitat wall.
- It is conceivable that regolith can now be applied over the shield. Retaining bags or pockets would need to be placed on the sides of the shield up to a height where the shield flattens sufficiently to hold the regolith. The top one-third can likely be covered with a free standing pile. If regolith is added, it is also likely that a load supporting longeron of some type may need to be placed along the top of the habitat. A sketch of the concept features and assembly sequence is presented in figure 38.

Technology Assessment:

The technology needs of Concept 3 include advances in both habitat and lander technology. The needs for habitat technology are peculiar. Of all the concepts presented in

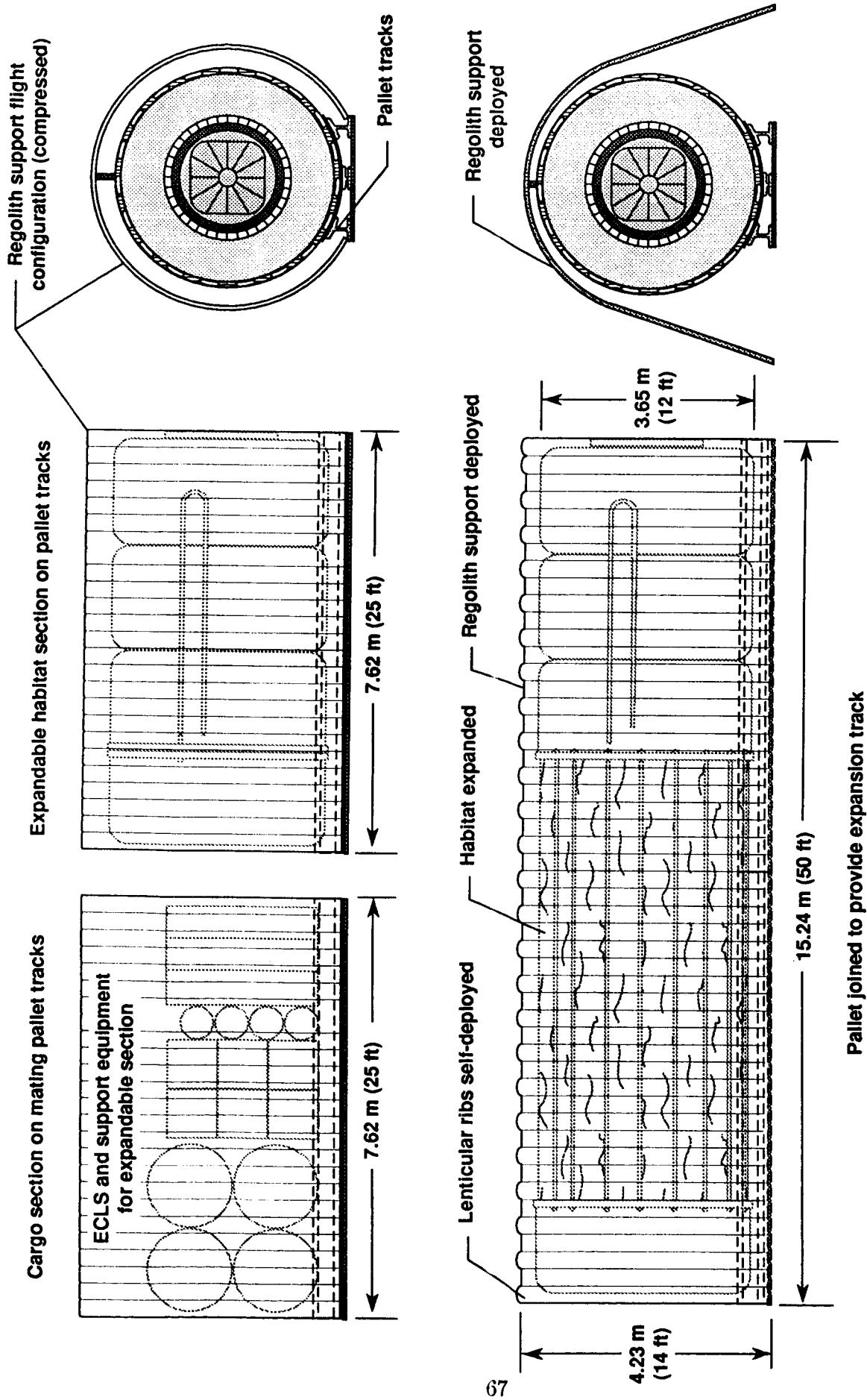


Figure 36. Concept 3 Habitat. Two element lunar delivery with a deployable regolith support structure.

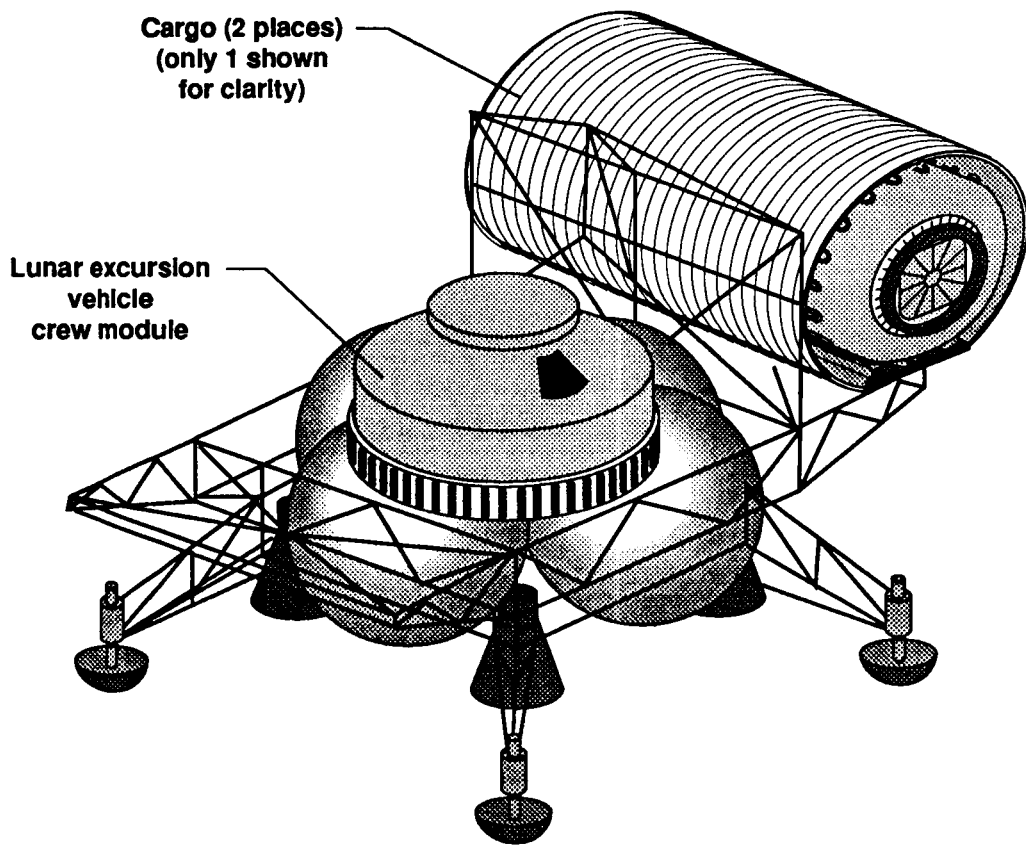


Figure 37. Lunar Excursion Vehicle

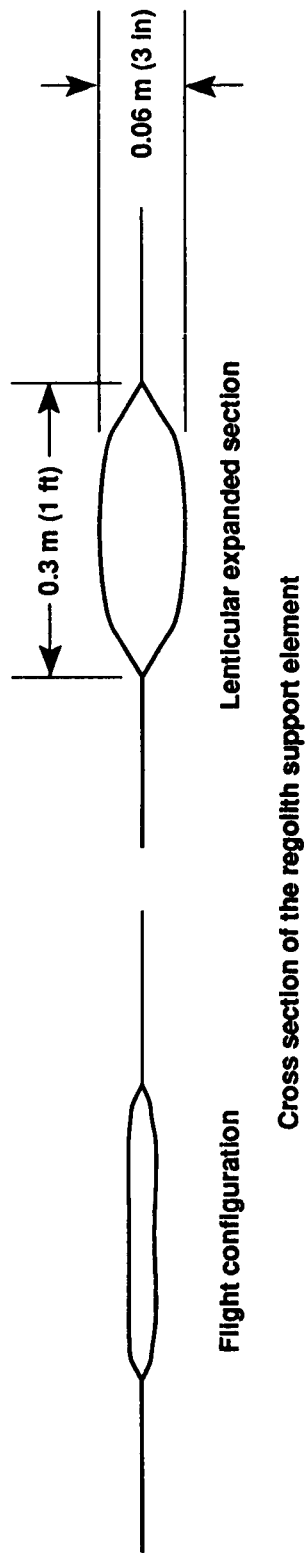
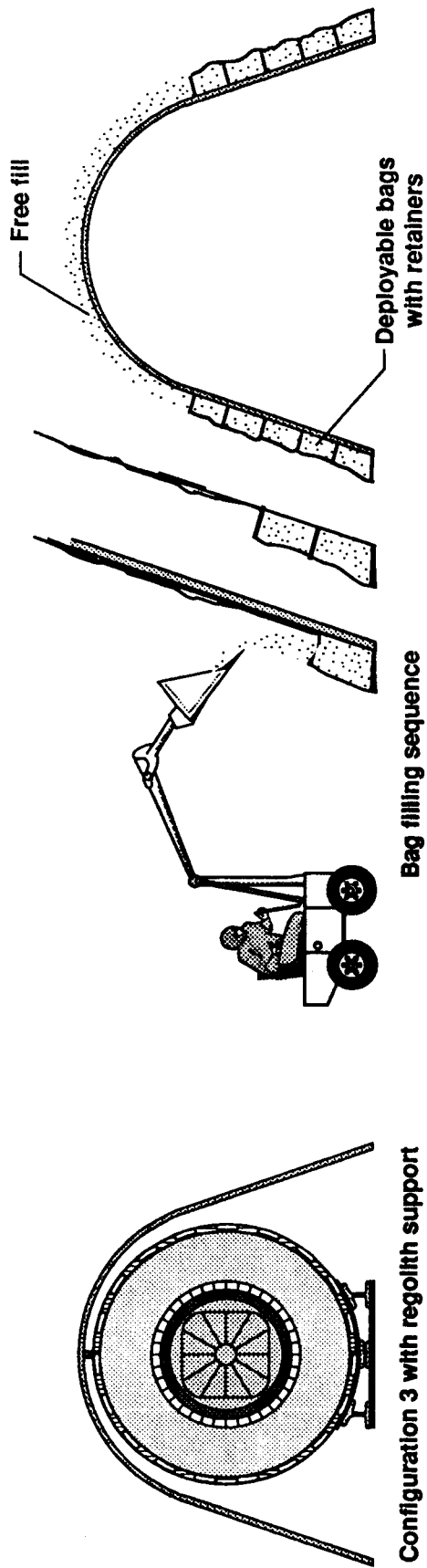


