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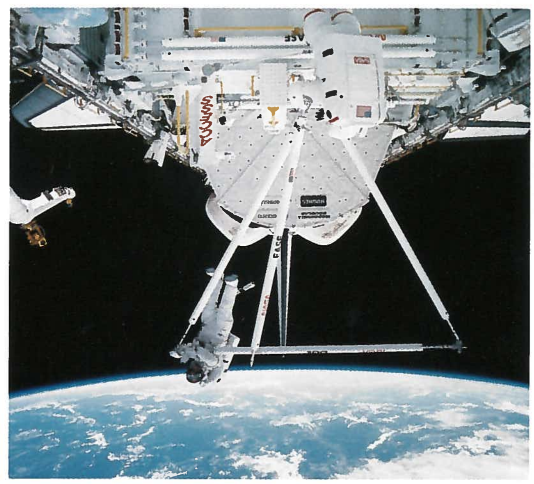
Special Information Topic Issue

SICSA OUTREACH
Sasakawa International Center for Space Architecture

Astrotectonics: Construction Requirements and Methods in Space

Astrotectonics is the science of constructing space structures and facilities for use in orbit, on manned voyages beyond Earth's magnetosphere, and to create lunar/planetary habitats. Current construction methods are limited to prefabricated systems including modules and other elements which are, at most, assembled together in space. The planned *Space Station Freedom* is an example. Future structures may be partially or totally created in space using materials obtained from extraterrestrial sources. This approach can potentially be most cost-effective for creating large complexes and structures such as lunar settlements and expansive solar power satellite platforms. Launch costs to lift all of the components out of Earth's strong gravity well might otherwise be prohibitive.

Realization of ambitious U.S. goals articulated by the National Commission on Space for the next 50 years will demand a rapid evolution of space construction technologies. Active programs are needed to develop and test new materials and production processes, component forming methods, and handling and assembly techniques to accommodate demanding space mission requirements and constraints. Advantages and limitations of alternative methods must be compared in terms of the amount of labor and equipment needed, durability in the space environment, process and product reliability, and versatility to accommodate changing and expanding applications.



New Construction in Space
NASA Photo

Construction Approaches

- *Prefabricated modules to reduce space construction labor time, costs and risks.*
- *Erectable and deployable frames designed for simple/automated assembly.*
- *Membrane structures for habitable and unpressurized enclosures.*
- *Structures using in situ materials for lunar/planetary base constuction.*

STAR★NET STRUCTURES INC.
106 Bell Street, West Babylon, New York 11704
SICSA is grateful to Wendel Wendel of STAR*NET for donating the funds to publish this issue.

Environmental Considerations

Natural conditions in free space and on lunar/planetary surfaces impose facility design and construction requirements that differ from those on Earth in many important aspects. Some special circumstances in space support economies in the ways that materials can be utilized and also facilitate certain assembly processes. Others impose additional requirements and difficulties.

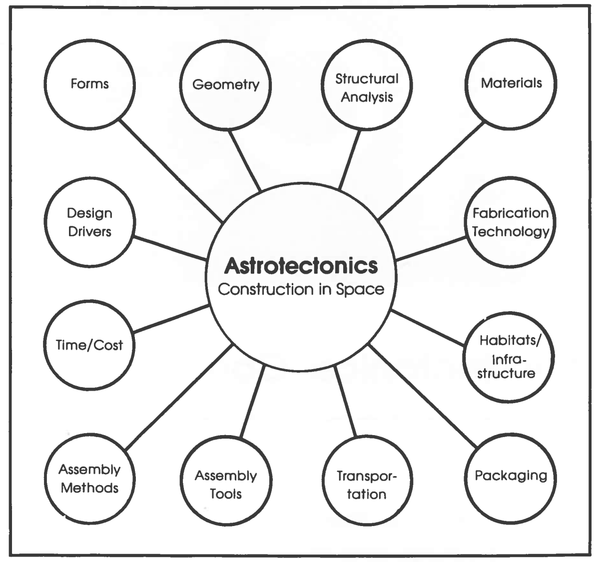
Structural Loads

Most structures, whether planned to operate in orbits, travel between orbits, or reside on surfaces of celestial bodies, are subject to force loads. Predominant forces on Earth are produced by gravity and winds. Earthquakes and other natural or man-made phenomena can also produce shear stresses, vibration damage and impact loads that affect certain locales and structural applications.

