RADIATION PROTECTIVE STRUCTURE ALTERNATIVES FOR HABITATS OF A LUNAR BASE RESEARCH OUTPOST

Submitted to:

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Dr. Wallace T. Fowler
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Dear Dr. Fowler:

Attached is our report entitled Radiation Protective Structure Alternatives for Habitats of a Lunar Base Research Outpost. The report outlines the advantages and disadvantages of each alternative, the method of analysis used, the final design selected, and recommendations of topics for further consideration.

We have enjoyed working with you throughout the semester, and we look forward to seeing you at the project presentation. Our presentation is scheduled for Tuesday, April 26, 1988 at 9 a.m. in Room 4.110 of the University of Texas at Austin. You are also invited to attend a catered luncheon at noon of the same day.

Thank you for your assistance throughout the semester.

Sincerely,

Fred J. Bell

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Lai T. Foo

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ACKNOWLEDGEMENTS

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Special thanks must go to Dr. Steven Nichols for serving as faculty advisor to the project team.

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ABSTRACT

RADIATION PROTECTIVE STRUCTURE ALTERNATIVES FOR HABITATS OF A LUNAR BASE RESEARCH OUTPOST

The solar and galactic cosmic radiation levels on the Moon pose a hazard to extended manned lunar missions. Lunar soil represents an available, economical material to be used for radiation shielding. Several alternatives have been suggested to use lunar soil to protect the inhabitants of a lunar base research outpost from radiation. The Universities Space Research Association has requested that a comparative analysis of the alternatives be performed, with the purpose of developing the most advantageous design. Eight alternatives have been analyzed, including an original design which was developed to satisfy the identified design criteria. The original design consists of a cylindrical module and airlock, partially buried in the lunar soil, at a depth sufficient to achieve adequate radiation shielding. The report includes descriptions of the alternatives considered, the method of analysis used, and the final design selected.

Keywords: lunar base research outpost
lunar radiation protection
radiation protective structure

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INTRODUCTION

The Universities Space Research Association (USRA) is a consortium of universities organized by the National Academy of Sciences in 1969. USRA is headquartered in Houston, Texas and is dedicated to promoting the exploration and development of space. USRA currently operates a program through which the National Aeronautics and Space Administration (NASA) sponsors design projects at universities throughout the country.

One of NASA's long range goals is the development of a manned lunar base. The base inhabitants will require radiation protection, because some solar flares produce radiation levels that could result in a lethal exposure after two to three hours. NASA has investigated a number of alternatives for the protection of lunar habitat structures, but to date, no satisfactory comparative analysis of the alternatives has been performed. USRA has now commissioned this comparative study, with the purpose of developing the most advantageous method of shielding lunar habitats from radiation. This report includes descriptions of the eight alternatives considered, the method of analysis used, and the final design selected.

Background

The Moon's environment is not hospitable to humans. Since it lacks an appreciable atmosphere, the surface of the Moon resembles the vacuum of space. Surface temperatures range from -171 to 111 degrees Celsius (-275.8 to 231.8 degrees Farenheit). Radiation also poses a threat to human habitation on the Moon. Extended exposure to radiation results in accumulated doses of dangerous levels.

The two major types of radiation reaching the Moon are Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP). GCR are high energy particles originating from outside the solar system. GCR are composed of protons, alpha particles, and the nuclei of heavy elements. SEP originate from the Sun and have a composition similar to GCR, but the particles are less energetic. On the surface of the Moon, an unprotected astronaut is subjected to 20 to 50 rem per year due to GCR. A rem is the measure of dosage acquired due to radiation exposure. Five rem per year is considered the maximum safe dosage for radiation workers. The amount of radiation due to SEP is about 1000 rem over the 11.7 year solar cycle. However, 95 percent of this radiation occurs during periods of intense solar activity which last only 2 to 3 days.[1*] The Radiobiological Advisory Panel[10] states that the maximum permissible radiation exposure for astronauts over 30 years of age is 38 rem per year, with a maximum of 200 rem per lifetime. Exposures exceeding this limit will cause radiation sickness and even death. An ideal protective structure will shield against all GCR and SEP.

The best current method of protection for all types of radiation exposure is mass shielding. Mass shielding is the placement of mass between a body

* All references in this report refer to the numbered references on pages 34-35.

and the source of radiation. The greater the intensity of radiation, the more mass is required for the same level of protection.

Radiation shielding is measured in mass per unit area. The mass shielding required to achieve adequate protection on the Moon has been determined for a number of different materials. For example concrete, graphite, water, and aluminum are four common materials used for radiation shielding. It takes 19.05 grams per centimeter squared (g/cm^2) of concrete to provide adequate protection against radioactive particles with energies of 150 mega electron volts (the most common lunar radiation energy level[1]). 18.06 g/cm^2 of graphite are required for the same level of protection, 14.35 g/cm^2 of water, or 20.41 g/cm^2 of aluminum.[2]

The common size of planned space station modules is 12.5 m (meters) long and 4.5 m in diameter. Even with a reduced module only 9 m long it would take 448,000 kgs (kilograms) of graphite to reduce the radiation inside such a cylinder to below 5 rem/year. If graphite composites are used it would take 436,000 kgs, or 534,200 kgs of aluminum. On Earth there is no problem in obtaining adequate amounts of mass for shielding. If mass is to be brought from Earth for shielding on the Moon or in outer space, the mass must be launched into orbit. The current estimated cost to place a kilogram of mass into orbit is approximately $2 million.

In addition to radiation, the lunar surface is subjected to a steady bombardment by rocks of all sizes. The most frequent strikes come from fragments about 1 micrometer in diameter, known as micrometeorites. The micrometeorites impact the Moon's surface with velocities averaging 20 kilometers per second (45,000 miles per hour).[14] Although the micrometeorites are very small, their high velocities cause craters upon impact. Over long periods of time, the cumulative damage from these impacts can be significant.

The cost to bring shielding material to the Moon can be avoided if lunar soil, known as regolith, is used for mass shielding. Using regolith for shielding also provides the needed protection against micrometeorite impact damage. The project goal is to determine the most efficient method of using regolith to shield the habitats of a lunar research outpost.

Project Requirements

The requirements of this project are to analyze proposed alternatives for providing radiation and micrometeorite protection on the Moon, and to develop a final design which best satisfies the desired design criteria.

The team chose to concentrate on the development of a manned lunar research outpost. The outpost will be an initial base that is temporarily occupied and totally supplied from Earth.

Design Criteria

The project team identified eleven design criteria by which to judge each alternative:

1. The protective structure must provide adequate shielding from GCR and SEP.
2. The shielding should be accomplished with maximum use of lunar resources.
3. The protective structure must provide adequate protection against micrometeorite impacts.

4. To achieve quick start-up operations, the structure should make maximum use of prefabricated parts.

5. To minimize waste, all equipment required should be transformable (multi-purpose).

6. All structures should allow for future expansion.

7. The protective structure should be as simple as possible to construct.

8. All structures should require minimum maintenance.

9. The structure configuration should provide access for maintenance.

10. The structure should require minimum transportation of materials from Earth.

11. All designs must be structurally sound.

Project Methodology

The project team performed the following steps during their investigations:

1. Researched alternative protective structures using computer search methods, reviews of books and technical reports, and interviews with experts in lunar base considerations.

2. Identified the criteria by which the best design was selected.

3. Synthesized an original composite design.

4. Analyzed each alternative by employing decision matrices.

5. Developed the selected best design as outlined below:

   i. assumptions

   ii. recommendation of site selection

   iii. protective structure configuration details

   iv. material selection

   v. structural integrity considerations

   vi. construction sequence outline

   vii. heat transfer considerations

   viii. maintenance aspects

   ix. future expansion.

ALTERNATE DESIGNS

The habitat alternatives are divided into two categories by location: above ground and below ground. The project team considered five alternatives for above ground regolith-shielded habitats, and three alternatives for below ground habitat placement. One of the below ground alternatives was synthesized by the project team. The design is a composite which incorporates ideas from other alternatives and original design concepts.

Above Ground Alternatives

Three of the above ground alternatives make use of a cylindrical, modular habitat structure covered with regolith. The other two employ inflated enclosures placed beneath a rigid structure which supports the regolith shielding. All of the above ground scenarios avoid the possibility of encountering bedrock or very large boulders in the regolith, which could hinder excavation efforts. The exception to this is the flat shield alternative, which employs girders set in the regolith. Although digging is not required for module emplacement, some means of gathering regolith must still be provided for all above ground alternatives.