Figure 38. Regolith Fill and Construction Details for the Deployable Regolith Support Structure

this paper, the flexible, multi-layer wall expandable module is the only one that has been advanced to testing of a full-scale flight prototype. From that perspective, it is the most advanced technology. On the other hand, the technology baseline is 25 years old and has been dormant for the entire period. Many advances in organic materials, filament reinforced fabrics, adhesives, etc. have occurred that essentially render the STEM and MOBY DICK wall structures as archaic. The technology of the entire composite wall structures would need to be updated. The lenticular rib cross-section folding panels suggested in the alternate concept require new technology, at least in the application proposed. It has, however, been applied to large antennae components. The choice of wire ropes for the expansion cables was a choice based only on known capability to provide a specific function. Modest advanced study with subsequent development certification may produce more favorable materials for this application. The technology needs for the Concept 3 spacecraft-lander and the assembly and transit profiles are similar to those discussed in Concepts 1 and 2. It is appropriate to reiterate the regolith containment device need discussed with Concept 1. Again, Concept 3 depends upon the development of such a device and a satisfactory deployment and fill technique. This need cannot be overemphasized. Future studies should not casually assume the availability of the item and related techniques. There are, however, some additional needs associated with the specific application of the smaller lander. Technology needs specifically related to the proposed Concept 3 are summarized in Table 8. The listing identifies needs, indicates the action or response required, and estimates technology readiness. A brief discussion of each of the needs follows the table.

Materials and Expandable Structures Technology Needs (1, 2, 3, 4)

The STEM and MOBY DICK developments established a demonstrated technology baseline for expandable habitat elements. The baseline, however, is 25 years old and needs to be revisited to incorporate new materials technology. The final design of an expandable element wall structure may well be application specific taking into account the internal operating pressure, oxygen content, unsupported span of the module, required configuration for packaging, and deployment techniques. Therefore, the materials technology update may proceed independently at any time, but the advancement in technology of wall design and fabrication techniques should await more detailed definition of overall habitat features and characteristics.

Furnishings Compatible With Expandable Structures Need (5)

One of the more difficult challenges and perhaps a most limiting factor in the use of expandables is the design of furnishings that must be carried into the expandable and be installed after expansion is complete. The reluctance to penetrate the wall and the inability to do so compels design efforts to focus on large, light weight components that nest to the shape of the expandable. The most simple example of a design challenge is the definition of a floor. It must be hand carried in by the crew, it must be large but light weight, and must nest well enough to be sturdy in use. A floor concept is presented in this study, but it may not be the optimum one for the configuration. Each remaining piece of interior furnishing is also a design challenge. If more detailed design studies are conducted on the use of expandables, the design of furnishings must be included.

Special Load Bearing Elements Need (6)

The selection of wire rope for the expansion cables was chosen quickly to establish a baseline for a broader concept. The cables may well be fabricated more advantageously

TABLE 8. SUMMARY OF TECHNOLOGY DEVELOPMENT NEEDS FOR CONCEPT 3

	Technology Need	Action or Response Required	Technology Readiness Level*
1	Advanced materials for use in expandable elements.	Survey of materials with tentative selection based on physical and structural characteristics.	4
2	Applied designs of multi-layer walls for expandables based on use of advanced materials.	Detailed design studies, test item fabrication, verification testing.	4
3	Update of fabrication techniques, foldable designs, packaging, and deployment techniques for modern expandable composites.	Detailed design studies, test, item fabrication, verification testing.	5
4	Development of designs for interfaces between expandable composite walls and metal element interfaces.	Detailed design studies, test item fabrication, verification testing.	3
5	Development designs for interior furnishings compatible with limited ability to fasten components to rigid frame members.	Detailed design studies, layout of concepts, development of assembly concepts.	3
6	The application of composite materials technology to special load bearing elements such as the expansion cables (tensile cables).	Detail design studies and limited testing on laboratory scale.	1-2
7	Spacecraft-lander optimized for mass efficiency coupled with self deploying features and dimensions compatible with a shuttle payload bay.	Interactive Trade Studies, Structural analysis and verification testing that defines a configuration which does not require a in-suit EVA during in-orbit assembly.	5
8	Control and operating techniques for the expansion operations on the lunar; surface.	Interactive trade and design study to define a configuration followed by verification tests.	5

*Level 1 Concept with no Previous Application
 Level 2 Related Concept Proposed for Application
 Level 3 Related Concept with Limited Application
 Level 4 Concept with Established Operation in Previous Flights
 Level 5 Concept in Active Update for New Application
 Level 6 Presently Operational in Reduced Scale or Complexity
 Level 7 Existing Capability in Present Use

from other materials such as metal or metal alloys, synthetic cables, or fiber reinforced composites. Fiber reinforced composite materials offer several advantages over metals; most notably, lower density (light weight). They also provide higher stiffness and low thermal expansion. Depending on location, the temperature fluctuation on the moon would cause significant expansion and contraction of metallic components whereas cables (straps) made of composites could be designed to have near zero thermal expansion behavior. The load bearing capability of a composite strap would meet the design requirements for a habitat with an internal pressure of 68.95 kPa (10.00 psi). Also, composites can be designed and fabricated to have strength and stiffness preferentially in the desired direction.

The long term stability of an unprotected organic matrix composite exposed to the harsh lunar environment where solar protons, galactic cosmic radiation, and micrometeorites would cause severe degradation is of concern. However, since the initial habitat is designed for temporary human occupation the material would perform well for the short time required.

Composite materials can offer certain advantages over metallic materials. The use of composites for applications on the moon will likely be necessitated by mass requirements. However, the effects of a lunar environment on these materials needs to be researched in greater detail in order to provide the level of confidence required to implement their use.

Spacecraft Design and Assembly Integration Need (7)

The mass estimates for the expandable habitat and the overall dimensions of the packaged assembly fall within the original capabilities of the shuttle. Consequently this configuration appears within a near-term achievement if a shuttle and shuttle C carrier can rendezvous in orbit and transfer payloads. Optimization of the spacecraft lander configuration becomes a unification of three interrelated studies applied to larger and more massive habitats. Larger units involve more than a single rendezvous with the in-orbit facility and thereby make design studies interactive but independently addressed. In this case all aspects need to proceed concurrently in a phased approach. Trades and analysis produce a comprehensive design of the spacecraft, handling techniques, specialized equipment and detail elements. Implementation requires verification testing at each step with a final verification using the proposed flight items.

Expansion Control and Operation Need (8)

Design and fabrication of the expandable sections implies a series of verifications that address bonding, flexing and load distributions within the structure. Seals and flexing integrity for the expandable material appear critical as well as the verification of load distributions relative to the expansion cables. The flight support cradle and its telescoping members appear as necessary elements in the verification process. Definition and evaluation of the lunar on-surface expansion techniques therefore are considered the final elements for completing the expandable habitat concept. Existing laboratories have the capability to support such experimentation.

PERMANENT HABITAT

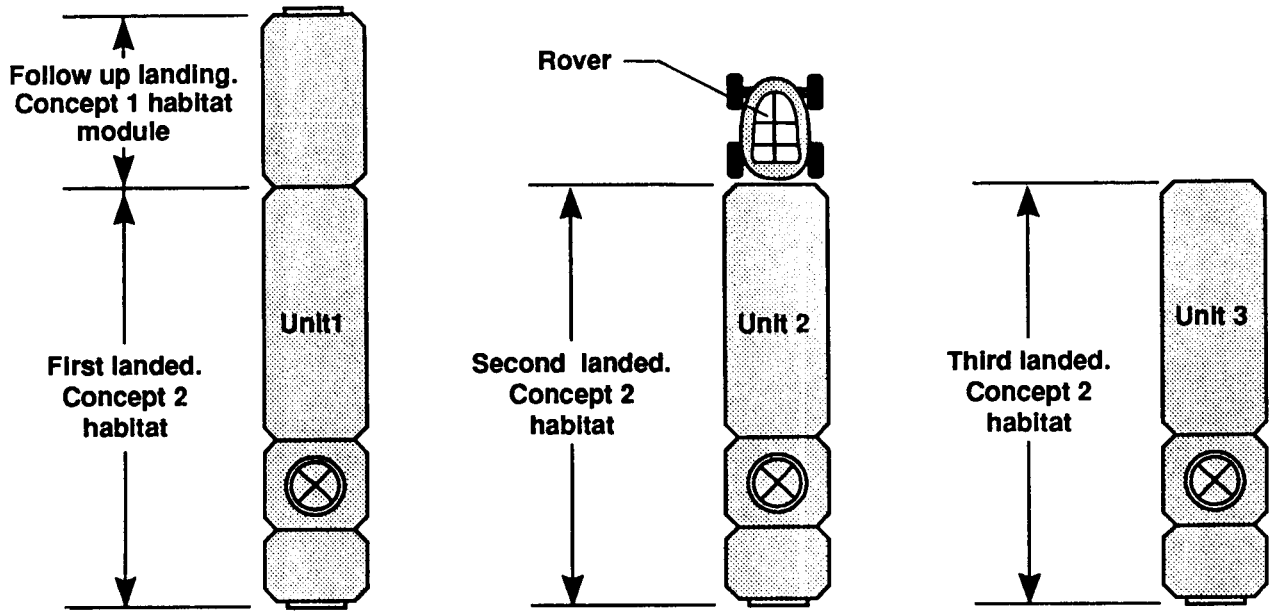
At the beginning of this study, it was expected that a concept or concepts for the 4 crewperson, 28- to 30-day initial habitats would be developed followed by the development of a different concept for the 12 crewperson, indefinite length permanent habitat. The study, however, did not evolve in that direction. As trade-off criteria and design guidelines came into focus, the study efforts resulted in the approach of using multiple initial habitats to evolve into a permanent habitat. The same rationale that steered initial habitat design guidelines toward techniques that use existing technology, are simple to transport and implant, require little on-surface operation, and result in maximum program economy also apply to permanent habitats. There appears to be no compelling reason to design a separate, large, complex habitat that is difficult to erect and costly to operate and maintain. In the lunar base scenario in which both hardware development and logistic costs are so great, it appears prudent to continue to utilize a hardware element once it has been transported to the moon. Growth of existing capability rather than new start when moving from the initial to permanent habitat phase is desirable.

