Design Concepts
for Pressurized Lunar Shelters
Utilizing Indigenous Materials

John Happel
Kaspar Willam
Benson Shing

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Structural Design Concepts for Pressurized Lunar Shelters Utilizing Indigenous Materials:

John Amin Happel, Kaspar Willam, Benson Shing

1. Design Objective:
Pressurized shelter built of indigenous lunar materials

2. Scope:
a.) Structural Design w/ Lunar Conditions
b.) Review of Previous Concepts
c.) Selection of Indigenous Material
d.) Design Variables
e.) Design 1: Cylindrical Segments
f.) Design 2: Arch-Slabs with Post-Tensioned Ring Girders

3. Lunar Conditions Which Impact Design:

Primary Factors:
* High Vacuum;

Pressure vessels
Tension loads
Primary design load
1 atm. pressure = 1440 psf load, terrestrial loads = 150 psf
100 ft. (30.5m) of regolith to balance pressure load

* High Radiation;

Radiation shielding required
15 ft. (4.5m) regolith (or more?)
Regolith excavation
* Poor Soil Conditions for Anchoring Foundations;
   Regolith depth > 16ft (5m) most locations
   Tension anchors difficult
   "floating" structures

* Very Remote Site;
   Setup & resupply expensive
   Indigenous materials permit rapid expansion
   Safety
   Speed & Simplicity

Secondary Factors:
   Meteoroids (impact damage)
   Low Gravity (construction)
   Long Days and Nights (construction)
   Extreme Temperatures (sealants)
4. Review of Previously Proposed Concepts:


![Diagram of pressurized self-supporting membrane structure (PSSMS)](image)

**FIG. 1.** Pressurized Self-Supporting Membrane Structure (PSSMS)

**FIG. 3.** Wall Construction and Latticed Web Details
Vanderbilt, M.D., Criswell, M.E., Sadeh, W.T.; C.S.U.; 1988

Figure 2. Cutaway and Section of Structure

Figure 3. Arched Membrane System

Figure 4. Cross Section of Arch Rib

Figure 5. Arch Rib System with Web
Figure 1. - Elevation

Figure 2. - Typical Framing Plan
5. **Rationale for Indigenous Materials:**

* Large structures need large quantities of materials

* Permits rapid growth and expansion of activities;
  
  Reduces shipping costs

  Reduces time

* Ship high tech equipment not structural mass

6. **Indigenous Material Choices:**

* Fused and Sintered Regolith, Bricks and Blocks;
  
  Easy to manufacture
  
  Low strength, highly heterogenous material properties

* Lunar Glasses and Glass-Glass Composites;
  
  High strength

  Very promising still experimental

* Lunar Concrete;
  
  Raw materials for aggregate and cement available

  Mechanical properties well understood

* Steel and other Structural Metals;
  
  Excellent mechanical properties

  Complicated, multi-step manufacturing process
* Cast Basalt;
  
  One step manufacturing process
  
  Good mechanical strength properties
  
  Selected as primary construction material
  
7. **Cast Basalt Properties:**

  Tensile strength: \( f_t = 34.5 \text{ MPa} \) (5,000 psi);

  Compressive strength: \( f_c = 538 \text{ MPa} \) (78,000 psi);

  Modulus of elasticity: \( E = 100 \text{ GPa} \) (14E6 psi);

  Fracture toughness: \( K_c = 2 \text{ MPa}\sqrt{\text{m}} \), +/- 50%

  Mass density: \( 3 \text{ g/cm}^3 \) (specific lunar weight = 31.2 lunar lb/ft³).

  Melting point: \( 1300^\circ\text{C} \)
8. Design Variables:

* Shelter sizing;
  
  large enough to contain Space Station Freedom modules

* Loading conditions;
  
  Internal pressure=10 psi (0.069 MPa)
  
  Regolith shielding depth= 15 ft (4.5m)

* Constraints imposed by cast basalt;
  
  Brittle:
    
    Low tensile stresses
    
    Compression should dominate structure
    
    Post-tensioning
  
  Material hardness
  
  Maximum volume of single component= 70.6 ft$^3$ (2 m$^3$)
  
  Determined by casting process

* Maximum moveable weight= 1,670 lunar lbs (44.5 kN)

* Minimize use of imported materials;
  