Superstructure Envelope Design

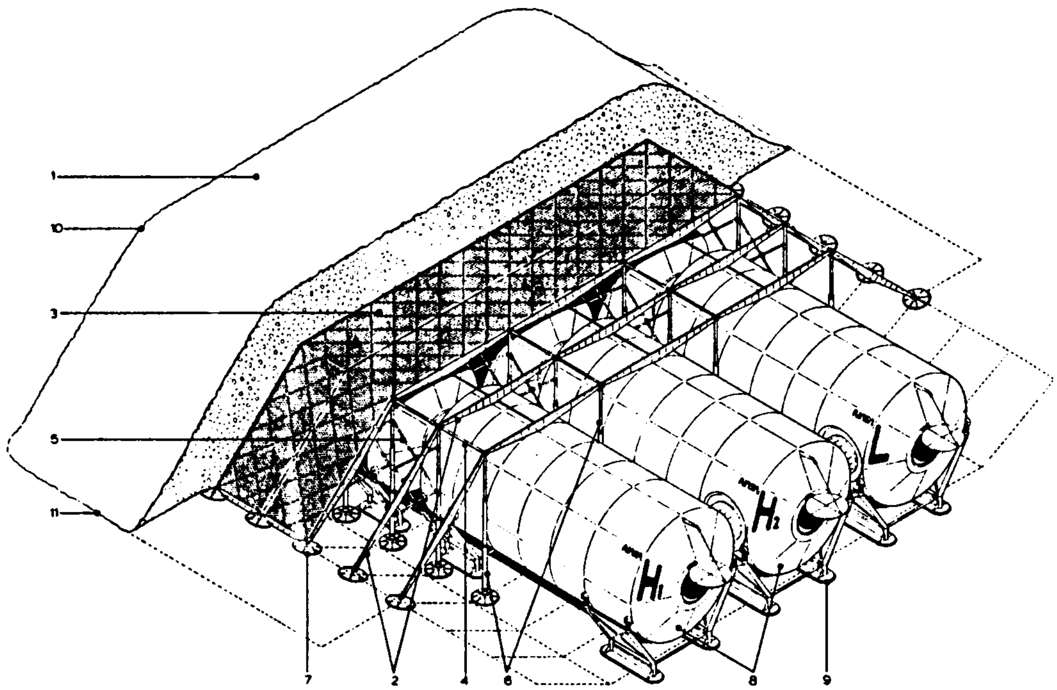
The superstructure envelope is configured as a flat-topped mound of loose regolith supported by a continuous tension membrane connected to a regular grid of telescopic columns and tapered beams beneath (see Figure 1).[9]

The advantages of this alternative are:

1. No digging or trenching device is required.
2. The configuration allows access to outside of module for maintenance.
3. The habitat module can be made lightweight, since it would not have to support weight of the regolith shielding.

The disadvantages of this alternative are:

1. All beams, struts, and mesh membrane panels must be brought from Earth (estimated launch weight 7,500 pounds).
2. The components require extensive construction on the Moon, including: unpacking, layout, assembly, hoisting, leveling, and tie-down.
3. The expected construction requirements will delay start-up operations.



Cutaway illustration of superstructure envelope system: 1—regolith mass shielding; 2—main tapered beams; 3—graphite fiber mesh; 4—longitudinal struts; 5—longitudinal bracing; 6—telescopic tubular columns; 7—circular footpads; 8—linked habitat/laboratory/workshop modules; 9—module ground support cradles; 10—crest of slope; 11—base of slope.

Figure 1: SUPERSTRUCTURE ENVELOPE DESIGN[11]

<u>Flat Shield With Inflated Substructure</u>

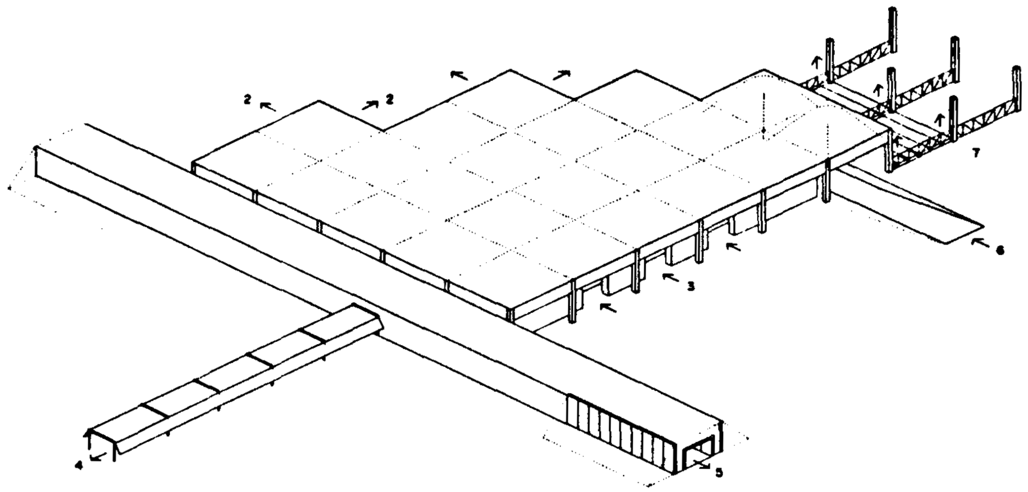
There are two parts to this design configuration: pressurized enclosures beneath radiation shielding canopies. The structure supporting the regolith consists of floors resting on lattice girders connected to columns and erected by pneumatic jacks. The pressurized enclosures can be made to whatever shape and size will fit under the shield (see Figure 2a).[11]

The advantages of this alternative are:

1. No digging or trenching device is required.
2. The design can be configured to provide large volumes of habitable space per kilogram of launch weight.
3. The pressurized enclosure weighs less than a habitat module, which reduces transportation requirements.

The disadvantages of this alternative are:

1. Girders must be placed and anchored, which could pose construction difficulties.
2. Pneumatic jacks are required to raise the roof of the structure.
3. All life support equipment and other machinery must be brought into the enclosure after it has been erected.



BASE CONCEPT I. Flat shield raised in sections, pressurized enclosures beneath. *Overall view of base. (1) Regolith shielding. (2) Perimeter expansion. (3) Base entry through overlapping radiation barrier walls, from lunar surface equipment and installations "park." (4) Solar shaded links to other parts of base. (5) Shielded links to other parts of base. (6) Ramp access to lower levels. (7) Initial erection sequence.*

Figure 2a: FLAT SHIELD WITH INFLATED SUBSTRUCTURE [11]

Low Arch Shield With Inflated Substructure

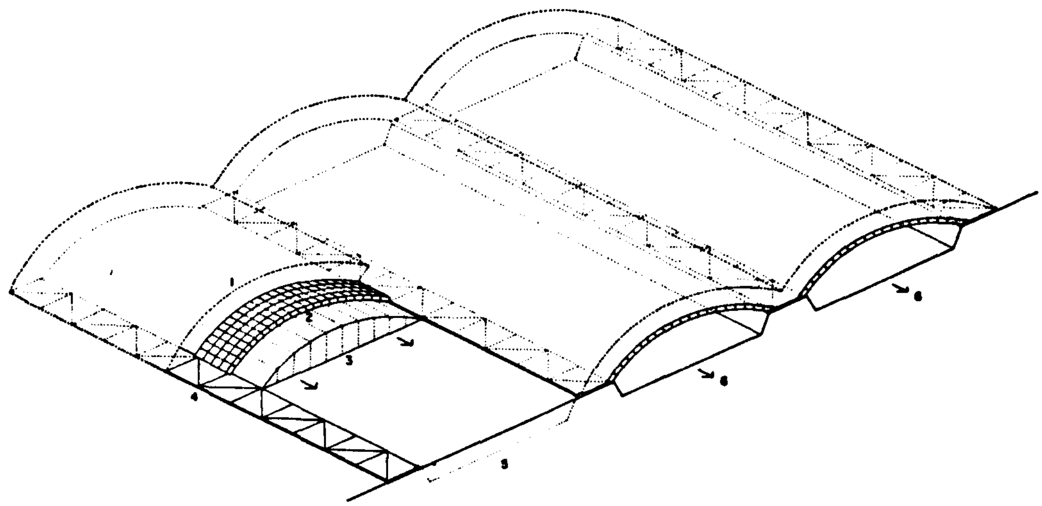
A low arch shield working in compression to support regolith requires less structural reinforcement than a flat shield. The only reinforcement required would be the girders needed to accommodate the outward (horizontal) thrust of the arch or arches. The components of such an arch would be made of molded regolith 'bricks' assembled over a movable pneumatic support form (see Figure 2b).[11]

The advantages of this alternative are:

1. An arch is very strong structurally.
2. The design can be configured to provide large volumes of habitable space per kilogram of launch weight.
3. The pressurized enclosure weighs less than a habitat module, which reduces transportation requirements.