Two of the three concepts presented for initial habitats could be extended to serve in a permanent habitat scenario. The habitats of Concepts 1 and 2 could be delivered in multiple units to build up to a base for a crew of 4, 8, and 12. The Concept 3 habitat was conceived only as an initial habitat and will not be carried further in the permanent habitat discussion. The 12 crewman base could be served by three or four of the habitats assembled into a single base but with separate habitat elements. Figure 39 illustrates two variations of a permanent lunar habitat. The figure is diagrammatic and only illustrates habitat layout options. Features of design and construction are not included. In the separated units variation, the three, 4-crewman units are shown as separate units with random alignment. One of the major advantages of this configuration is that habitat units supporting crews with specific missions could be located as desired to be near a lunar base operational system such as an observatory, liquid oxygen plant, or laboratory and yet remain part of a total base social infrastructure. Other advantages of the separated units configuration include:

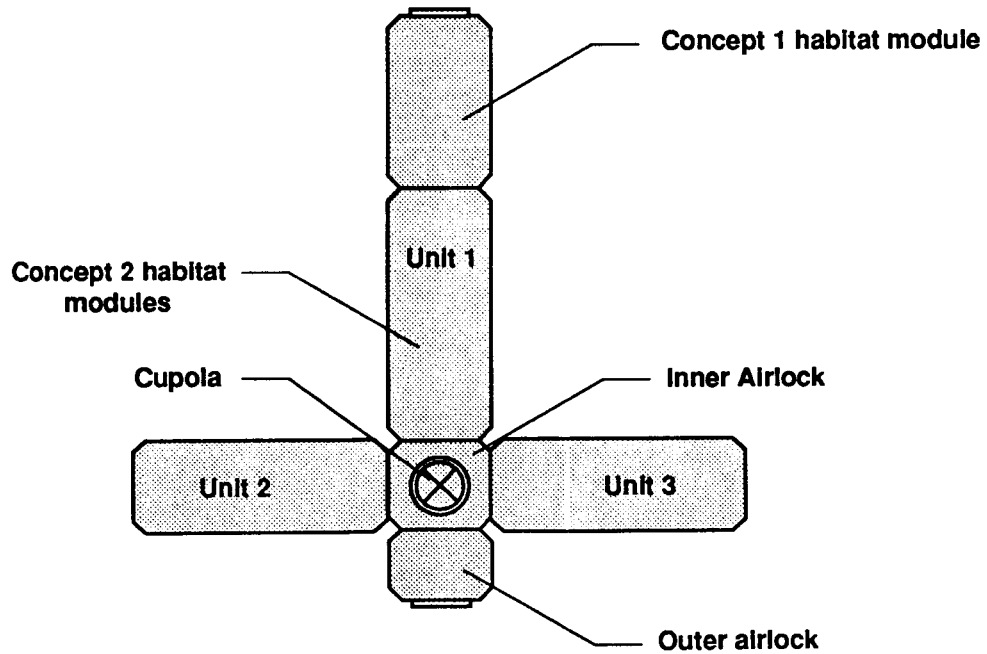
- The potential for a single catastrophic failure is reduced. Each unit could provide safe haven for the others.
- Material for a regolith shield can be obtained from a smaller, local area for each unit.
- Individual units could be shutdown or restarted at will giving some flexibility to the long term base operational scenario.
- The equipment and emplacement procedures developed for the initial habitat would continue to be useful during later phases of base development.

In the connected unit configuration, launch masses have been reduced by tying three habitat units to a common double airlock thus eliminating two sets of double airlocks. This configuration would also permit shirt sleeve movement between units except when airlock operations are underway.

Three additional features that may have application to the permanent base scenario are also depicted on Figure 39. Unit 1 shows the addition of a smaller module, the 2/3 SSF module of the Concept 1 configuration, to the Unit 1 habitat. The 2/3 module could house the majority of the subsystems freeing the interior of the habitat module for more living space desirable with the longer durations of crew stay. The inner airlock based on a SSF



(a) Lunar base as separate units



(b) Lunar base as connected units

Figure 39. Permanent Lunar Base Configuration, using Elements from Concepts 1 and 2

node shows a cupola extending above the airlock. The top of the cupola would extend above the lunar regolith to provide a port for visual observation of the surface. The cupola could be transported withdrawn into the airlock and be extended upon pressurization of the airlock. The Unit 2 habitat shows a rover vehicle connected to the rear of the unit. In concept, the rover would maintain the same pressure as the habitat unit and permit personnel movement from habitat to habitat or habitat to surface travel without having to don and doff pressure suits. The ability to quickly enter a vehicle and move away from the habitat could also be considered a safety feature.

The major criterion for selecting a configuration of a permanent habitat or group of habitats will probably be the overall operational use plan for the base. The evolution of the buildup and the final layout of the base relative to the functional capabilities sought may dictate the permanent habitat configuration more than individual structural considerations.

ADDITIONAL CONCEPTS OF HABITATS AND SUPPORT EQUIPMENT

Prior to and during the period of this study, several concepts related to the scope of the study emerged but because of the lack of study depth, documentation in previous publications, or highly specialized application, they have not been written into the text. They are, however, potentially useful concepts and are included for information exchange in Appendix B.

CONCLUDING REMARKS

At the current point in the program to define that total scenario to return to the lunar surface and establish an operational lunar base, it is not clear what the optimum design of an initial and a permanent habitat should be. The initial habitat, however, is closer to being defined because its function is clear and the features that it must possess are straight forward and somewhat independent of the ultimate use plan for the base. With today's high cost of systems development, overall cost effectiveness must drive designs. This implies that features such as simplicity, adaptation of existing systems, minimum logistics, minimum set-up time, and continued use of all elements once emplaced on the surface will greatly impact habitat selection. Perhaps the single most important selection criterion, and the one whose absence prevented a firm selection in this study, is the decision relative to which location should require the least operations, an Earth orbiting node such as SSF, a lunar orbiting node, or the lunar surface. Once this decision has been made, the optimum design for the initial habitat can quickly be focused.

The pressurized elements of the Space Station Freedom program are leading candidates for early lunar base habitats. They offer proven designs with development costs prepaid. Their designs, however, must be adapted to the lunar gravity field which changes the interior layout and utilization patterns. A significant design driver in the utilization of the SSF elements and all other habitat design concepts is the technique used for regolith coverage. The structure for the regolith support has to be built into the habitat or a separate structure has to be included. Results of this study indicate that it may be feasible to design and deliver a lander that becomes the regolith support structure after completing its mission as a lander.

The optimum design for a permanent lunar habitat has not been a goal of this study. Its selection is more closely linked to an overall use plan for the base. The use plan may contain features that become design drivers for the habitat. In the absence of such a use plan, however, the trade-off criteria and design philosophy used to guide the selection of initial habitat concepts appear to remain valid. The best concept is the one that is most cost effective; making use of existing technology, hardware systems, transportation systems, and the elements previously implanted on the surface. Thus the permanent habitats grow and evolve from the initial habitats.

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APPENDIX A - TRADE-OFF CRITERIA INITIAL HABITAT

Absolute Criteria:

The habitat must meet the absolute criteria. The rating is limited to "yes" or "no." If a concept does not meet one or more of the absolute criteria, the concept is rejected. If it does meet the criteria, it is evaluated against the primary criteria.

Protection From Environment Hazards - The habitat must protect the crewman from the lunar vacuum, extremes in temperature, and the radiation environment (ionizing and galactic cosmic).

Habitable Enclosure - The habitat must provide adequate atmospheric pressure (10.0 to 14.7 psia), nominal sea level oxygen partial pressure (160 mm Hg), and controlled carbon dioxide partial pressure. In addition, the habitat must provide a minimum volume per crewperson for conducting living functions for a 30-day period.

Safe Haven - The habitat concept must provide a safe haven for crew survival assuming the primary pressurized module has to be abandoned. The length of the safe haven period is the time required for rescue and return of the crew to an Earth orbiting space station.

Capability to Support Mission - The habitat concept must support the mission objectives, i.e., allowing the 4-person crew to remain on the lunar surface for a period of 30 days and to permit crewpersons, working in pairs, to have routine access to the lunar surface for conducting experiments and to prepare the site for a permanent lunar base.

Primary Criteria:

The primary criteria are the criteria upon which the relative ranking of habitat concepts are based. During this study, each of the criteria were judged to be of equal importance, thus weighting of criteria was not applied.

Compatibility With Transportation Systems - To be a viable concept, the candidate concept must be capable of being transported to the moon in a reasonable scenario. A reasonable scenario is defined as the use of the STS orbiter or shuttle C for lift to Earth orbit and the Orbital Transfer Vehicle and Lunar Landing Vehicle as defined in the NASA-JSC 90-Day Study.

Total Effort To Reach Operational Status - This criteria includes the total of the activities and time required to reach operational status once the lander has landed on the lunar surface. The assumption is that the initial landing of the crew and the preparation of the first habitat will be a stressful, intense period. The less time and less activity required, the better the concept. Especially to be avoided are activities requiring the suited crewmen to climb, lift, crawl under or over elements. Another major goal is to reduce the difficulty and amount of surface preparation required (scraping, leveling, digging) and to make the enormous task of covering the habitat with regolith (or other protective material) as easy as possible. Coincident with the goal of minimum surface preparation and ease of applying a protective cover, it is desirable that the emplacement sequence require the fewest number of large, specialized pieces of moderate or heavy equipment (cranes, dozers, front end loaders, etc.).

Potential For Catastrophic Failure - There are two parts of this criterion; safety related failures and mission related failures. An EVA task that requires a suited crewmen to

work around heavy construction equipment during emplacement offers the potential for a catastrophic safety related failure. A single compartment habitat that has to be lifted and/or moved during emplacement offers a potential for a catastrophic mission failure. The potential for these failures are always present; however, the more favorable concepts would be one that minimize the odds of occurrence.

Development Risks and Costs - It is important to minimize development risks and costs, especially for the initial habitat. One way to minimize both is to use elements of earlier spacecraft for elements of the habitat. In addition to having proven structural integrity front end DDT and E (Design, Development, Test and Engineering) costs should be minimum. The extensive use of new technology would increase both risks and costs. New technology should be incorporated only if it provides a feature overpowering the increased development risks and costs.

Secondary Criteria:

Secondary criteria should not identify a winning candidate, rather they should add backing and support to selected concepts.

Requirement for Specialized Tools and Equipment - This criterion overlaps the primary criteria of development risks and costs. The use of specialized equipment to lift, haul, grade, align, etc. adds weight, risks, time, and costs. Some specialized equipment will be required, but a need for a large cadre of special tools, vehicles, etc. should be avoided.