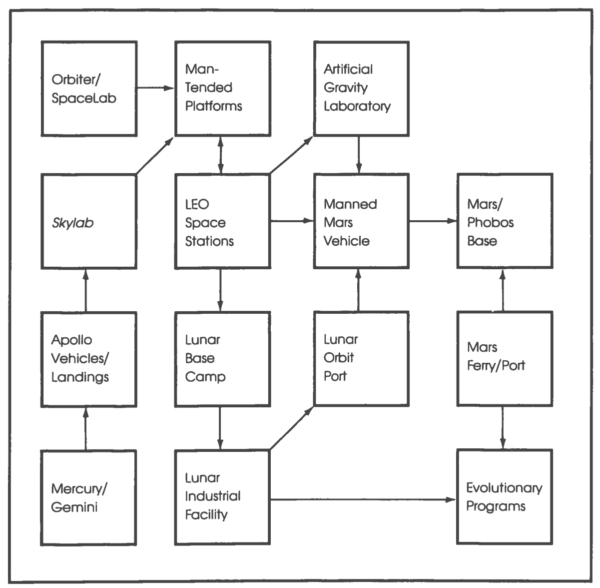
Major dynamic forces on present day space structures (such as satellites) are limited to short periods of rapid velocity changes enroute to destinations. Lateral and axial loads during Earth launch stages, for example, can be quite severe.[1] Engine vibrations transmitted through the launch vehicles can also add significantly to the dynamic load effects on structures.[2]

Some future space structures may be exposed to continuous load forces equal to a fraction of Earth's gravity. These include orbiting laboratories that rotate to create artificial gravity for life science experiments, and habitats located in 1/6 and 1/3 Earth gravity environments of the Moon and Mars.

All habitable structures in the hard vacuum of space must be capable of containing internal pressure loads of 0.6 to 1.0 atmosphere without leaking. They must also resist dynamic loads imparted by crew activities, impacts during docking operations, and stresses caused by component motions. Such motions include expansion and contraction due to exposure to extreme thermal changes.



Space Construction Considerations
Wendel Wendel, Star*Net Structures



Example Space Structure Evolution Scenario
Larry Bell, SICSA

1 *Quasi-static launch thrust and staging loads.*
Source: Agriwal. 1986. Design of Geosynchronous Spacecraft. *Prentice Hall.*

	Lateral	*Axial*
Shuttle	*5.1 g*	*3.3 g*
Ariane	*2.0 g*	*7.9 g*

2 *Structural dynamic load from engine vibration transmitted through vehicle.*
Source: Ibid.

Shuttle	*5-35 hz*	*.075 g*
Ariane (avg.)	*5-7 hz*	*7.7 mm*
	7-15 hz	*1.5 g*
	15-100 hz	*1.0 g*

Structural Loads
- *Design, secure and orient elements to avoid damage during accelerations.*
- *Insulate and design structures to minimize transfer/damage from engine vibrations.*
- *Provide adequate skin thickness/strength to accommodate internal pressures.*
- *Select/insulate materials to resist heat deterioration and mechanical fatigue.*

Radiation and Contamination
- *Select materials/thickness to minimize ionizing space radiation effects.*
- *Provide radiation shelters to protect crews during major solar flare events.*
- *Use surface materials that resist etching effects of atomic oxygen in LEO.*

Space Debris
- *Provide a double-layered outer hull or bumper to reduce penetration risks.*
- *Provide structural redundancy and means to repair critical penetration damage.*

Important Design Concerns and Strategies

Meteoroid Impacts

Mass of Meteroid	Time Between Impacts on One Square Yard Surface
One-millionth gram*	116 days
One-thousandth gram	63 years
One gram	3,200,000 years
Ten grams	320,000,000 years

*About 30 grams/ounce

Meteoroid Penetrations

Thickness of Aluminum Skin	Frequency of Penetration
0.015 inch	10 per day
0.2 inch	1 per year
2.75 inches	1 per 10,000 years

Meteoroid Impact/Penetration Risks in LEO
Damon, Thomas. 1989. *Introduction to Space.*
Orbit Book Company, Inc.; Malabar, FL

3 *More space radiation information will be provided in the next* SICSA Outreach *"Space Radiation Health Hazards" (July-Sep. 1989).*

4 *These effects are most severe in the direction of spacecraft travel due to the high flux caused by orbital velocity/collision energy.*

5 *Using a double-layered spacecraft hull increases protection from the small, most prevalent meteoroids significantly, shattering the particles before they reach the inner pressure skin.*

Environmental Influences

Exterior materials used in structures on Earth are exposed to weathering effects of seasonal and regional temperatures; rain, snow and trapped ice crystals; wind-driven sand abrasion; and other climate-related conditions. While we may not ordinarily think of weather in space, the effects of environmental influences upon material selection and design are profound.