The disadvantages of this alternative are:

1. It requires a digger to excavate below the arch and to create an entrance ramp.
2. The arch is labor intensive to construct.
3. There is a need for a regolith molder or brick maker.
4. A pneumatic form is required to support the arch assembly during construction.
5. All life support equipment and other machinery must be brought into the enclosure after it has been erected.



BASE CONCEPT II. Low arch shield using moulded regolith components assembled over temporary, movable pneumatic support form, pressurized enclosures beneath. *General view of base. (1) Regolith shielding. (2) Interlocking, moulded regolith arch components. All components identical dimensions. (3) Movable pneumatic form supporting arch assembly. (4) Aluminum lattice girders to accommodate outward thrust of arches. Girders assembled flat on surface with short components and anchored to surface with vertical pins or connected with transverse cables at convenient, widely space intervals. (5) Height increased where required by excavation. (6) Expansion.*

Figure 2b: LOW ARCH SHIELD WITH INFLATED SUBSTRUCTURE [11]

Lunar Soil Bags

The soil bag alternative proposes placing a habitat module directly on the ground and then surrounding it to the required depth by 'sandbags' filled with lunar soil (see Figure 3).[15] The bags would be made of Kevlar or other material which is resistant to ultraviolet radiation degradation. Although the bags could possibly be filled manually, the project team assumed that an automatic bagging device would be used.[6] Placement of the bags around the habitat would be performed by hand.

The advantages of this alternative are:

1. No digging or trenching device is required.
2. The bags would be easy to remove for future expansions.
3. The bags would reduce the regolith's tendency to slide away from habitat walls during construction and later.
4. Bags could be used to construct vertical walls if such were needed.

The disadvantages of this alternative are:

1. Material for the bags would have to be brought from Earth (estimated launch weight 100 pounds).
2. The bag-filling device would have to brought from Earth (estimated launch weight 1,000 pounds).
3. The bagger would not be transformable to other purposes.
4. Bagging would take approximately 300 hours to fill enough bags to protect one module.

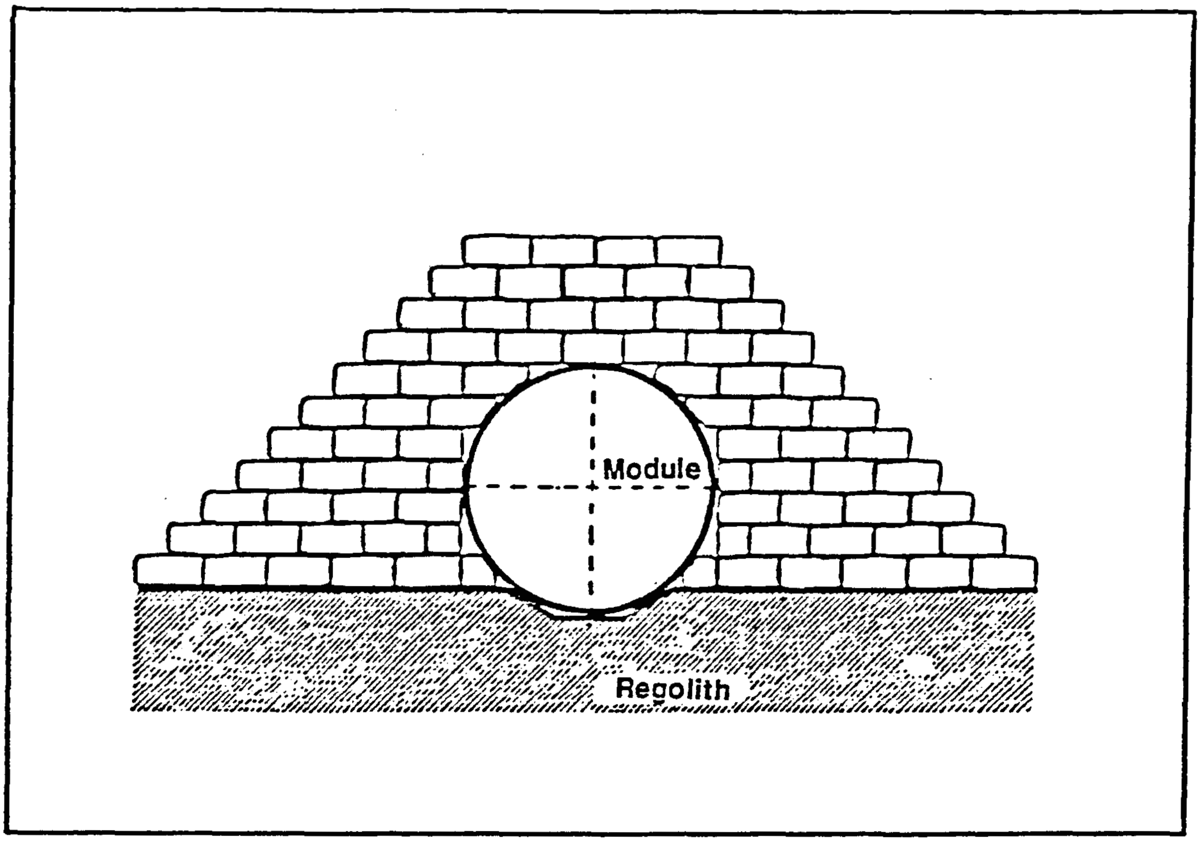


Figure 3a: LUNAR SOIL BAGS[15]

Loose Regolith Shielding

A variation of the lunar soil bag proposal is to place the regolith directly on and around the habitat (see Figure 3b). This loose regolith alternative needs no bags or bagging device. The soil would still have to be gathered and deposited around the habitat using some type of mechanical implement.

The advantages of this alternative are:

1. The construction time required is minimal (estimated to be approximately 15 hours).

2. No digging or trenching device is required.

The disadvantage of this alternative is:

1. The regolith mound might tend to subside away from the habitat.

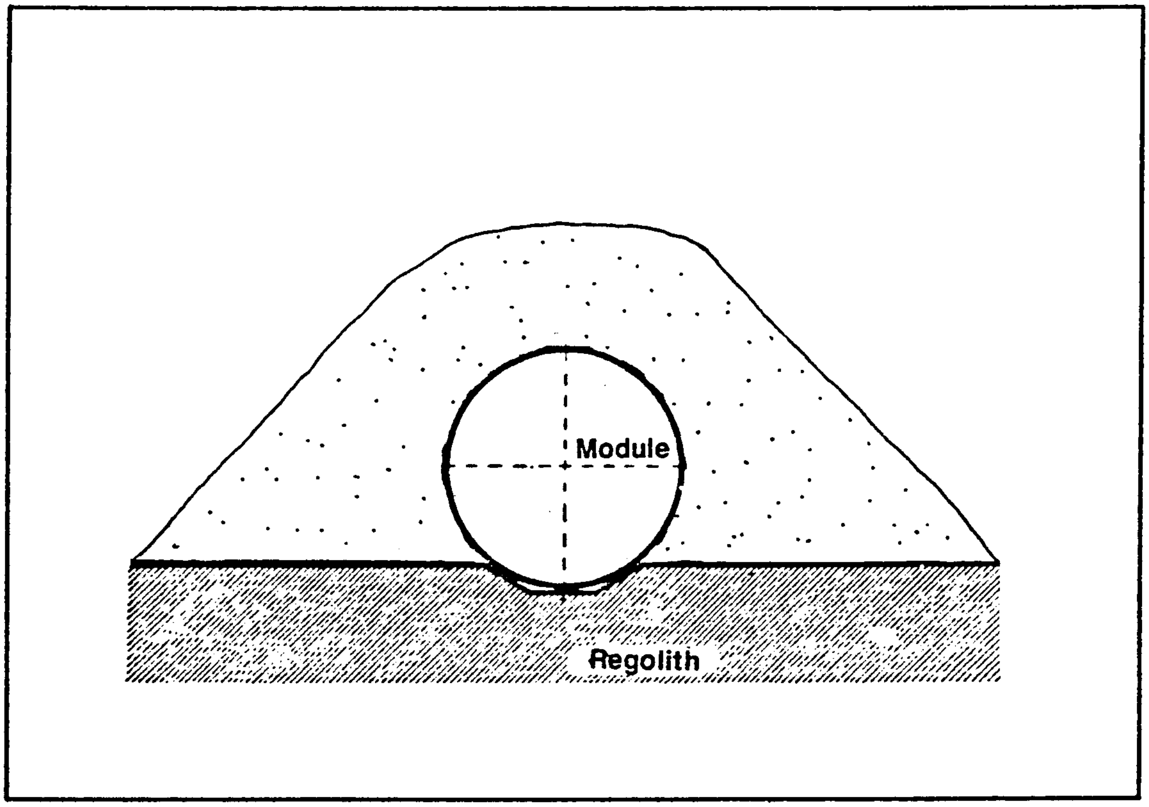


Figure 3b: LOOSE REGOLITH SHIELDING

Below Ground Alternatives

Two of the below ground alternatives require an ability to dig into the lunar soil. This necessitates bringing digging equipment of some sort to the Moon. For the purposes of analysis, the project team used an opposed-bucket digging implement developed at Georgia Tech.[6] After the habitat is placed below ground, the excavated material is used as backfill to cover the module.