Usability During Permanent Base Phase - The requirement for habitat re-usability cannot be considered of primary importance since reusability at a later date is not required of a concept suitable for an initial base; however, the significance of the life cycle costs of a lunar base strongly suggests that the habitat used in the initial phase remain useful during later phases of the base life.

PERMANENT HABITAT

Absolute Criteria:

The habitat must meet the absolute criteria. The rating is limited to "yes" and "no." If a concept does not meet one or more of the absolute criteria, the concept is rejected. If it does meet the criteria, it is evaluated against the primary criteria.

Protection From Environment Hazards - The habitat must protect the crewperson from the lunar vacuum, extremes in temperature, and the radiation environment (ionizing and galactic cosmic).

Habitable Enclosure - The habitat must provide adequate atmospheric pressure (10.0 to 14.7 psia), nominal sea level oxygen partial pressure (160 mm Hg), and controlled carbon dioxide partial pressure. In addition, the habitat must provide a minimum volume per crewman for conducting living functions for an indefinite period.

Safe Haven - The habitat concept must provide a safe haven for crew survival assuming the primary pressurized module has to be abandoned. The length of the safe haven period is the time required for rescue and return of the crew to an Earth orbiting space station.

Capability to Support Mission - The habitat concept must support the mission objectives; i.e., allow the 12-person crew to remain on the lunar surface for an indefinite period and to permit crewmen, working in pairs, to have routine access to the lunar surface for conducting the operational activities of the base.

Primary Criteria:

Compatibility With Transportation Systems - To be a viable concept, the candidate concept must be capable of being transported to the moon in a reasonable scenario. A reasonable scenario is defined as the use of the STS orbiter or shuttle C for lift to Earth orbit and the Orbital Transfer Vehicle and Lunar Landing Vehicle as defined in the NASA-JSC 90-Day Study.

Complexity of Set-Up Sequence - This criterion is similar to Total Effort Criterion related to the initial habitat trades; however, there are differences between the two. With the initial habitat, the issue is the urgency with which the habitat needs to gain operational status—minimum number of activities and minimum elapsed time. With the permanent habitat, the time urgency to become operational is not as strong, but other issues such as the amount of EVA time, the number of unique surface vehicles and equipment needed to emplace the base, the complexity of the habitat deployment and coverage, etc. are factored into the criterion.

Failure Modes - This criterion includes the potential for catastrophic failure, the ability to continue operation if elements of the base habitat fail, the margin of safety remaining as elements fail, and the ease with which failed elements can be repaired and placed back into operation.

Logistics Considerations - This criterion may be the primary factor in determining life cycle costs. Of first order importance in establishing logistics requirements is the fact that diluent gas, probably nitrogen, will be supplied from Earth. All habitat concepts must strive to reduce the need for diluent gas logistic requirements.

Habitability Features - Under the absolute criteria a concept must provide a habitable enclosure; i.e., it must provide a habitable atmosphere and protect the crew from environmental

hazards. For long term use, however, the habitat must provide more than physiological survivability. Adequate volume, privacy, convenience of movement, sense of well-being, etc. contribute to crew morale and productivity and are to be considered in habitat selection.

Adaptability to Growth and Change - A lunar base planned for many years of operation, or possibly for indefinite long term operation, will experience new requirements that will impact crew size, base layout, site change, etc. It would be advantageous for any habitat concept to have the flexibility to adjust to the changes while retaining the basic design and operational characteristics.

Long Term Life - Any habitat for a permanent lunar base must exhibit long term life. Its expected life may be driven to a great extent by its exposure, or lack of exposure, to the extremes of the lunar environment, i.e., one that is totally covered by regolith vs. one that is partially or totally uncovered. Regardless of the degree of exposure, the basic structural elements need to exhibit long term life.

Maintainability/Repairability - The capability for long term life will carry with it the need for maintenance and repair. Their criterion is one that surfaces based on reasonable logic upon first assessment. A more advanced study may conclude that it is not a criterion of primary importance.

Transition to Surface Activities - The primary reason for a lunar habitat is to serve as a base of operations on the surface. The level of difficulty of transition between the pressurized habitat and the surface is of major importance to the habitat concept.

Secondary Criteria:

Secondary criteria should not identify a winning candidate, rather they should add backing and support to selected concepts.

Requirement for Specialized Tools and Equipment - This criterion overlaps the complexity of set-up sequence primary criteria. Specialized equipment to lift, haul, grade, align, etc. adds weight, risks, time, and costs. Some specialized equipment will be required but a need for a large cadre of special tools, vehicles, etc. should be avoided.

Site Specificity - It is not likely that a habitat concept would be limited to use at specific sites; however, if one were site specific, its value as a candidate would be reduced.

Effective Use of Initial Habitat - The initial habitat will have completed its mission once the permanent habitat or habitats are operational. At that time there is no requirement for continued use of the initial habitat; however, from the perspective of the total life cycle costs of the base, it is desirable to retain continued reusability of the initial habitat.

New Technology Requirements - The need for some new technology usually cannot be avoided, and should not be avoided if it provides a needed or increased capability. New technology requirements do, however, equate to additional DDT and E costs. Thus, the presence of extensive new technology requirements would increase the total cost of applying a habitat concept.

APPENDIX B - ADDITIONAL CONCEPTS

Upright Cylinder Habitat

A Single-Launch Lunar Habitat Derived From an NSTS External Tank

Lunar Regolith Transport System Concept

Deployable Strut Supported Regolith Standoff System

Rover and Cable Joining Concept

Upright Cylinder Habitat

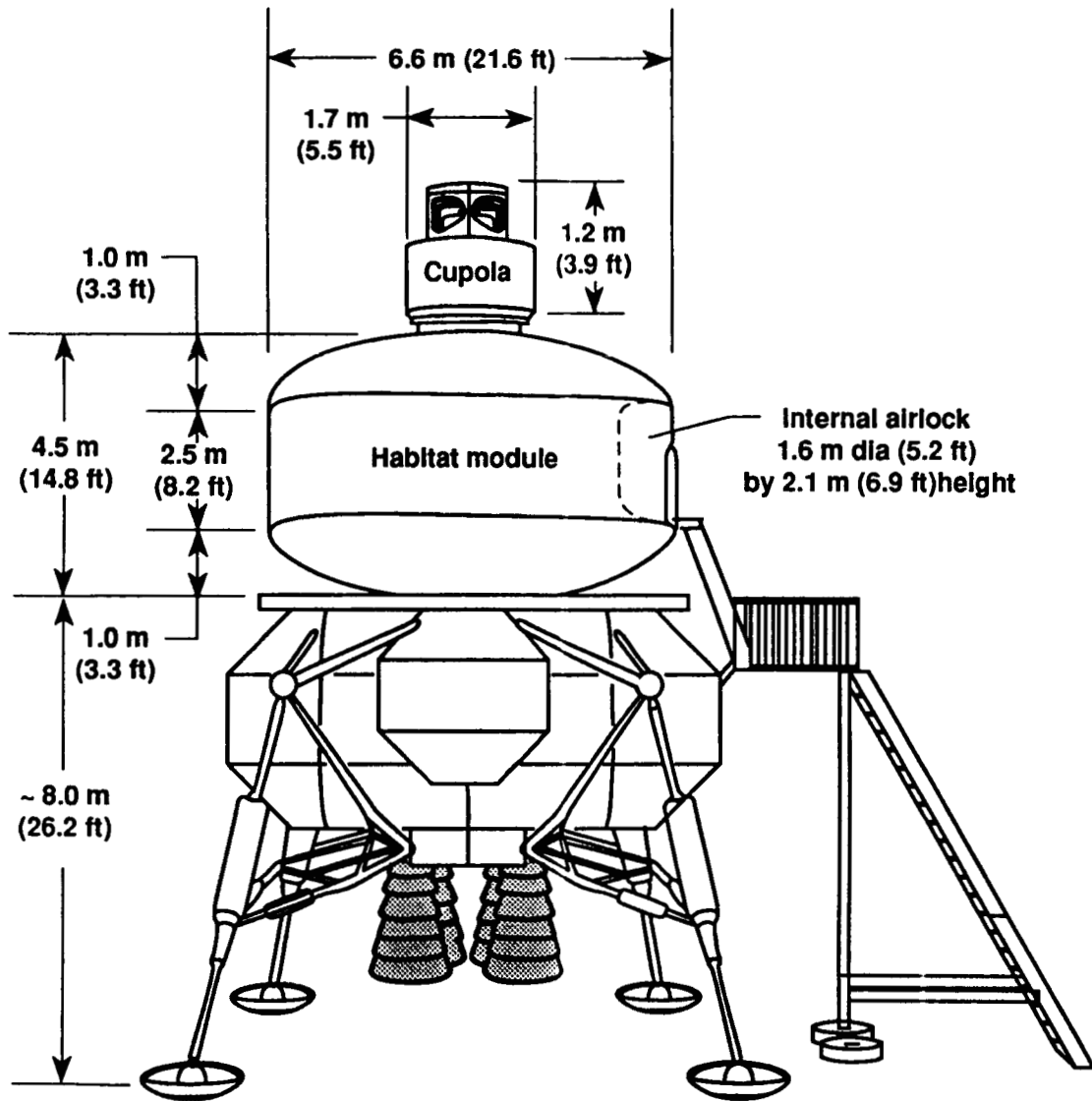
One concept pursued briefly during the study was the upright cylinder delivered to the surface on a more conventional legged lander of the type proposed by Eagle Engineering. A sketch of the configuration and the habitat element dimensions are presented in figure B-1(a). The configuration and dimensions of the habitat were sized to provide maximum habitable volume while permitting the habitat to fit within the 7.6 m (24.9 ft) diameter payload envelope of the proposed Shuttle C, Block 1 launch system. The mass empty estimate for the module is scaled from the SSF module according to their ratios of surface area assuming the wall structure for the pressure vessels would be of similar construction and similar materials. The mass outfitted estimate is volume scaled from SSF element data with the same lunar-gravity field adjustment used in the Concept 1 and 2 estimates (the assumption that the module cannot be utilized in lunar-gravity as it can in zero-gravity because the ceiling area is not as accessible).

The habitat configuration sketch shows the outline of one interior airlock. Although this one element serves as the only personnel ingress and egress airlock, another element of equal volume needs to be included to provide the advantages of the double airlock arrangement. This additional element would need to be carried under the top of the lander platform. This element could be a simple pressure vessel of any configuration which would fit conveniently. The airlock pump down system, described under Concept 1, will be included to limit the gas loss during airlock operation.