Structures outside our planet's shielding atmosphere and magnetic field lack protection from high solar thermal loads and radiation levels. Surface areas that are shielded or directed away from the Sun, on the other hand, are subjected to very cold temperatures. They are denied the convectional warming benefits afforded by the Earth's surface and surrounding air masses. Spacecraft that maneuver in a manner that alternately expose areas towards and away from the Sun must be designed to accommodate large thermal changes and to resist structural fatigue induced by expansion-contraction cycles.

Radiation environments in space can kill living organisms, incapacitate electronic systems, and degrade structural materials. Natural sources include colossal energy-releasing events on the surface of the Sun, and explosions of other stars which have occurred throughout the long history of our galaxy. Damage is caused when the high-energy electromagnetic waves and particles strike and ionize critical numbers of constituent atoms required for vital performance functions. Secondary particle emissions released from these events compound the effects.[3]

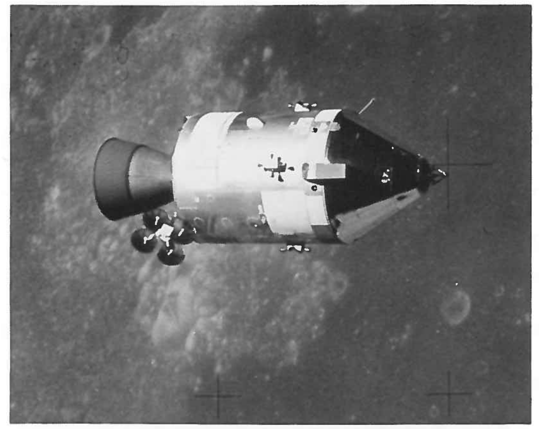
The "vacuum" of space is also populated by other particles of widely ranging size and destructive potential. Spacecraft operating in low-Earth orbit (LEO) encounter sufficient numbers of free oxygen atoms to cause extensive surface material oxidation.[4] In LEO, higher orbits, and on the Moon, meteoroid strikes pose threats.[5] Orbital man-made space debris such as exploded rocket fragments are becoming an even greater concern as these populations increase.

Prefabricated Modules

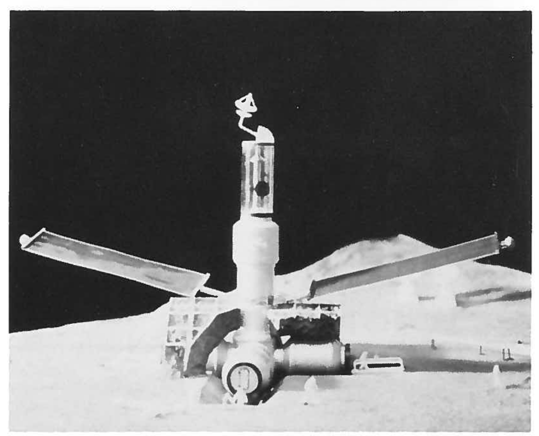
All habitable space structures are fundamentally designed as pressure vessels which incorporate atmosphere supply and control systems essential for life, safety and comfort. The most conventional and proven approach for creating these artificial environments is to build the vessels on Earth with utilities and safety-critical equipment fully integrated and checked out prior to launch. Objectives are to minimize expensive in-orbit labor time and equipment requirements, to ensure proper operation of all systems prior to launch, and to realize earliest possible crew occupancy and benefits.

Space habitat module size, shape and construction is influenced by a number of factors. Allowable geometries, volumes and weights must conform with launch system constraints and possible freeflight requirements. The small, truncated cone-shaped crew capsules used in Project Mercury and Gemini missions, and the somewhat larger "gumdrop" shape of the Apollo Command Module, were designed to minimize payload mass and to optimize Earth atmosphere reentry characteristics. These sleek and rugged spacecraft were built to withstand very large deceleration shock waves and temperatures which reached 5,000° F. A protective shield at the large end of the modules took the brunt of the impact force and much of the heat.

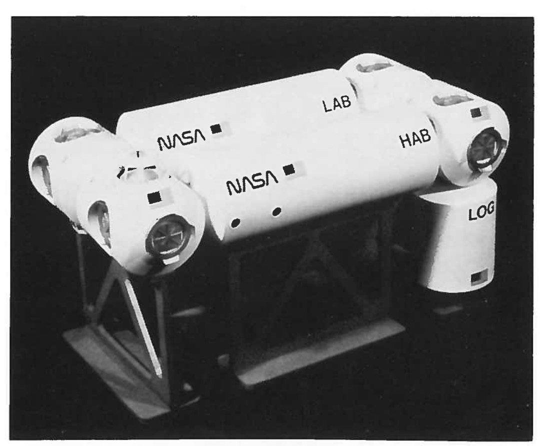
Space station module design places a priority upon spacious and useful interior volumes. Walls of pressure hulls need only be strong enough to contain pressurization forces, resist relatively gentle acceleration and vehicle docking loads, and provide reasonable protection from space debris penetrations. Simple cylindrical geometries are usually favored because they conform with launch payload standards while also enabling flexible internal layouts of living and work accommodations. Alternative vessel shapes for special purposes include spheres and toroids. Large flat surfaces that will "oil can" outward under inflation pressure should be avoided.