Underground With Support Structure

This alternative by the Lunar Operations Company[12] is similar to the superstructure envelope design, but the habitat is located underground instead of on the surface (see Figure 4).

The advantages of this alternative are:

1. There is a cradle and anchoring system which would prevent point loads from occurring on the bottom of the module.

2. The configuration allows access to the module's exterior for maintenance.

3. The habitat module can be made lightweight, since it would not have to support weight of the regolith shielding.

The disadvantages of this alternative are:

1. Truss structure components must be brought from Earth.

2. The truss requires extensive construction efforts to erect.

3. Future expansions would require additional truss components.

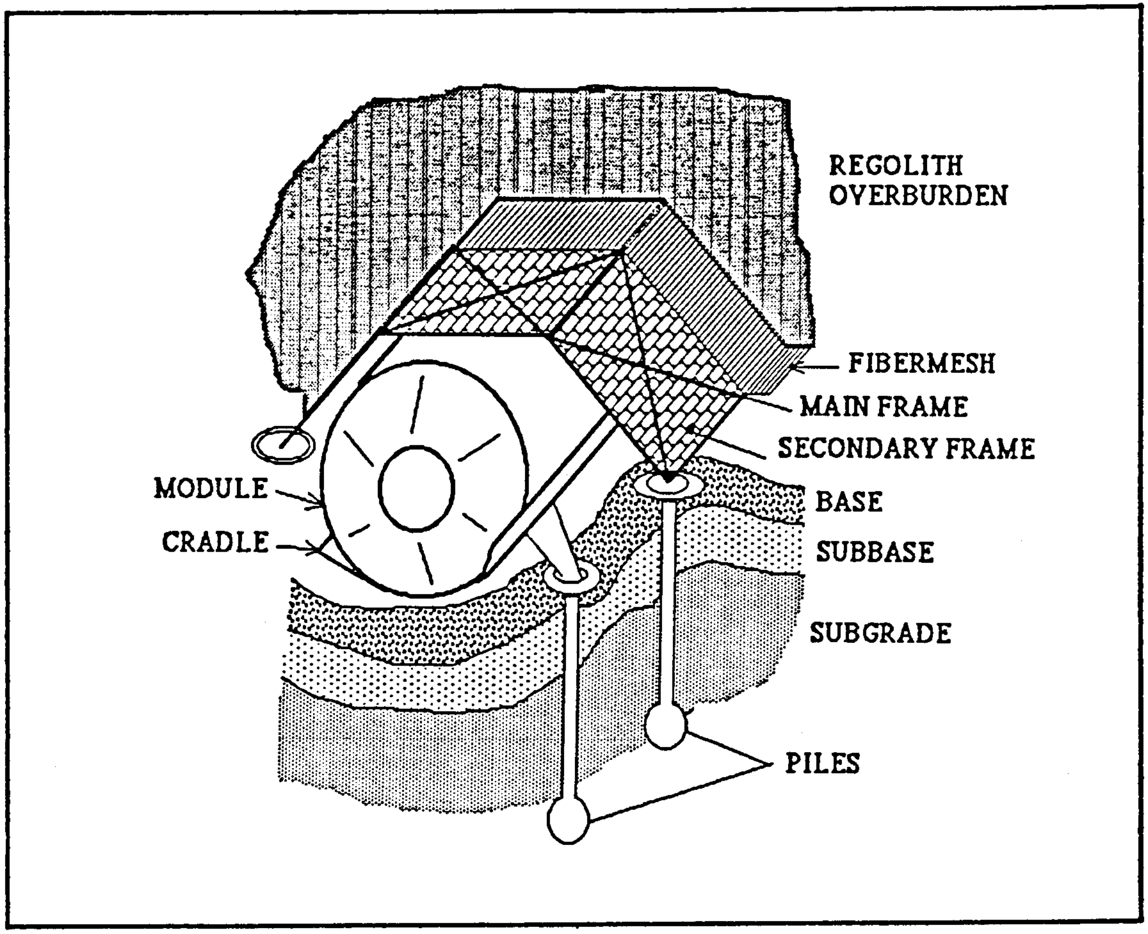


Figure 4: UNDERGROUND WITH SUPPORT STRUCTURE[12]

Lunar Lava Tubes

Natural caverns occur on the Moon in the form of lava tubes, which are drained conduits of subsurface lava rivers.[8] The tubes offer preformed structures that are deep enough to provide natural protection from radiation and micrometeorite impact (see Figure 5). The research outpost in a lava tube is envisioned to be a modular habitat, set onto guide rails three times its length. The rails are the only site preparation needed, and allow the habitat to be slid into the tube under the uncollapsed roof section.

The advantages of this alternative are:

1. No support structure is required, which reduces transportation requirements and construction efforts.
2. There is a constant thermal environment, estimated to be -20 degrees Celsius.
3. No digging or trenching is required.
4. The habitat module can be made lightweight, since it would not have to support weight of the regolith shielding.
5. No hauling and placing of regolith is needed.

The disadvantages of this alternative are:

1. The tube may be hard to access (i.e., all materials will have to be lowered and raised to and from the tube).
2. As yet no lava tubes have been explored on the Moon.
3. The lava tubes do not offer flexibility of site selection.

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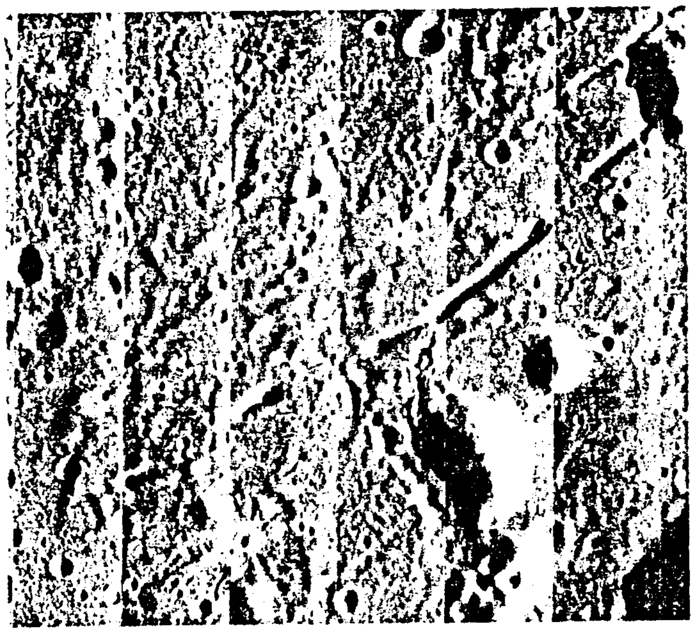

Lunar lava rille with uncollapsed roof sections that measure hundreds of meters. Note that mountains are close by which certainly differ in chemistry and mineralogy from the relatively flat basalt surfaces. This rille was extensively described by Cruikshank and Wood (1972) (Lunar Orbiter 5, frame M-191).

Figure 5: LUNAR LAVA TUBES [8]

Underground Without Support Structure

The module is buried in a trench so that its roof is 0.5 meters above ground level. Primary access is achieved through an airlock, and an escape exit is provided for emergency use (see Figure 6).

The advantages of this alternative are:

1. No regolith support structure is required.
2. Placing the module close to the surface reduces the volume of excavation required.
3. Access by means of a ramp provides for ease of entrance and exit.
4. A habitat with built-in reinforcement avoids construction requirements and the potential for associated problems on the Moon.
5. The module is equipped with hydraulic legs which facilitate leveling and prevent point loads from occurring on the bottom of the module.