The habitat and lander is proposed as an initial habitat for the 28- to 30-day mission. It could remain unshielded if a solar storm shelter were available internally or at some other location (such as the crew lander). If the habitat were to be used for manned occupancy later in the permanent phase of the base, regolith could be added with the habitat remaining on the lander provided the lander was engineered to support the additional load of regolith and containment panels. A concept for the regolith shield is illustrated in figure B-1(b) the panels are envisioned to be of composite honeycomb construction and would need to be secured to the top of the lander and the top of the pressurized module by tubular struts. The void between the panels and the module diameter is 0.5 m (19.7 in) thus maintaining the required regolith thickness of 50 cm. In the configuration shown, 73 m³ (95.5 yds.³) of regolith is needed. It is significant to note that of the four concepts included in this study, the upright cylinder on the legged lander requires the least volume of regolith while providing the environmental shield.

A Single-Launch Lunar Habitat Derived from an NSTS External Tank

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 using



HABITAT ELEMENT	APPROXIMATE MASSES				APPROXIMATE INSIDE VOLUME
	EMPTY		OUTFITTED		
Habitat module	8,152 kg	(17,971 lb)	9,590 kg	(21,142 lb)	151.0 m ³ (5,332 ft ³)
Airlock	526 kg	(1,160 lb)	582 kg	(7,283 lb)	8.4 m ³ (297 ft ³)
Cupola	1,505 kg	(3,317 lb)	1,505 kg	(3,317 lb)	2.7 m ³ (95 ft ³)
TOTAL	10,183 kg	(22,448 lb)	11,677 kg	(25,742 lb)	162.1 m³ (5,724 ft³)

Figure B-1(a). Upright Habitat Cylinder on Legged Lander

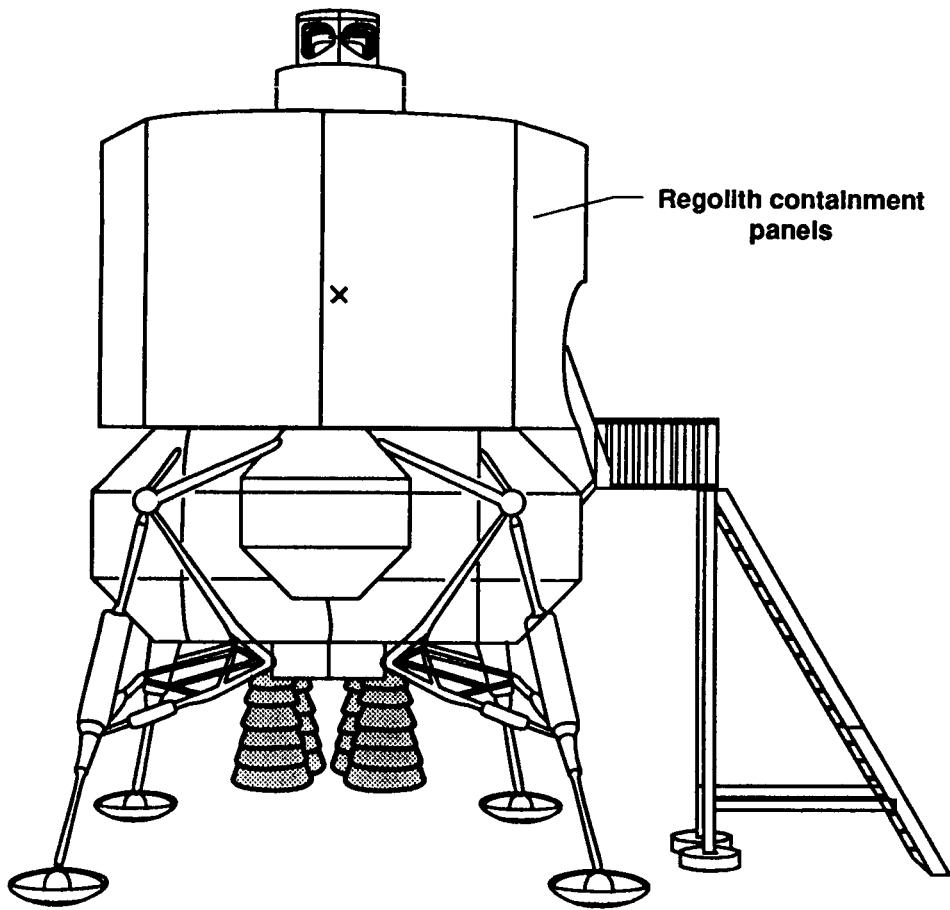


Figure B-1(b). Regolith Containment Environmental Shield

existing NSTS propulsion capability. Orbiter astronauts would disassemble the external tank in LEO by extravehicular activity (EVA). The LO₂ tank-intertank subassembly of the external tank could be outfitted as a lunar habitat in LEO while berthed at Space Station Freedom (SSF). Preliminary estimates of the EVA and intravehicular activity (IVA) required to disassemble the external tank, outfit the lunar habitat, and perform the initial post landed operations have been made. A SSF based orbital maneuvering vehicle (OMV) could aid in the disassembly of the external tank, berthing the subassembly of the external tank with SSF, and later, moving the outfitted lunar habitat away from the SSF for addition of propellant tankage 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 (STV). 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 STV for return to LEO.

On the lunar surface, the lunar habitat would be prepared for occupancy with 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 LO₂ tank wall with regolith as shown on figure B-2 will enhance the habitat's protection from micrometeoroid impact and reduce the astronaut's radiation dose to well below the 50 rem/year 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 exploration of the lunar surface.

A lunar habitat could be soft landed on the lunar surface and supplied with crew and consumables by the year 2003 contingent upon the development of an OMV, STV with a lunar lander, and a permanently manned SSF or assembly node in low Earth orbit. The concept provides a means to establish permanently-manned or revisitable habitats using current and near-term projected technology. Habitats could be used for exploration, observation, housing work crews for beneficiation of regolith, and construction of a permanent lunar or other planetary base.

A more detailed description of this single launch lunar habitat derived from an NSTS external tank is found in a NASA Technical Memorandum (Reference 4 to the main text).

Lunar Regolith Transport System Concept

The transport system concept provides a means of moving regolith from the vicinity of a landed habitat through a suitable tube or duct for collection and deposit into a cavity about the exterior of the habitat. The filled cavity will provide sufficient regolith thickness for protection from micrometeorites, solar energetic particles, and galactic cosmic radiation.

A lunar habitat has not been established to date on the lunar surface to house personnel for lunar exploration purposes. Several mechanical concepts are being proposed at this time to collect and transport regolith for space radiation protection for the inhabitants of a lunar habitat. Examples of alternate concepts are (a) a front-end loader, (b) a tractor-driven scraper bucket, similar to that used in road construction, (c) a conveyor having scoops or buckets which can scoop material at one end and transport by conveyor belt to a discharge point at the opposite end of the conveyor, and (d) a three drum cable way scraper bucket or slusher method whereby a large bucket is dragged across the lunar surface to scoop up

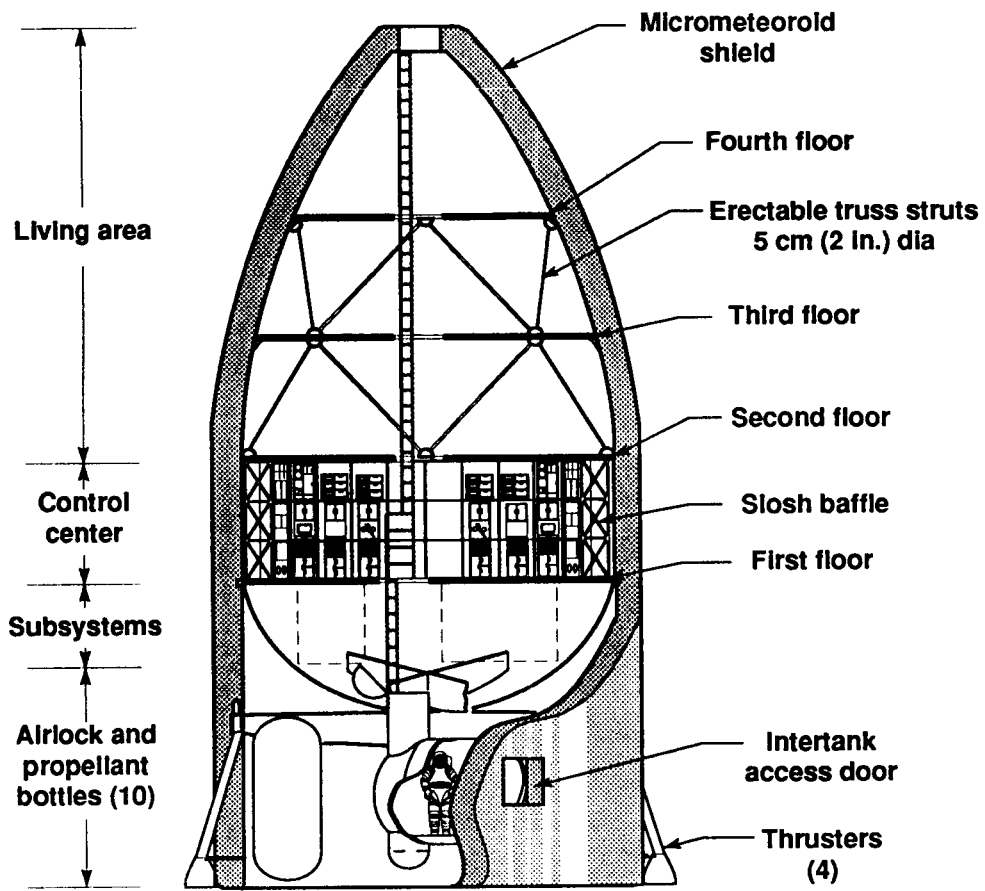


Figure B-2. Cross Section of the Lunar Habitat as Landed

regolith material and transport it to the extreme travel of the bucket path. The alternate concepts were reviewed with the following concerns.

- a. A front end loader could be utilized to scoop up soil or regolith and transport it to the habitat site. The loader could not distinguish between finely divided regolith and aggregate. The front end loader would require an operator or robotic machine and the equipment by design would require mass to assure sufficient thrusting force for the bucket to shear the regolith for capture in the bucket.
- b. A road scraper bucket similar to road construction equipment would also require mass to assure traction to shear the regolith to accumulate material and would still require auxiliary equipment to move the scraped mounds of material to the habitat.
- c. A conveyor would be limited by its own length as to the ability to transport material from one point to another. It could be used to move material from a regolith mound, adjacent to the habitat, lifting the material so that it may fall upon the habitat to accomplish coverage.
- d. The three-drum drag bucket or slusher requires a power unit to operate the cables necessary to drag the bucket across the surface of the regolith and the bucket could accumulate a large mound of regolith by this concept. A practical depth of regolith fines is considered approximately 30 cm and after the drag bucket had reached that depth it would be necessary to move the power unit, cables, three drums, and bucket to a new location. The transport of regolith from the mound to the habitat is still required by other methods.