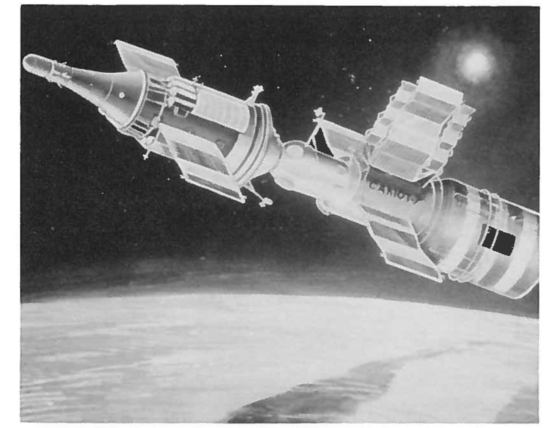
Apollo Command Module
NASA Photo



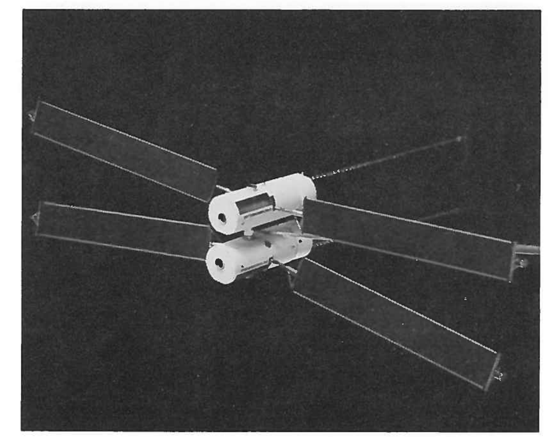
Lunar Base Concept (Cruciform)
SICSA Design



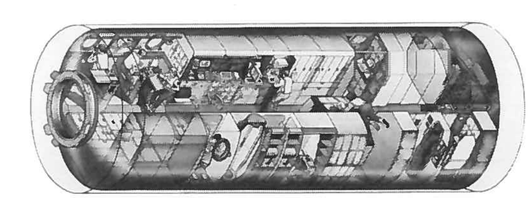
Model of *S.S. Freedom* (Closed-Loop)
Photo Courtesy of Bell & Trotti, Inc.



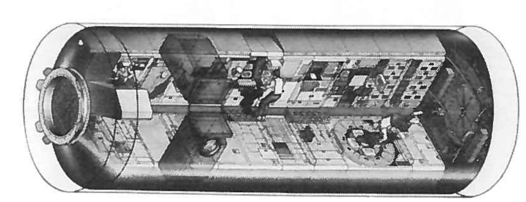
Soviet *Salyut 7* Space Station (Stacked)
Soviet Photo Courtesy of Jim Oberg



Man-Tended Free Flyer Space Platform (Raft)
Photo Courtesy of Space Industries, Inc.



Habitation Module



Laboratory Module

S.S. Freedom Module Interior Configurations
Illustrations by Li Hua for Boeing

Module Applications and Types

Prefabricated modules in various forms are likely to comprise primary building blocks for all types of manned space complexes for many decades to come. Examples can include Earth and lunar-orbiting space stations, manned Mars transportation vehicles and lunar bases. Representative module types potentially include living quarters, laboratories, airlocks and transfer tunnels, and attached or detached command stations. Standardization of connector systems and utility pass-throughs enables these elements to be combined, configured and added in a versatile and appropriate manner for each application.

Multi-Module Configurations

Multi-module space complexes can be organized in a variety of geometric patterns. Basic configuration options include "stacked", "cruciform", "raft" and "closed-loop" layouts. Selection of the best scheme for a given application must take the special requirements of each assembly phase into account. For example, space station and man-tended platform planning must consider ways that changes in overall mass distribution will influence orbital flight dynamics each time a module is added. Maximizing useful volume while minimizing space transportation and assembly costs are always important goals.

Module Interior Configurations

Interiors of cylindrical modules can be divided longitudinally (in a "banana split" fashion), cut into transverse segments (in a "bologna slice" configuration), or laid out in a manner which combines these two approaches. A longitudinal division creates the largest uninterrupted volumes, enabling two levels to share a common floor under zero gravity conditions.

Transverse layouts create multilevel, circular spaces. Smaller floor areas with short viewing vistas produced by this approach limit applications to vessels with relatively large cross sections. The 22 foot diameter *Skylab* was an example.