The disadvantage of this alternative is:

1. It is not easily adapted to provide large volumes of habitable space.

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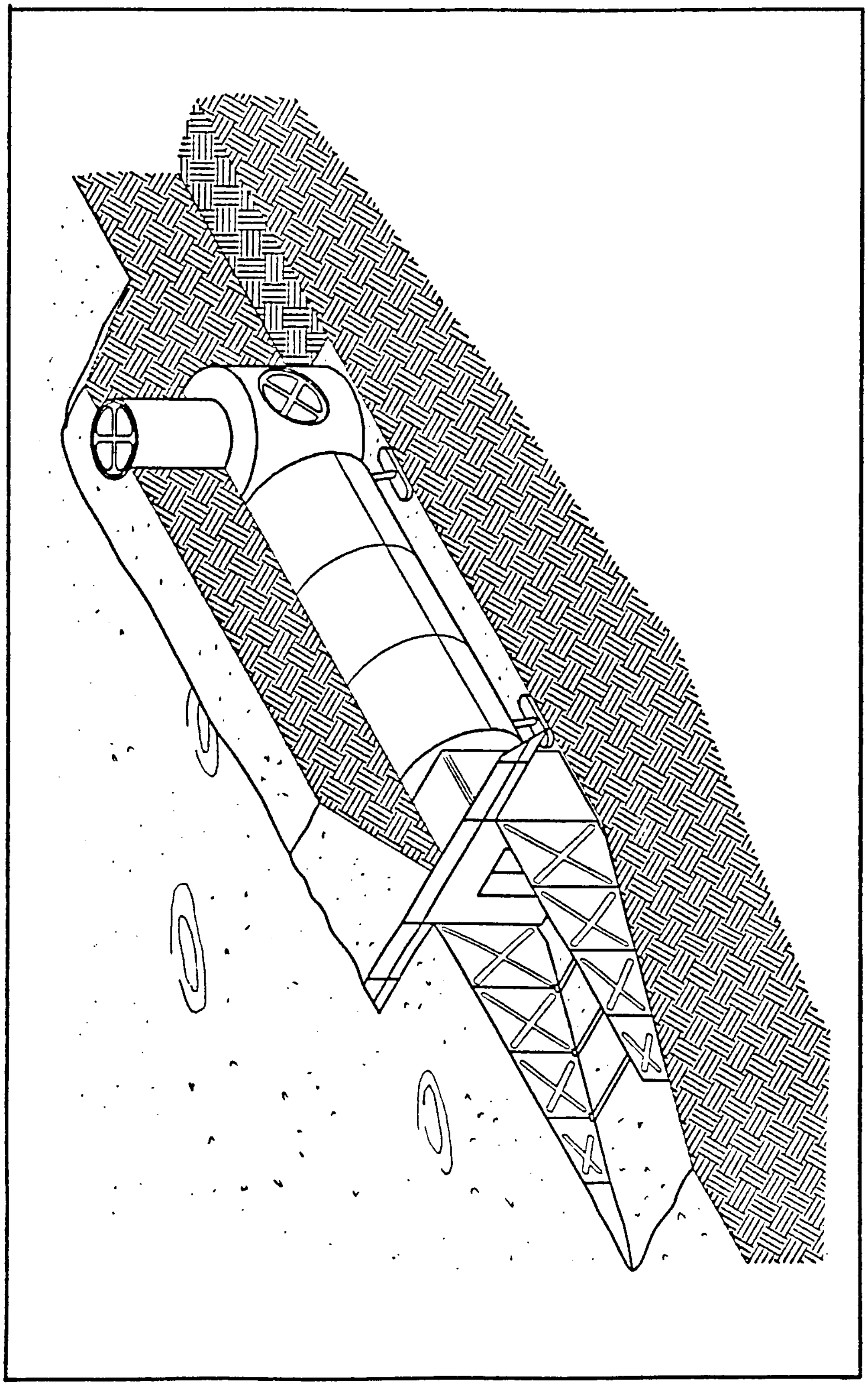

Figure 6: UNDERGROUND WITHOUT SUPPORT STRUCTURE

METHOD OF ANALYSIS

During the research stage of the project, the team assembled a set of quantitative attributes for each alternative. The attributes include estimates for the volume of excavation required, expected construction time, and the weight of equipment to be brought from Earth. The attributes are presented in Table B1 of Appendix B, along with supporting descriptions and references.

Each alternative was analyzed according to how well it satisfied the eleven identified design criteria. The analysis was performed by assigning a weighting factor to each criterion, after which a decision matrix was used to determine a numerical rank for each alternative. The team used the quantitative data to aid in assigning decision matrix rating factors. In order to assess the sensitivity of the analysis method, three different weighting schemes were employed. The weighting factors and decision matrices used are found in Appendix A. The results are given in Table 1 on page 25.

Table 1: SUMMARY OF DECISION RESULTS

ALTERNATIVES	RANKING		
	BASED ON WEIGHTINGS GIVEN IN TABLE A1	BASED ON WEIGHTINGS GIVEN IN TABLE A3	BASED ON EQUAL WEIGHTINGS
ABOVE GROUND			
1) SURFACE ASSEMBLED SUPERSTRUCTURE ENVELOPE	8	8	6
2A) FLAT SHIELD	7	5	7
2B) DOME SHIELD	6	4	8
3A) SOIL BAG SHIELDING	5	6	4
3B) LOOSE REGOLITH SHIELDING	4	3	2
BELOW GROUND			
4) BURIED WITH SUPERSTRUCTURE ENVELOPE	3	7	5
5) BURIED WITHOUT SUPERSTRUCTURE ENVELOPE	2	2	2
6) LAVA TUBES	1	1	1

PROJECT SOLUTION

In all three cases, the lava tube alternative received the highest ranking as the best design solution. However, there is a serious drawback to selecting lava tubes as the best method of protecting lunar outpost inhabitants. Only a few lava tubes are recognized, and none have been explored. Because no suitable tubes are currently identified, the project team chose to develop the second-ranked alternative, the buried module without a regolith support structure.

This alternative is a composite design developed by the project team to best satisfy the desired design criteria. The design consists of a cylindrical habitat structure, an airlock with attached trench walls, and a module configured for emergency escape and future habitat expansions. The design is shown in Figure 7. The design details were developed as outlined in step five of the design methodology section, and are presented below.

Assumptions

The project team assumed there would be equipment available for digging and lifting material on the Moon. Specifically, previous USRA teams have developed a lunar crane[5] and digger.[6] Also, an all-terrain device known as the Skitter[4] has been developed to provide mobility for the crane, digger, and other equipment. The Skitter is also assumed to be available for lunar construction.