The proposed lunar regolith transport system concept will utilize a gas at a positive pressure to fluidize and transport regolith fines from a point of regolith accumulation, causing the regolith fines to flow freely through a conduit or duct to a cavity formed between the wall of the habitat and an outer shield. The shield maintains a uniform minimum cavity width of 50 cm (19.7 in) to assure adequate radiation protection after filling with lunar regolith. The entry point of the regolith into the shield can be at a variety of locations which may include entry through the shield wall near the lunar surface or the conduit could be positioned at the uppermost point of the shield and allow the material to free-fall at lunar Earth gravity to compact in the cavity provided. The concept of a pre-positioned regolith shield and the lunar regolith transport concept of moving regolith from a collection point to fill the shield cavity will establish a uniform micrometeoroid and radiation protection barrier with a minimum of regolith required.

Details of the operation of the lunar regolith transport concept can be described by referring to figures B-3(a), (b), (c) and (d).

Figure B-3(a) describes a bell-shaped collection head having a ring manifold of tubular probes which can be filled with compressed gas. In operation, the edges of the bell are pressed into the regolith with sufficient force to contain the pressure within the bell created by the compressed gas. The gas escapes from the extremities of the tubular probes thus fluidizing and causing the regolith to flow upward through a flexible conduit. As long as sufficient force is applied the gas pressure will not blow out from underneath the edges of the bell end and regolith will continue to flow through the conduit. When operations are ceased, the valve is closed and the purge line pressurized to continue forcing any residual regolith from the conduit to the receiver point. The purging operation will prevent the flexible conduit from blocking.