  Minimize tensile reinforcement

* Self-equilibrating structure;
  
  Tensile loads self-contained
  
  No arches, vaults, or domes

* Minimize excavation
9. **Design One, Cylindrical Segments:**

**Dimensions:**
- Diameter = 23 ft (7m)
- Wall thickness = 3 in. (7.6 cm)
- Total length = 60 ft (18.3m), forty segments
- Segment length = 1.5 ft. (46 cm)
- Floor thickness = 8 in. (20 cm)
- Leg width = 15 in. (38 cm)
- Segment mass ≈ 2200 lunar lbs (6000 kg)

**Design Features:**
*Positive;*
- Pre-cast floor
  - Passage for utilities
- Rapid assembly
- Readily expandable
- Only three components
- Minimal use of reinforcing
- Efficient

*Negative;*
- Feasibility of casting basalt into large structural elements
  - a.) under lunar conditions
  - b.) mold design
- Uncertain crack and notch sensitivity of cast basalt
Construction Sequence:

1. Cast 40 segments, 2 end caps
2. Smooth site, area = 33 x 60 ft (10 x 18m)
   or excavate a flat-bottomed trench, depth = 6.5 ft. (2m)
3. Place two long guide-rail beams
   a.) cast in segments
   b.) cast in place
4. Align rail sections and bolted together
5. Place first cylindrical segment
   a.) Insert eight tendons into ducts
   b.) Install the gasket material
6. Place following segment on rails
   a.) advance tendons through the current segment
   b.) repeat steps 5 & 6 until the last segment is in place
7. Install end caps
8. Post-tension tendons to pull entire structure tightly together
9. Pressurize structure
10. Bury the structure
11. Fit out interior with partitions and utilities
Step One

Step Two

Step Three

Assembled Base

18m (60')
10. **Design Two, Arch-Slabs with Post-Tensioned Ring Girders**

**Dimensions:**

* Overall Dimensions;
  
  Height= 18 ft (5.5m), Width = 23 ft (18m)
  
  Length= 60 ft.(18m)

*Slab Dimensions;

  Span= 76 in (193 cm),  
  Edge thickness= 10 in (25 cm)
  
  Center thickness= 3 in (7.6 cm)

*Girder Dimensions;

  Span= 25 ft (7.6m),  
  Width= 7 in (17.8 cm)
  
  Center depth= 36 in (91.5 cm),  
  End depths= 12 in (30.5 cm)

**Design Features:**

*Positive;

  Compression dominated
  
  Inherently safe design
  
  Crack growth limited
  
  Components utilize simpler molds
  
  Orthogonal expansion
  
  All surfaces flat

*Negative;

  Greater number of cast pieces
  
  More complicated construction sequence
  
  Much more reinforcement material needed
Archslabs With Post-Tensioned Ring Girders

End View

Side View
Construction Sequence:

1. Cast; 36 arch-slabs, 40 girders, 2 end caps
2. Level site
3. Place first 2 floor girders
   a.) lay tendons beneath,
   b.) set slab between them
   c.) repeat nine times
4. Place end cap in position and brace
5. Install 2 opposing wall slabs,
   a.) set ceiling slab on top
6. Install first complete ring girder set
   a.) wrap tendons around girder set
   b.) post-tension first two tendons
7. Repeat steps (5.) and (6.) nine times
8. Install final end cap
9. Install and post-tension longitudinal tendons
10. Pressurize
11. Bury
12. Fit out interior
Construc\textsuperscript{t}ion Sequence

Steps 1 to 3

Steps 4 to 6

Step 7 (etc.)
11. **Future Research:**

* Mechanical properties of cast basalt;
  
  a.) fracture toughness & notch sensitivity
  
  b.) distribution of tensile strength values

* Feasibility of casting basalt into large structural elements

* Gasket material and design

* Additional design(s) under consideration;
  
  a.) evaluate three designs
  
  b.) select one for detailed design and testing

* Develop FE predictive model for full stress analysis of final concept

* Build and test 1/6 scale model in laboratory utilizing cast basalt or simulant materials

12. **Conclusions:**

  1.) Cast basalt selected
  
  2.) Several designs are feasible
  
  3.) Additional research needed
INVERTED COMPRESSION ARCH

REGOLITH BACKFILL

Space Station Freedom Module Cross Section