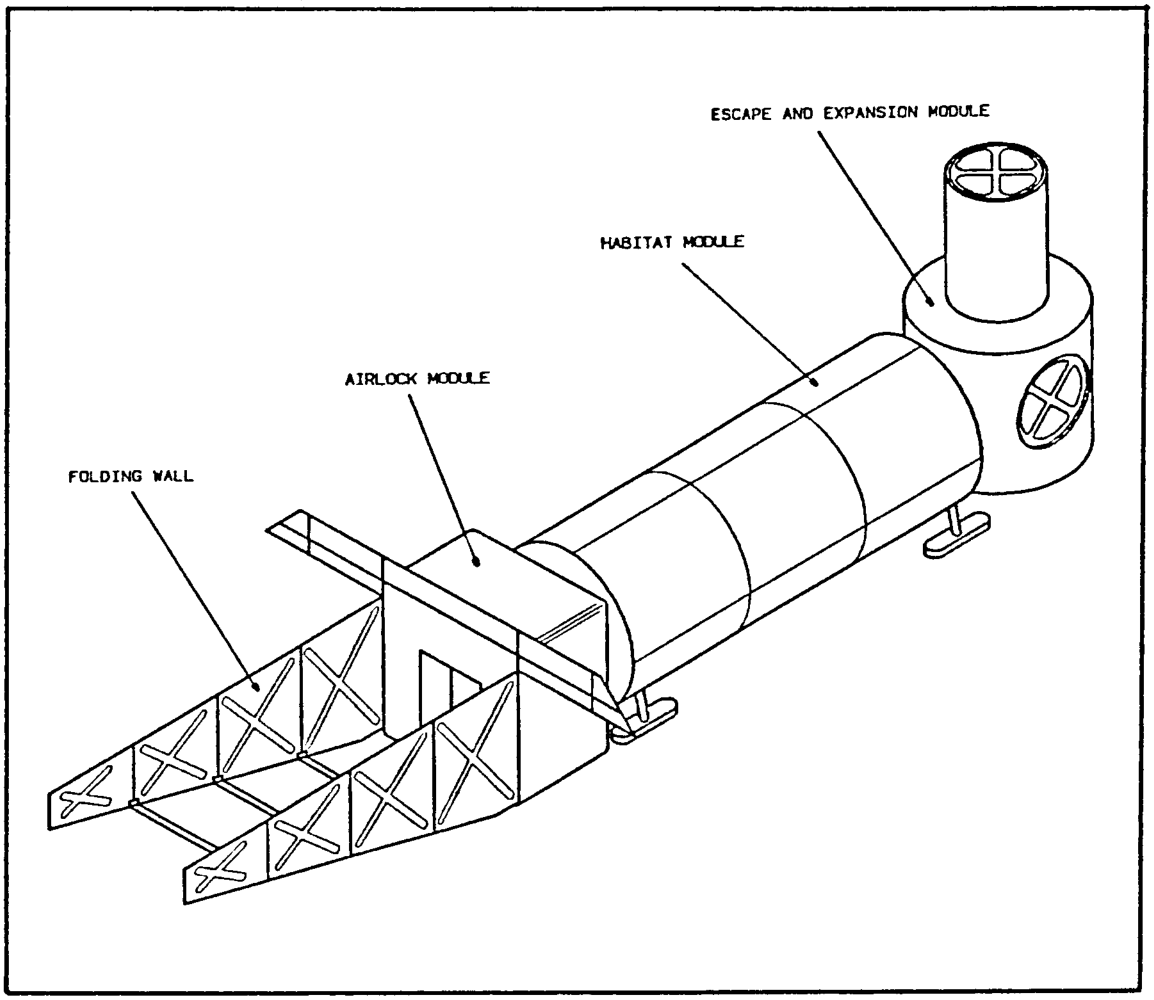

Figure 7: MODULE LAYOUT FOR FINAL DESIGN

Recommendation of Site Selection

Sites which have been previously explored offer the advantage of familiarity with local terrain and soil conditions. But because there is so much to learn about the Moon, the team recommends that an unexplored site be chosen for a research outpost. Specifically, we recommend that any site selected should have proof that there are lava tubes within reach. The analysis results indicate that situating a lunar base inside a lava tube would be a most advantageous alternative. Consideration should especially be given to a location on the lunar limb (the visible edge of the Moon's near side). Such a site would offer proximity to the Moon's far side. The Moon's far side is shielded from the radio noise of Earth, which makes it desirable for radio astronomy research.

Protective Structure Configuration Outline

Three and one half meters (11.5 feet) of regolith cover the habitat module. This depth is enough to provide adequate shielding against all GCR and SEP.[13] The habitat and support modules are seated in a trench that is approximately 35.6 meters long by 4.5 meters wide by 4.0 meters deep (see Figure 8). Four hydraulic legs support the habitat and allow for ease of placement and leveling.

An airlock with attached ramp walls provides primary access to the habitat module. The walls fold down to conserve space during transport, and can be unfolded by hand once the airlock is in place. The walls are designed to shore up the trench, and are formed with X-shaped corrugations to increase

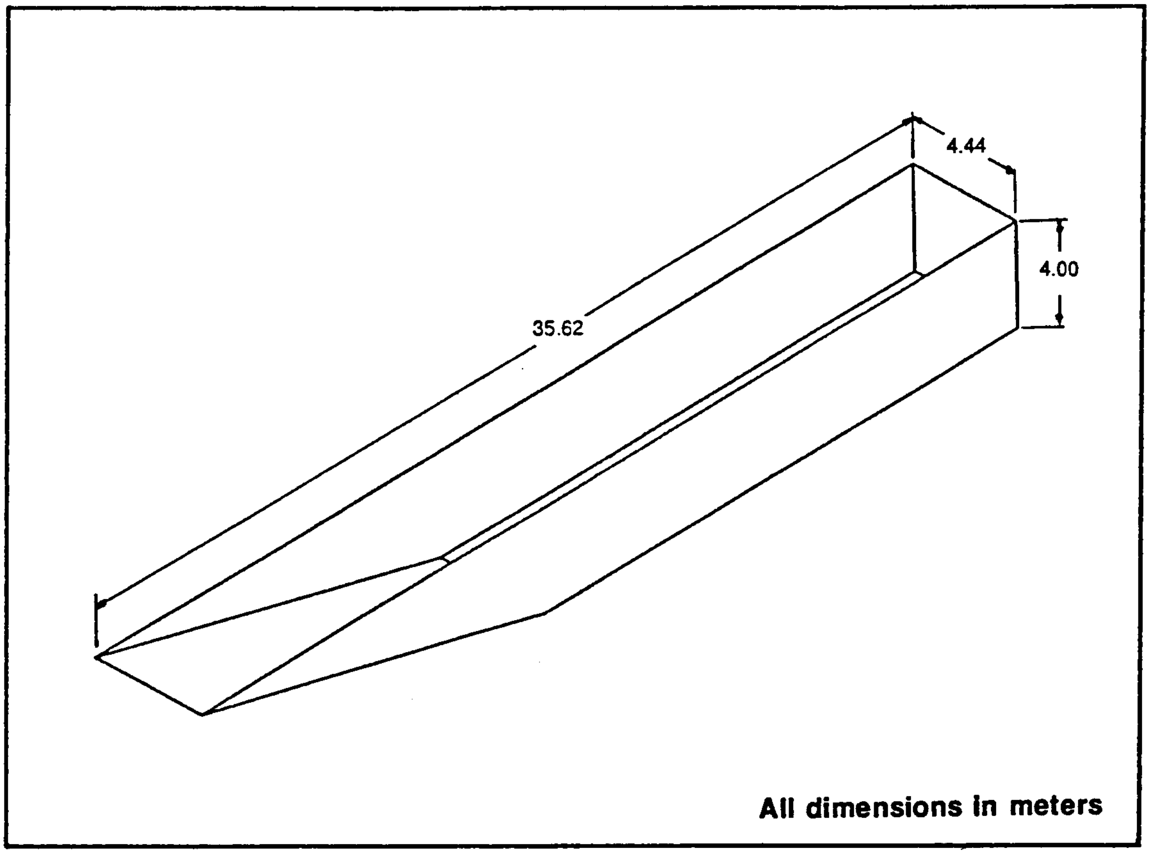

Figure 8: TRENCH DIMENSIONS

their stiffness. Thin braces placed across the ramp floor provide additional strength.

An emergency exit and expansion module is located opposite of the airlock. Escape is accomplished through a vertical tube with ladder rungs leading to the surface. The top of the vertical tube provides a 'yardstick' during construction to indicate the height required of the regolith mound. The module is envisioned as having a pressurized closet containing spare pressure suits. In the event of a fire inside the habitat, the crew could get into the closet and vent out the habitat's air, which should extinguish the blaze. The emergency module is also configured with side ports to allow for future habitat additions.

Material Selection

A lightweight titanium alloy such as Ti-6Al-4V is recommended for the folding ramp walls. This alloy is a readily available aerospace material, and is recommended because it will keep the launch weight low. All moving joints must have a protective coating such as Teflon, since bare metal surfaces will cold vacuum weld upon contact. Teflon has the added advantage that it does not degrade when exposed to ultraviolet radiation.

Structural Integrity Considerations

All of the modules must be must be made strong enough to withstand the weight of the regolith mass shielding. Using an average regolith density of 1750 kilograms per cubic meter[7], the 3.5 meter of soil covering will produce a pressure of approximately 10 kiloPascals (kPa) per square meter. By way of comparison, a pressure of one atmosphere is equal to approximately 101 kPa.

Although the habitat's internal pressure will exceed the expected external pressure, all modules should be designed to withstand the regolith's weight unaided. This will prevent collapse of the structure due to a loss of internal pressure.

Construction Sequence Outline

The lunar construction operation will consist of digging the trench, placing and leveling the modules, deploying the ramp walls, and covering the modules with backfill. The modules and construction equipment should be landed ahead of the crew. If landing-related problems occur, the mission can be aborted without endangering human lives. Equipment unpacking will begin after the crew has landed. A heavy-lift crane attached to the equipment lander will facilitate the unpacking and it can be used to place the module into the trench.