Erectable and Deployable Frames

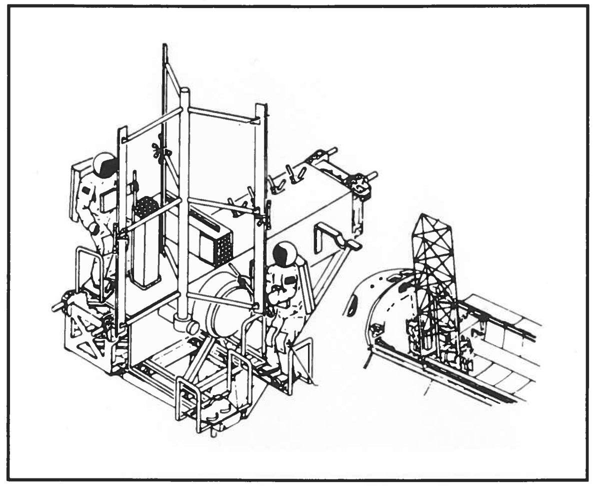
Lightweight metal or synthetic beams, trusses and platforms offer launch-efficient means to build large structures in orbit and on lunar/planetary surfaces. Representative applications include major space station infrastructure keel and mast elements, expansive frameworks for proposed solar space satellites to beam power to Earth, and antenna systems of diverse forms and sizes.

Technologies currently exist to erect or deploy frame structures in a variety of ways. Some systems are comprised of individual tubular members and connector nodes that are assembled in "tinker toy" fashion by spacesuited astronauts, or attached together using teleoperated devices. Other are preassembled with hinged joints, compactly folded during launch and unfurled in completed forms when released. Possible future methods might apply automatic fabrication processes in space using "beam builders" that form, position and weld metal strips into rigid truss structures. This procedure would take advantage of manufacturing processes which are presently used in industry.

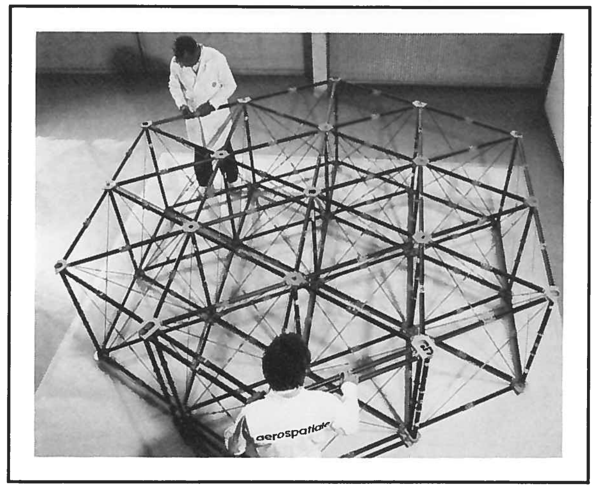
One of the first U.S. space assembly experiments was the **Assembly Concept for Construction of Erectable Space Structure (ACCESS)** which was demonstrated on the Shuttle during November and December 1985. The success of this manned operation influenced NASA's decision to use erectable structures for *Space Station Freedom's* primary framework.

During recent years more emphasis is being directed to telerobotic and automated assembly methods that reduce extravehicular activity (EVA) time and risks. In its laboratories at the NASA Langley Research Center in Hampton, Virginia, NASA is exploring a wide range of off-the-shelf industrial manipulators and testing their usefulness for space construction. The ultimate goal of these activities is to eventually automate all assembly processes, elevating man in teleoperator role to a high-level supervisory position. Results to date with simple trusses are encouraging.

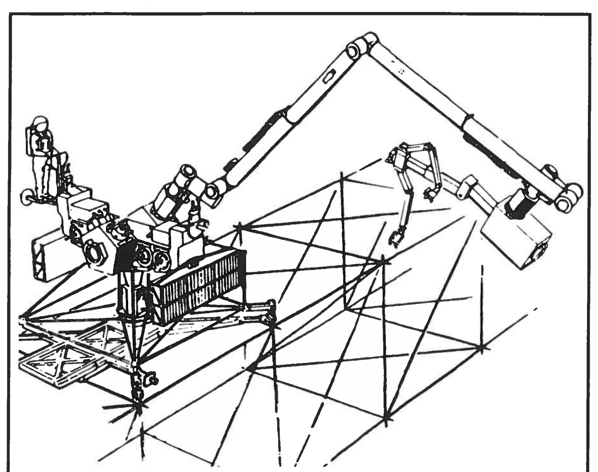
* In *Engineering, Construction and Operations in Space: Proceedings of Space 88.* ASCE, New York, NY.