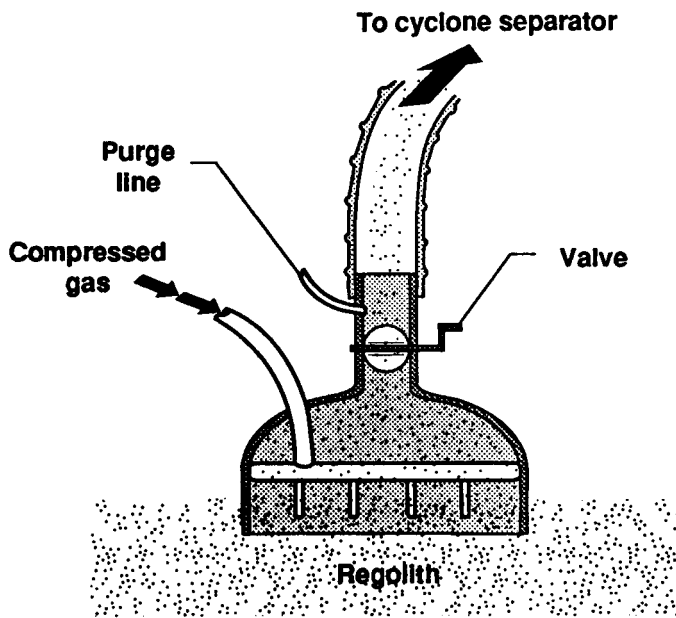


Figure B-3(a). Collection Head

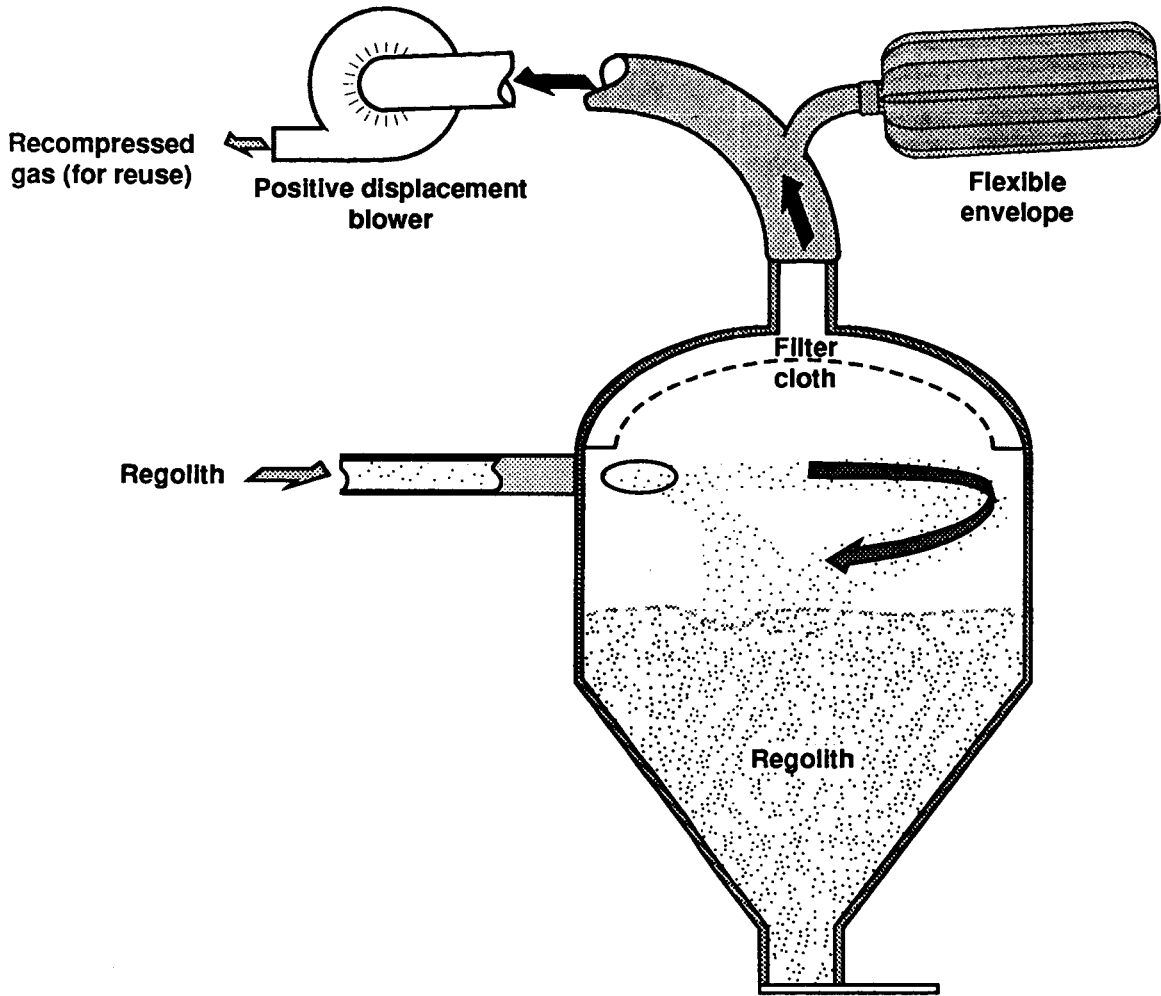


Figure B-3(b). Cyclone Separator

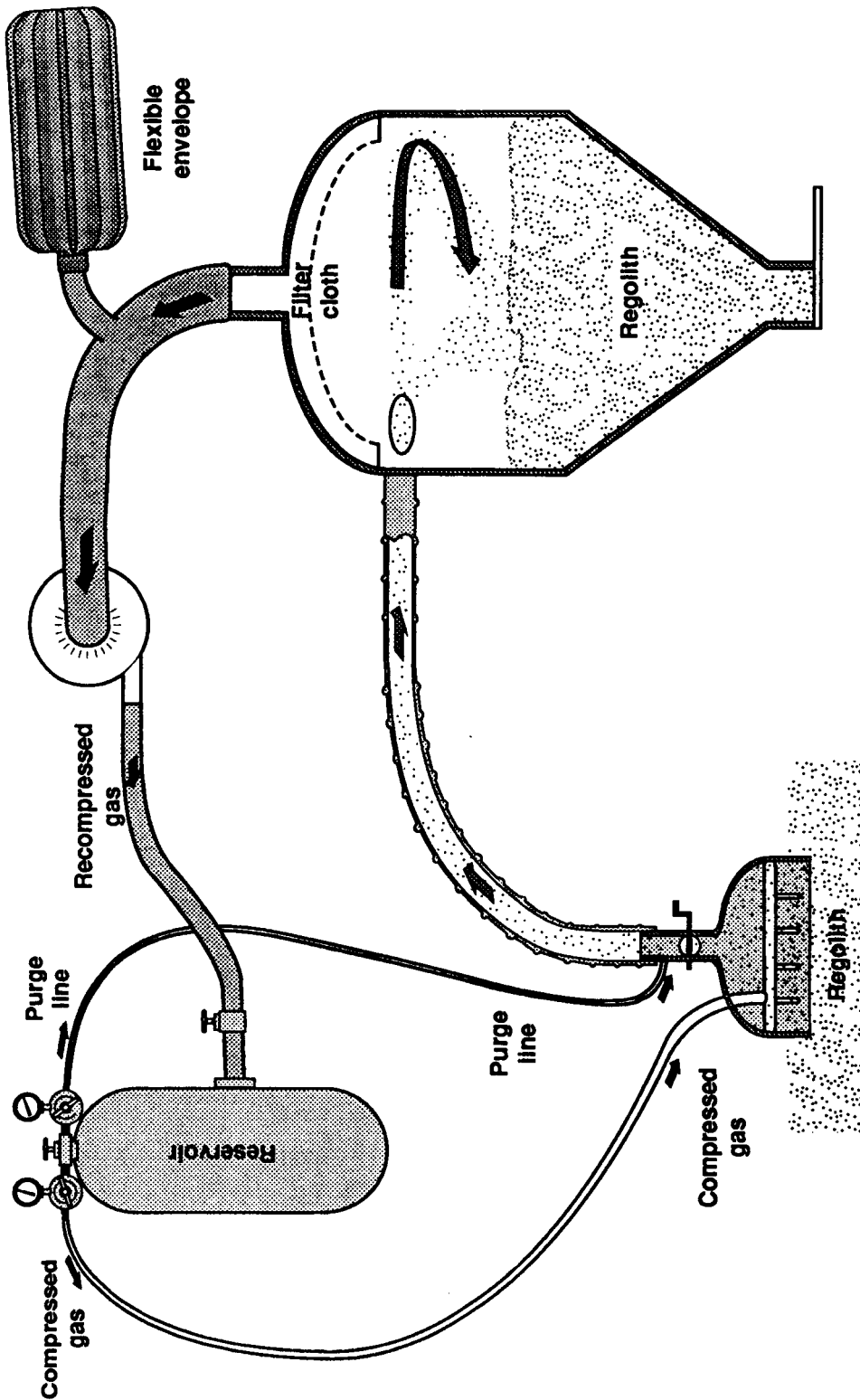


Figure B-3(c). Lunar Regolith Transport System

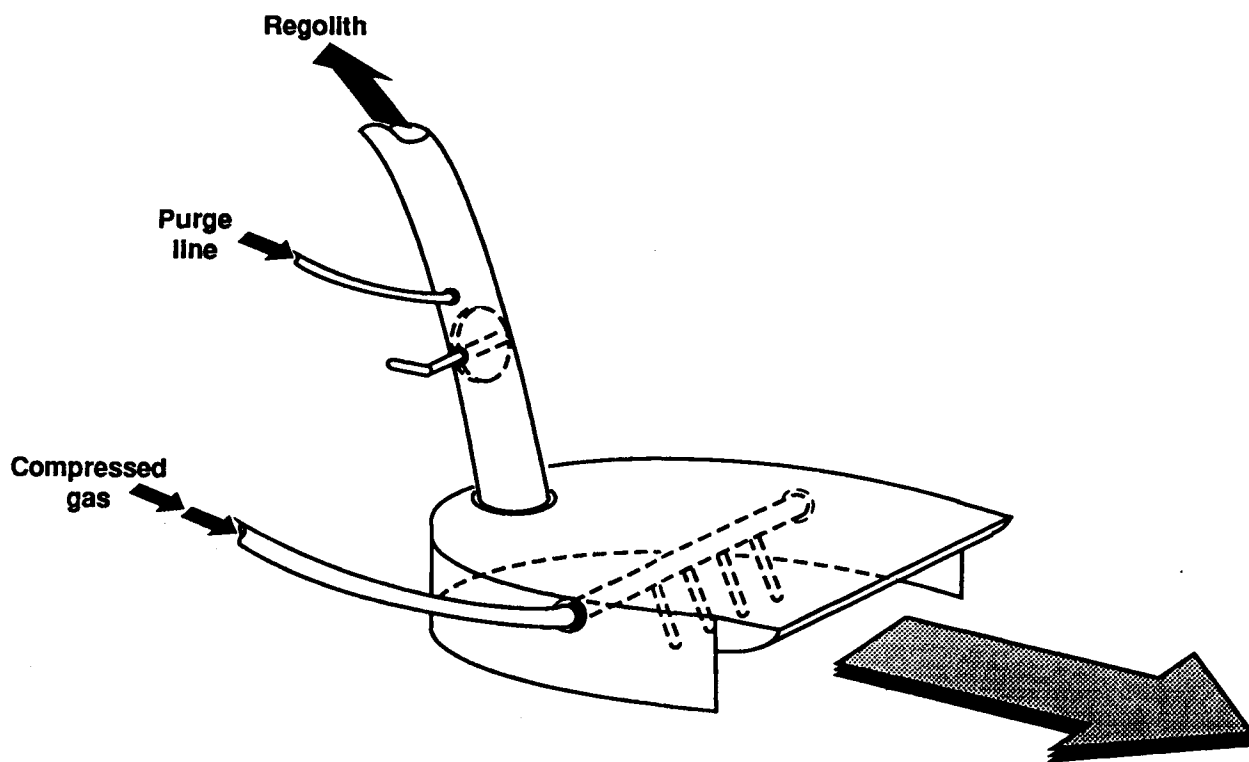


Figure B-3(d). Regolith Mobile Scoop

Figure B-3(b) shows a flexible conduit conveying regolith through a tangential opening of a cyclone separator so that regolith under lunar gravity may separate from the pressurant gas and accumulate in the conical reservoir of the separator. Filter cloth located at the upper dome of the separator allows the compressed gas to flow through a flexible conduit into a flexible envelope for low pressure storage. A compressor is used to compress the gas for resupply to the bell-end of the regolith transporter.

Figure B-3(c) indicates how the bell-end regolith transporter can transport regolith through the conduit to the cyclone separator with the transport gases passing through the filter and through the compressor for accumulation at a reservoir whereby both the compressed gas for the bell-end and purge line can be controlled as to pressure and volume, thus assuring maximum reuse of the gas. Some gas will be lost on each transport cycle due to gas permeation of the regolith. This concept suggests the regolith cyclone separator would be positioned above the entry point of the habitat outer shield to permit periodic release of regolith filling the shield by gravity.

Figure B-3(d) shows a scoop which could be mounted beneath a robotic machine capable of applying sufficient thrust pressure to the scoop to prevent compressed gas blow-out of the regolith as the scoop moves forward in the direction shown by the arrow. Again, a manifold with tubular hollow probes force compressed gas into the regolith causing it to become fluidized and flow upward through the conduit. A purge line and valve are shown so that when the regolith collection operation ceases the conduit can be blown free of residual regolith to prevent blockage.

The advantages of the concept are that regolith can be transported both in a horizontal and vertical direction to permit filling operations of regolith retainer shields. The concept can be adopted to robotic collection of regolith with simultaneous transport to a cyclone separator which may be in a fixed position at the habitat site. The regolith shield could be assembled with the habitat at low Earth orbit with stand-offs to assure a controlled thickness of lunar regolith for micrometeoroid protection and space radiation protection. The shield will provide uniform shielding but with a minimum volume of regolith required to accomplish protection of the inhabitants of the habitat. The gas transport concept should cause minimum dusting of regolith about the vicinity of the habitat. The equipment is extremely light weight and compact for stowage and transport to the lunar site.

An alternative method of construction of the regolith conveyor would utilize a robotic machine capable of collecting regolith from a remote site and returning to the location of the habitat, whereby, with a connection of the conduit hose and a pressurization line, the hopper contents of the robotic regolith collector could be conveyed to fill the cavity between the shield and the habitat wall.

Deployable Strut Supported Standoff System

The Deployable Strut Supported Standoff concept provides a means of receiving and retaining lunar regolith of controlled thickness about the outer surfaces of the landed habitat. The 50-cm minimum thickness of regolith will provide protection from solar energetic particles and galactic cosmic space radiation.

The strut supported standoff is shown deployed about the lunar habitat in Figure B-4 in preparation to receive regolith. The features of the Deployable Strut Supported Standoff system are listed in Table B-1.

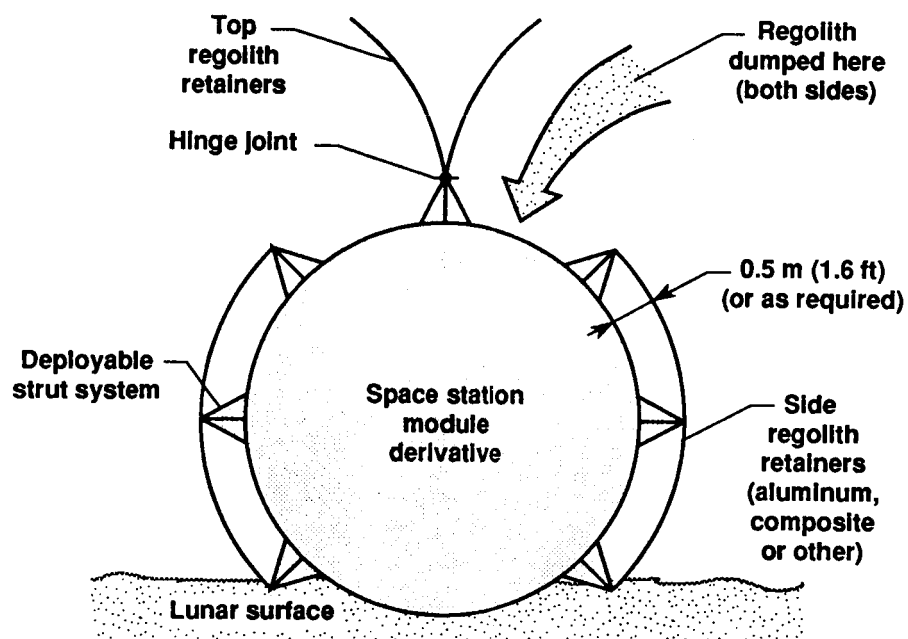


Figure B-4. Deployable Strut Supported Regolith Standoff System

TABLE B-1. FEATURES OF THE DEPLOYABLE
STRUT SUPPORTED REGOLITH STANDOFF SYSTEM

- Deployable strut system is folded flat against SS module exterior during transport.
- Regolith retainer is also transported essentially flat against module exterior, depending on design, it may or may not be attached to deployable strut system during transport.
- Side regolith retainer panels would be designed to extend to the lunar surface based on whether the module sits directly on the surface or is partially buried.
- Regolith is dumped using the "existing" 3-leg gantry crane with an appropriate attachment. (Example—bucket shovel, conveyor belt, etc.) The crane could approach the module from the side or may be able to straddle it.
- Height of the deployable strut system of 50 cm is based on our assumed regolith density of 1.5 gm/cm^3 . Since regolith density is reported to vary between 0.8 and 2.15 g/cm^3 , strut system height and panel sizing and strength could be designed for site specific density or made large enough to accommodate the least dense regolith.
- Regolith retainer panels at module ends would be pre-fabricated with the required shapes.
- Expansion of the habitat could be with additional modules of similar design (or with a completely different design) connected by pressurized tunnels. Minimum removal of regolith (around module hatches) would be necessary for habitat expansion.
- Regolith retainer panels could also be made of a metal-framed, high-strength, radiation resistant fabric. This approach could use a cloth supporting truss structure having a shape conforming to the module (similar to the retaining panels).
- Instead of panels, a cloth "roll-up" system could be implemented with the cloth retainer rolling up from the surface to the top as it is filled with regolith.

Rover and Cable Joining Technique

The technique for moving habitat elements on the lunar surface has been addressed previously in terms of cranes or other landed equipment items. The two-part landings of the Concept 2 habitat is predicated upon control of trajectories to a degree that assures a second landing within one kilometer of the first landing site. Such control for landings implies a detail characterization and knowledge of the lunar surface at the location intended for establishment of the lunar base. The Apollo mission photographs of lunar surface operations indicate the terrain features that must be accommodated, however the surface shown from Apollo 14 (Fra Morro) with the handcart and Apollo 15 (Handley Rille) with the rover suggest lunar surfaces exist that are free from rock outcrops or larger depressions over more than a kilometer radius. Utilization of such an area at the landing site provides an opportunity for remotely joining the Concept 2 elements after landing. The operation which brings the two elements into contact utilizes a small surface rover to place a tow cable between the sections followed by a winching action that pulls the two elements together.