Heat Transfer Considerations

The lunar soil is a poor conductor of heat. The thermal conductivity of Moon soil ranges from 0.0021 watts per meter Kelvin (w/m·k) at the surface to 2.077 (w/m·k) at a depth of twenty feet.[2] At this point it is unknown how much heat will be generated inside the habitat by onboard electronics and the crew members themselves. Once the expected heat transfer requirements have been determined, some form of radiant heat exchanger will have to be devised, since the soil covering will act as a thermal insulator.

Maintenance Aspects

Most of the habitat structure is located below surface level, so the regolith mound should have little tendency to subside. The presence of the ramp walls will prevent the trench wall from collapsing. Thus little or no maintenance of the regolith shield and ramp is expected.

The exterior of the structure will be covered with soil, making it inaccessible for outside maintenance. Therefore all planned maintenance of the habitat must be designed to be accomplished from inside. This aspect is actually desirable to exterior maintenance, where the need for a space suit imposes severe restrictions on mobility and sensitivity. Interior maintenance can be performed in the 'shirtsleeve' environment of the habitat.

Future Expansion

The emergency exit module has five ports, three of which can be used to attach additional habitats or other modules. When it is desired to add on to the base, only the regolith covering the end of the structure would need to be removed.

CONCLUSIONS AND RECOMMENDATIONS

The team's original design satisfies all the identified design criteria. The structure will adequately protect its inhabitants from both galactic cosmic and solar radiation, as well as micrometeorite impacts.

The project team believes it is more advantageous to build all module components so that they are strong enough to support the weight of the regolith shielding. Adding this strength to the modules greatly simplifies lunar construction by eliminating the need to assemble a truss structure at the site.

It is highly recommended that this initial operations habitat be provided with complete radiation protection. Future additions to the base can be provided with less regolith shielding protection. Reducing the regolith overburden will lower the structural strength requirement, which will decrease the transport weight of additional modules. In the event of a solar flare or any other radiation increase, the initial habitat can be used as a 'storm cellar' until the radiation has decreased to a tolerable level.

The project team recommends that future development of this project should include a detailed design of all structures (i.e., the airlock, habitat, and emergency escape modules).

A recommended future project would be the analysis and development of protective structures for a post-outpost base that is permanently occupied and at least partially self-sufficient.

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APPENDIX A

Analysis of Alternatives by Decision Matrix

ANALYSIS OF ALTERNATIVES BY DECISION MATRIX

A decision matrix is a tool used as an aid in the decision making process. Decision matrices are usually employed when a selection must be made from several possible design alternatives. To use a decision matrix, a set of design criteria must be identified. Every criterion is assigned a weighting factor determined by its relative importance in the set. Each alternative is then assigned rating factors based on the designer's judgement of how well it satisfies the design criteria. The products of the weighting factors and rating factors are then summed to assign a numerical rating to each alternative. The alternative with the highest sum of products is ranked number one, that is, the 'best' possible alternative.

Weighting factors for the criteria were determined using the method of pairs. The method is a sequential process by which every possible pair of criteria is compared. A tally mark is given to the criterion considered to be of greater importance. The total number of marks each criterion received is then divided by the total number of tally marks to obtain a weighting factor between zero and one.

Table A1 outlines the results of the initial method of pairs analysis. The weighting factors from Table A1 were used in an initial decision matrix to determine the numerical rank of each alternative. The decision matrix is presented in Table A2.

Table A1: INITIAL WEIGHTING FACTORS

CRITERIA	TALLY MARKS	TOTAL	WEIGHTING FACTORS
SHEILDING AGAINST RADIATION	*********	9	0.153
USE OF LUNAR RESOURCES	*******	7	0.119
PROTECTION AGAINST MICROMETEORITES	*********	9	0.153
USE OF PREFAB. PARTS	***	3	0.051
USE OF TRANSFORMABLES	*	1	0.017
PROVISION FOR EXPANSION	**	2	0.034
EASE OF CONSTRUCTION	******	6	0.102
STRUCTURAL INTEGRITY	*********	9	0.153
MAINTENANCE REQUIREMENTS	*****	5	0.085
ACCESS FOR MAINTENANCE	*******	7	0.119
TRANSPORTATION REQUIREMENT	*	1	0.017
		SUM TOTAL OF WEIGHTING FACTORS	1.000

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Table A2: INITIAL DECISION MATRIX

DESIGN CONSIDERATION / ALTERNATIVES	SHIELDING AGAINST RADIATION	USE OF LUNAR RESOURCES	PROTECTION AGAINST MICROMETEORITES	USE OF PREFABRICATED PARTS	USE OF TRANSFORMABLES	PROVISION FOR EXPANSION	EASE OF CONSTRUCTION	STRUCTURAL INTEGRITY	MAINTENANCE REQUIREMENTS	ACCESS FOR MAINTENANCE	TRANSPORTATION REQUIREMENTS	SUM OF PRODUCTS	NUMERICAL RANKING
WEIGHTING FACTOR →	0.153	0.119	0.153	0.051	0.017	0.034	0.102	0.153	0.085	0.119	0.017		
ABOVE GROUND													
1) SURFACE ASSEMBLED SUPERSTRUCTURE ENVELOPE	9 / 1.377	8 / 0.952	9 / 1.377	8 / 0.408	6 / 0.102	7 / 0.238	6 / 0.612	9 / 1.377	8 / 0.680	9 / 1.071	5 / 0.085	8.279	8
2A) FLAT SHIELD	10 / 1.530	7 / 0.833	10 / 1.530	4 / 0.204	3 / 0.051	9 / 0.306	4 / 0.408	10 / 1.530	9 / 0.765	8 / 0.952	9 / 0.153	8.263	7
2B) LOW ARCH	10 / 1.530	8 / 0.952	10 / 1.530	5 / 0.255	4 / 0.068	4 / 0.136	5 / 0.510	10 / 1.530	9 / 0.765	8 / 0.952	9 / 0.153	8.381	6
3A) SOIL BAG SHIELDING	9 / 1.377	8 / 0.952	9 / 1.377	8 / 0.408	5 / 0.085	6 / 0.204	7 / 0.714	9 / 1.377	9 / 0.765	9 / 1.071	7 / 0.119	8.449	5
3B) LOOSE REGOLITH SHIELDING	9 / 1.377	10 / 1.190	9 / 1.377	10 / 0.510	10 / 0.170	7 / 0.238	9 / 0.918	8 / 1.224	8 / 0.680	10 / 1.190	8 / 0.136	9.010	4
BELOW GROUND													
4) BURIED WITH SUPERSTRUCTURE ENVELOPE	10 / 1.530	8 / 0.953	10 / 1.530	8 / 0.408	6 / 0.102	7 / 0.238	5 / 0.510	9 / 1.377	8 / 0.680	9 / 1.071	5 / 0.085	9.203	3
5) BURIED WITHOUT SUPERSTRUCTURE ENVELOPE	10 / 1.530	9 / 1.071	10 / 1.530	9 / 0.459	9 / 0.153	7 / 0.278	8 / 0.816	9 / 1.377	9 / 0.765	10 / 1.190	8 / 0.136	9.305	2
6) LAVA TUBES	10 / 1.530	10 / 1.190	10 / 1.530	8 / 0.408	8 / 0.136	9 / 0.306	9 / 0.918	10 / 1.530	10 / 0.850	10 / 1.190	7 / 0.119	9.707	1

The project team employed two additional weighting schemes in order to assess the validity of the initial decision results. The second weighting system was devised so that the minimum transportation requirement criterion would be equal in weight to the other top-ranked criteria (i.e., radiation and micrometeorite shielding, and structural integrity). This weighting scheme was developed at the suggestion of NASA's Dr. John Allred, and is presented in Table A3.

The weighting factors from Table A3 were used with the original rating factors to construct the decision matrix shown in Table A4.

The final decision matrix was constructed with all criteria weighted equally. The results contain a tie for second place, and are presented in Table A5.