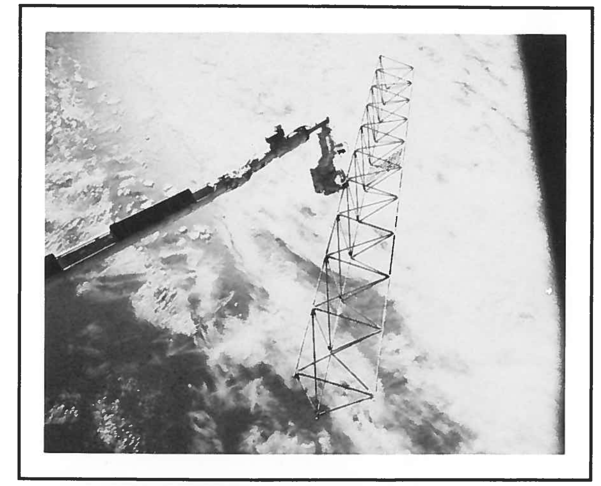
Two Person ACCESS Construction Operation
Heard, W.L. et al. 1988, "Space Truss Construction Studies." *



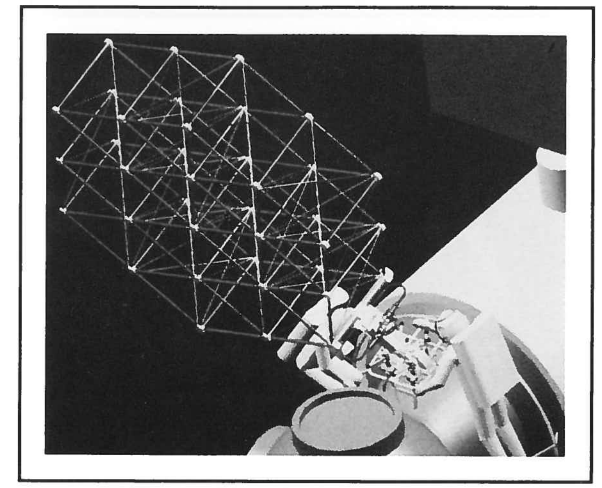
ERA Unfurlable Structure Being Checked
Aerospatiale Photo



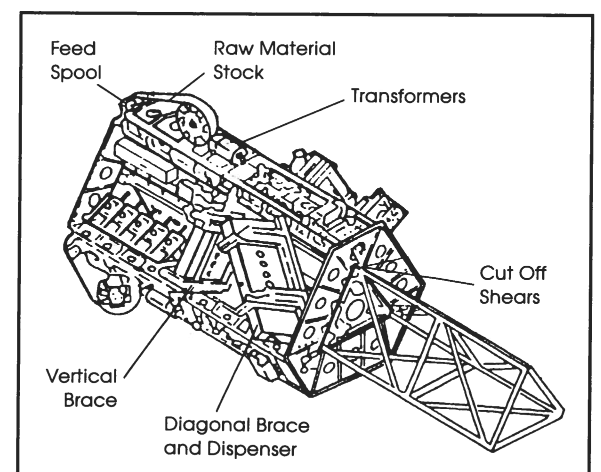
Telerobotic Assembly and Servicing
Adkisson, R.W. 1988. "The Role of a Mobile Transporter in Large Space Structures Assembly and Maintenance." *



Astronaut Working on ACCESS from RMS Arm
NASA Photo



ERA Unfurlable Structure Deployed
Aerospatiale Photo



Automated Beam Builder Concept
Sanger, G.F. 1988. "Robotic Influence in the Conceptual Design of Mechanical Systems in Space and Vice Versa: A Survey."*

Erectable ACCESS System Demonstration

ACCESS was designed to demonstrate the capability of astronauts to perform on-orbit construction tasks reliably and efficiently using current EVA technology. During one experiment, two astronauts worked from foot restraints attached to a special support structure in the Orbiter payload bay to assemble an erectable 45 ft. long truss with 4.5 ft. bays. In another experiment, one astronaut worked from a foot restraint attached to the end of the Remote Manipulator System (RMS) arm to evaluate its use for assisting limited EVA construction and maintenance tasks. All planned operations were accomplished.

Deployable ERA System Demonstration

A "large unfurlable structure" (deployed size about 12.5 ft. x 11.8 ft. x 3.3 ft.) developed by Aerospatiale for the French space agency CNES, was deployed by a French astronaut aboard the Soviet space station *Mir* in late 1988. The experiment, called **ERA,** is made up of 1.18 inch diameter carbon fiber tubes linked together by light alloy joints forming 24 prismatic-shaped sections. The assembly contains more than 5,000 parts, including more than 1,300 bearings. Undeployed, the structure forms a bundle about 1 ft. in diameter and 2 ft. high. Deployment takes 2.5 seconds after a thermal knife cuts a Kevlar cable which restrains the bundle in its folded state.