In the flight sequence, the habitat section lands first and initiates a beacon that provides a homing signal for landing the airlock section. The airlock section carries a small rover mounted adjacent to the mating ring; figure B-5(a) shows its location during flight and final descent. After touchdown, the rover is released from its carrying brackets and moves toward the habitat section while placing a tow cable on the lunar surface; figure B-5(b) illustrates the operation. Movement toward the habitat section uses the homing beacon to bring the rover into contact with the mating ring and a subsequent latch to a hard point for tow. At completion of the deployment a tow line extends from the airlock to the habitat with the points of contact at the bottom of each mating ring. At this time, a capstan and winch located in the airlock cradle assembly, draws the two sections together until the mating rings come into contact. Final alignment and lock-up then proceeds either crew-tended or by other means.

An assessment of the motions involved with joining operations anticipates an initial rotation of each section such that the mating rings face each other followed by relative movement as determined by local surface friction. Since each element will be resting on deflated air bags, rotation for alignment would proceed with relatively low friction forces. Movement over the lunar regolith is expected to favor the less massive airlock section, and for a friction coefficient of one (unity) the cable tension becomes 25,088 N (5,640 lb). An aramid based fiber operating at a working stress of 680 MPa (100,000 psi) equates to a stranded cable 1 cm (0.4 in) in diameter. A kilometer length could be carried on a spool with a 0.32 m (12 in) inner diameter, a 0.7 m (27 in) outer diameter and a 0.4 m (16 in) face. These dimensions are readily accommodated. The energy required for accomplishing movement will be determined by the actual distance and the local surface friction. A worst case scenario requires about 90 ampere hours from a 120 volt supply. A nominal case has a coefficient of friction equal to the tangent of the slump angle ($\tan 36^\circ = 0.72$) and a distance of 0.6 km; the corresponding energy requirement could be obtained from a 40 amp hr source. The Ni-H₂ battery units planned for Space Station Freedom application are rated at 50 amp hrs at 120 volts.

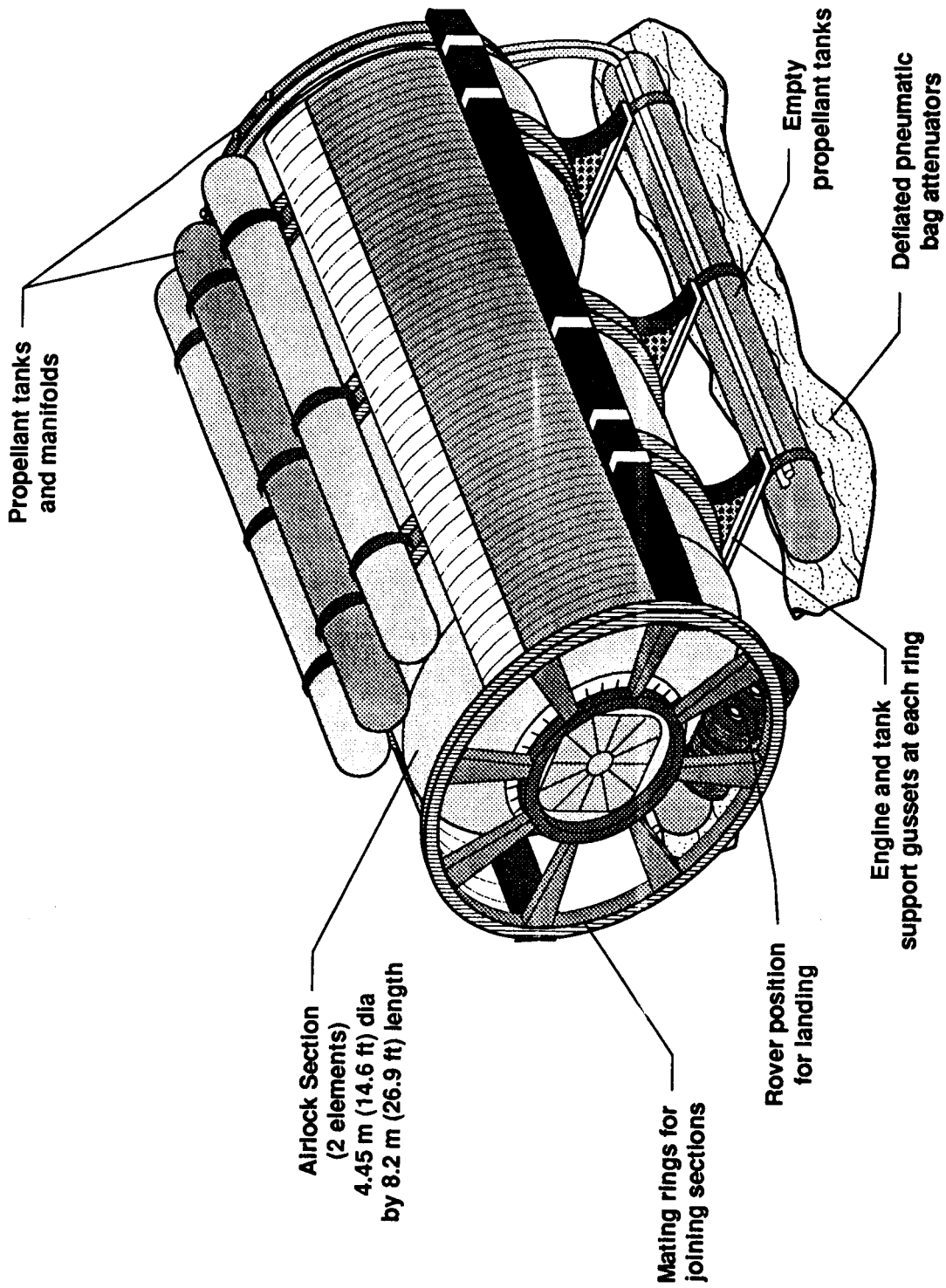


Figure B-5(a). The "As-Landed" Concept 2 Airlock Section with Rover.

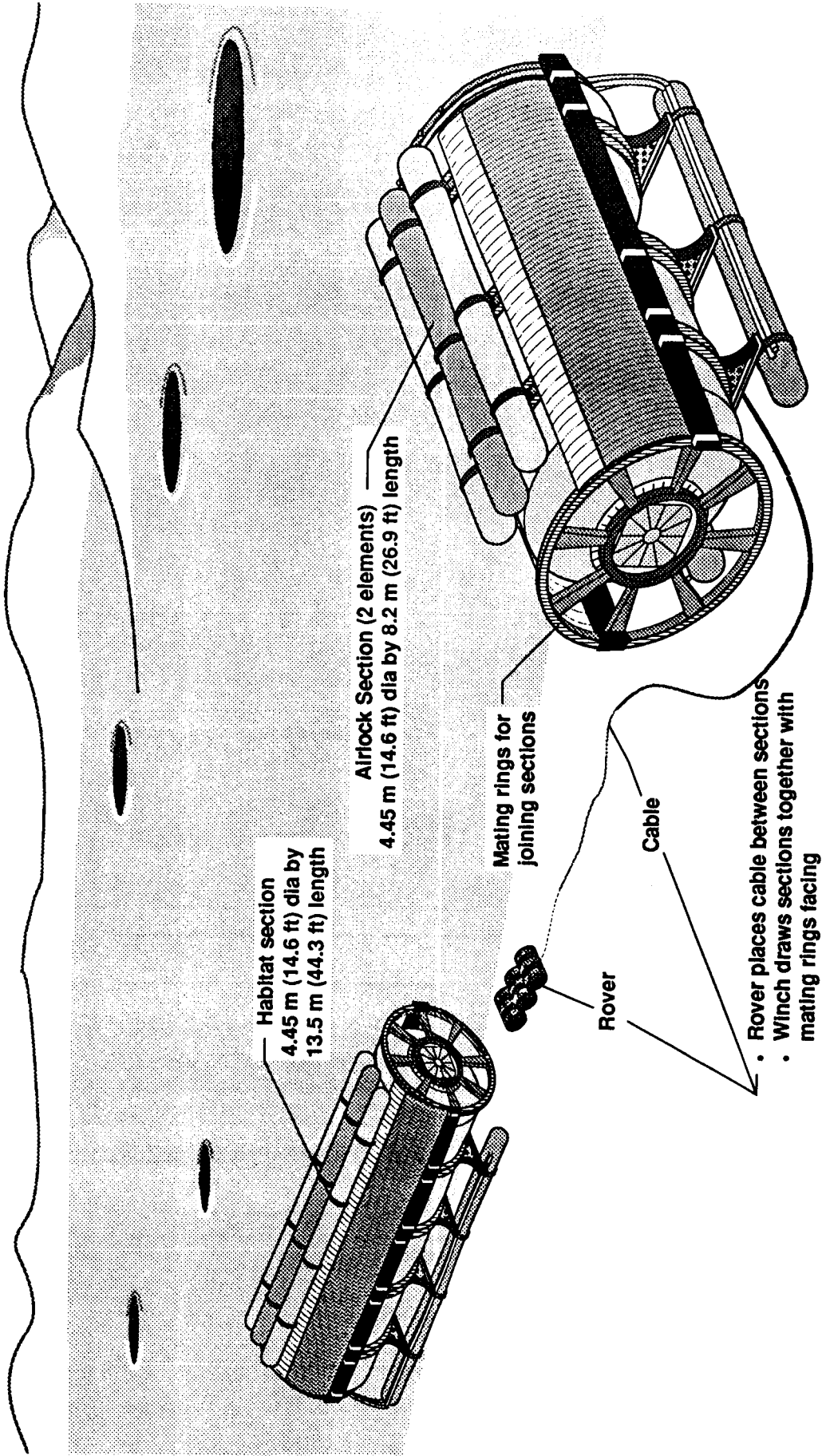


Figure B-5(b). Landed Sections of Concept 2 at Deployment of the Rover for Joining on the Lunar Surface

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16. Abstract The design of initial lunar bases will be based on a compromise between the desired capabilities of the base and the economics of its development and implantation. To achieve this compromise, the design will be simple, make use of existing technologies, require the least amount of lunar surface preparation, and minimize crew activity. Three concepts for an initial habitat capable of supporting a crew of four for 28 to 30 days have been studied. Two concepts are based on using Space Station Freedom structural elements modified for use in a lunar-gravity environment. The third concept is based on an earlier technology base of expandable modules. The expandable concept offers significant advantages in launch mass and packaged volume reductions. It appears feasible to design a transport spacecraft-lander that, once landed, can serve as a habitat and a stand-off for supporting a regolith environmental shield. A permanent lunar base habitat supporting a crew of twelve for an indefinite period can be evolved by using multiple initial habitats. There appears to be no compelling need for an entirely different structure of larger volume and increased complexity of implantation.					
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