Table A3: WEIGHTING FACTORS WITH TRANSPORTATION REQUIREMENTS EMPHASIZED

CRITERIA	TALLY MARKS	TOTAL	WEIGHTING FACTORS
SHEILDING AGAINST RADIATION	********	8	0.140
USE OF LUNAR RESOURCES	******	6	0.105
PROTECTION AGAINST MICROMETEORITES	********	8	0.140
USE OF PREFAB. PARTS	**	2	0.035
USE OF TRANSFORMABLES	*	1	0.017
PROVISION FOR EXPANSION	*	1	0.017
EASE OF CONSTRUCTION	*****	5	0.088
STRUCTURAL INTEGRITY	********	8	0.140
MAINTENANCE REQUIREMENTS	****	4	0.070
ACCESS FOR MAINTENANCE	******	6	0.105
TRANSPORTATION REQUIREMENT	********	8	0.140
SUM TOTAL OF WEIGHTING FACTORS			1.000

Table A4: SECOND DECISION MATRIX

DESIGN CONSIDERATION / WEIGHTING FACTOR → / ALTERNATIVES	SHIELDING AGAINST RADIATION	USE OF LUNAR RESOURCES	PROTECTION AGAINST MICROMETEORITES	USE OF PREFABRICATED PARTS	USE OF TRANSFORMABLES	PROVISION FOR EXPANSION	EASE OF CONSTRUCTION	STRUCTURAL INTEGRITY	MAINTENANCE REQUIREMENTS	ACCESS FOR MAINTENANCE	TRANSPORTATION REQUIREMENTS	SUM OF PRODUCTS	NUMERICAL RANKING
WEIGHTING FACTOR	0.140	0.150	0.140	0.035	0.017	0.017	0.088	0.140	0.070	0.105	0.140		
ABOVE GROUND													
1) SURFACE ASSEMBLED SUPERSTRUCTURE ENVELOPE	1.260 (9)	1.200 (8)	1.260 (9)	0.280 (8)	0.102 (6)	0.119 (7)	0.528 (6)	1.260 (9)	0.560 (8)	0.945 (9)	0.700 (5)	8.214	8
2A) FLAT SHIELD	1.400 (10)	1.050 (7)	1.400 (10)	0.140 (4)	0.051 (3)	0.153 (9)	0.352 (4)	1.400 (10)	0.630 (9)	0.840 (8)	1.260 (9)	8.676	5
2B) LOW ARCH	1.400 (10)	1.200 (8)	1.400 (10)	0.175 (5)	0.068 (4)	0.068 (4)	0.440 (5)	1.400 (10)	0.630 (9)	0.840 (8)	1.260 (9)	8.881	4
3A) SOIL BAG SHIELDING	1.260 (9)	1.200 (8)	1.260 (9)	0.280 (8)	0.085 (5)	0.102 (6)	0.616 (7)	1.260 (9)	0.630 (9)	0.945 (9)	0.980 (7)	8.618	6
3B) LOOSE REGOLITH SHIELDING	1.260 (9)	1.500 (10)	1.260 (9)	0.350 (10)	0.170 (10)	0.119 (7)	0.792 (9)	1.120 (8)	0.560 (8)	1.050 (10)	1.120 (8)	9.301	3
BELOW GROUND													
4) BURIED WITH SUPERSTRUCTURE ENVELOPE	1.400 (10)	1.200 (8)	1.400 (10)	0.280 (8)	0.102 (6)	0.119 (7)	0.440 (5)	1.260 (9)	0.560 (8)	0.945 (9)	0.700 (5)	8.406	7
5) BURIED WITHOUT SUPERSTRUCTURE ENVELOPE	1.400 (10)	1.350 (9)	1.400 (10)	0.315 (9)	0.153 (9)	0.119 (7)	0.704 (8)	1.260 (9)	0.630 (9)	1.050 (10)	1.120 (8)	9.501	2
6) LAVA TUBES	1.400 (10)	1.500 (10)	1.400 (10)	0.280 (8)	0.136 (8)	0.153 (9)	0.792 (9)	1.400 (10)	0.700 (10)	1.050 (10)	0.980 (7)	9.791	1

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Table A5: DECISION MATRIX WITH ALL WEIGHTING FACTORS EQUAL

DESIGN CONSIDERATION / WEIGHTING FACTOR / ALTERNATIVES	SHIELDING AGAINST RADIATION	USE OF LUNAR RESOURCES	PROTECTION AGAINST MICROMETEORITES	USE OF PREFABRICATED PARTS	USE OF TRANSFORMABLES	PROVISION FOR EXPANSION	EASE OF CONSTRUCTION	STRUCTURAL INTEGRITY	MAINTENANCE REQUIREMENTS	ACCESS FOR MAINTENANCE	TRANSPORTATION REQUIREMENTS	SUM OF PRODUCTS	NUMERICAL RANKING
WEIGHTING FACTOR	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000		
ABOVE GROUND													
1) SURFACE ASSEMBLED SUPERSTRUCTURE ENVELOPE	9	8	9	8	6	7	6	9	8	9	5	84	6
2A) FLAT SHIELD	10	7	10	4	3	9	4	10	9	8	9	83	7
2B) LOW ARCH	10	8	10	5	4	4	5	10	9	8	9	82	8
3A) SOIL BAG SHIELDING	9	8	9	8	5	6	7	9	9	9	7	86	4
3B) LOOSE REGOLITH SHIELDING	9	10	9	10	10	7	9	8	8	10	8	98	2
BELOW GROUND													
4) BURIED WITH SUPERSTRUCTURE ENVELOPE	10	8	10	8	6	7	5	9	8	9	5	85	5
5) BURIED WITHOUT SUPERSTRUCTURE ENVELOPE	10	9	10	9	9	7	8	9	9	10	8	98	2
6) LAVA TUBES	10	10	10	8	8	9	9	10	10	10	7	101	1

APPENDIX B

Quantitative Attributes of Alternatives

QUANTITATIVE ATTRIBUTES OF ALTERNATIVES

Volume of Regolith Excavation Required

The volume of regolith excavated is determined by the geometric shape of the trench.

Volume of Regolith Required for Shielding

The regolith depth required for shielding is 3.5 meters. The total volume of regolith required varies with each alternative due to surface area differences.

Construction Time

The construction time is estimated based upon the expected construction sequence of each particular alternative. The sequences include unpacking, layout, trenching, structure assembly, habitat placement, regolith gathering, and regolith deposition.

Estimated Weight of External Support Structure

The weight of each support structure is estimated relative to the specified weight of the surface assembled superstructure envelope alternative.[9]

Estimated Weight of Additional Equipment Required

When available, the weight of additional equipment is cited from the report on the specific device. Otherwise, the weight is estimated based on similar equipment found on Earth.

Total Weight Brought From Earth

The total weight represents the weight of additional equipment required plus the weight of the external support structure, if any.

Table B1: QUANTITATIVE ATTRIBUTES OF ALTERNATIVES

ALTERNATIVES \ ATTRIBUTES	VOLUME OF REGOLITH EXCATION REQUIRED (CUBIC M)	VOLUME OF REGOLITH REQUIRED FOR SHIELDING (CUBIC M)	CONSTRUCTION TIME (HRS)	EXTERNAL SUPPORT STRUCTURE REQUIRED	ESTIMATED WEIGHT OF EXTERNAL SUPPORT STRUCTURE (LBS)	ADDITIONALEQUIPMENT REQUIRED	ESTIMATED WEIGHT OF ADDITIONAL EQUIPMENT REQUIRED (LBS)	TOTAL WEIGHT BROUGHT FROM EARTH EXCLUDING COMMON MODULE (LBS)
ABOVE GROUND								
1) SURFACE ASSEMBLED SUPERSTRUCTURE ENVELOPE	-	888	100	SUPPORT STRUCTURE (7,500 LBS)	7,500	BUCKET FOR CRANE (250 LBS)	250	7,750
2A) FLAT SHIELD	-	917	120	SUPPORT STRUCTURE (7,500 LBS) PRESURIZED ENV. (2,000 LBS)	9,500	PNEUMATIC JACKS (500 LBS)	500	10,000
2B) LOW ARCH	278	879	120	LATTICE GIRDERS (5,000 LBS) PRESSURIZED ENV. (2,000 LBS)	7,000	BRICK MAKER (3,375 LBS) MOVABLE FORM (1,000 LBS)	4,375	11,375
3A) SOIL BAG SHIELDING	-	1,373	400	-	-	BAGGER (1000 LBS)	1,000	1,000
3B) LOOSE REGOLITH SHIELDING	-	1,373	15	-	-	-	-	-
BELOW GROUND								
4) BURIED WITH SUPERSTRUCTURE ENVELOPE	2,870	2,200	120	SUPPORT STRUCTURE (7,500 LBS)	7,500	BUCKET FOR CRANE (250 LBS)	250	7,750
5) BURIED WITHOUT SUPERSTRUCTURE ENVELOPE	765	460	20	FOLDING WALLS (835 LBS)	835	-	-	835
6) LAVA TUBES	-	-	80	RAILINGS (1,100 LBS)	1,100	-	-	1,100

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APPENDIX C

Layout Drawings