Automated Beam Fabrication

Fully automated manufacturing processes might eventually transfer existing terrestrial technology to the space environment. Proposed beam builders, for example, would transform metal strips contained on spools to triangular beam sections complete with struts and ties. The vertical and diagonal braces would pass through internal rolling mills, be positioned and cut to length, and then welded in place. While necessary equipment to accomplish this operation might be complex and bulky, the process could be valuable to create structures using extraterrestrial materials obtained from the Moon, Mars or asteroids.

* In *Engineering, Construction and Operations in Space: Proceedings of Space 88.* ASCE, New York, NY.

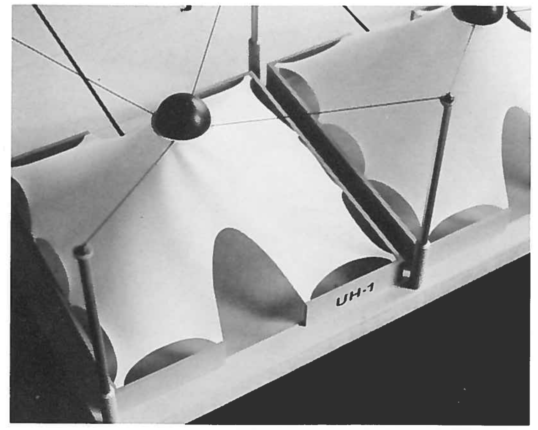
Membrane Structures

Stretched fabric and inflated bladder structures offer clear advantages to create large, easily deployed protective screens or enclosures which are highly compactible for launch. Examples of uses can include shields for protection from natural and man-made debris, sun shades for thermal and lighting control, large trash management containers, airlocks and transfer tunnels, and pressurized habitats for people or plants.

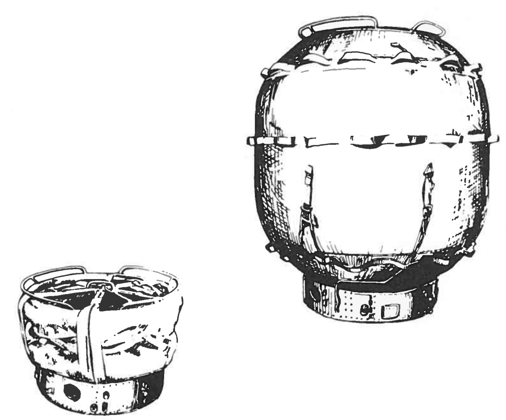
Possibilities for practical, beneficial membrane applications in space are being enhanced by continuing advancements in nonmetallic material technology. Some of these materials, such as Kevlar 29 used for bulletproof vests, are stronger than stainless steel and comparable in weight to nylon and Dacron. Others can withstand very high temperatures. Nicalon®, a silicone carbide fiber produced by the Nippon Carbon Co., Ltd. of Japan remains flexible at temperatures up to 3,000°F. Nextel®, a ceramic fiber manufactured by the 3M Corporation, becomes rigid at temperatures in the 2,500-3,000°F range.

The Goodyear Aerospace Corporation (GAC), now part of the Loral Systems Group, developed and demonstrated a variety of innovative flexible composite material applications for space throughout the 1960s and '70s. Many of these contributions, along with other design concepts by SICSA, were presented in the May-June 1988 issue of *SICSA Outreach* titled "Inflatable Space Structures".

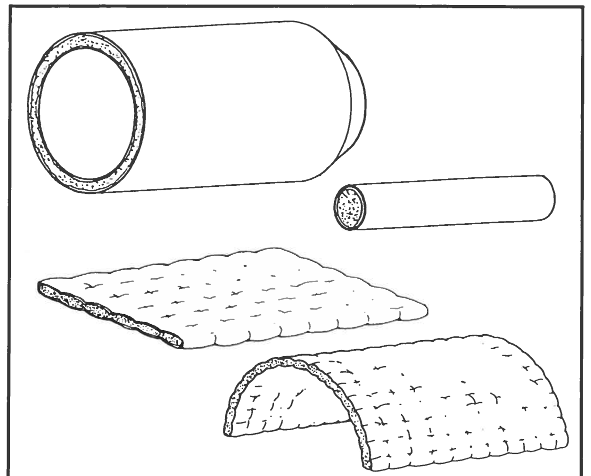
GAC conducted comprehensive tests of different combinations of materials that were then available, proving that composite wall systems could meet stringent NASA flammability and offgassing limitation standards. Working prototypes also demonstrated impressive leak resistance under pressurization, repackability, thermal performance and structural characteristics. Some of GAC's structures, including a 5,000 cubic foot module, offered a 12:1 deployed to packaged volume ratio and endured repeated inflation-compaction cycles with low leak rates.



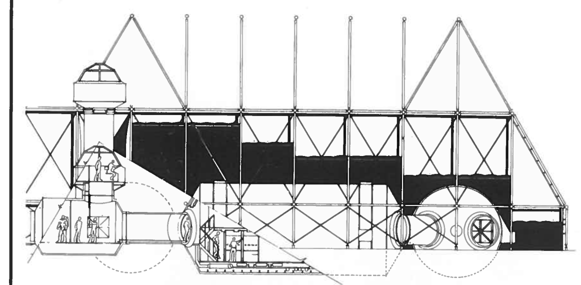
Lunar Base Membrane Structures
Photo Courtesy of Bell & Trotti, Inc.



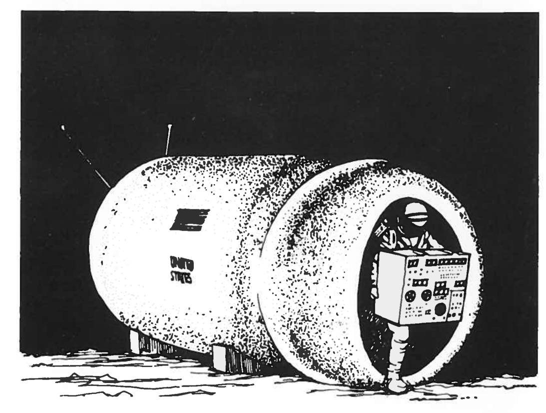
GAC Inflatable Airlock
Goodyear Aerospace Corp., Drawn by Li Hua



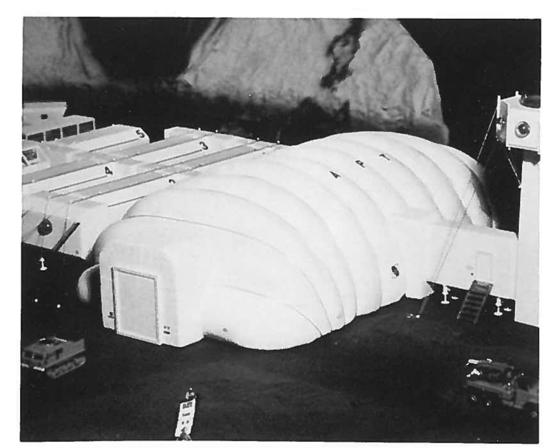
Foam-Rigidized Tubes/Bladders
Goodyear Aerospace Corp., Drawn by Li Hua



Thermal Protection Concept for a Lunar Base
SICSA Concept Drawn by Eval Akhidime



GAC Inflatable Lunar Shelter
Goodyear Aerospace Corp., Drawn by Li Hua



Foam-Rigidized Inflatable Shelter Concept
SICSA Photo

Tents and Screens

Fabric structures can help shield people and equipment in exposed space environments from extreme day-night thermal cycles, solar glare, and abrasive, sometimes hazardous debris particles. One orbital application could be a tent-like enclosure serving as an unpressurized hangar and maintenance facility for Orbital Transfer Vehicles (OTVs). Lunar or Mars surface applications might include screens and canopies to protect vulnerable areas from rocks ejected during landing and launch operations. They can also be used to protect supply and equipment storage areas from heat, micrometeoroids and dust.

Laminated Bladder Systems

Multi-layered inflatable membranes have been used by the U.S. to create a Shuttle-Spacelab transfer tunnel, and by the U.S.S.R. to produce a *Vostok 2* spacecraft airlock. In addition to creating and testing systems for both of these types of purposes, GAC also applied composite wall technologies to produce a 7 ft. diameter, 15 ft. long lunar shelter and larger pressurized habitats. This laminated construction typically embodies an outer thermal protection coating, a micrometeoroid barrier, a pressure bladder, and an inner flame/gas barrier. The resulting flexible but semi-stiff structures can be folded in an "accordian" or necked-down "toothpaste tube" fashion.

Resin Foam-Rigidized Structures

It is theoretically possible to develop structures that remain rigid after the inflation gases are gone. This may be a desirable approach, for example, to create hangars requiring large openings to accommodate vehicles, and which are impractical to pressurize. Rigidization can be accomplished by impregnating a flexible mesh core inside the bladder wall with a plastic resin foam that is activated to expand and harden under space vacuum conditions. Another method would be to pump the foam into a double bladder wall cavity following inflation. In either case, the foam can provide added protection against micrometeoroids and other debris.

Structures Using In-Situ Materials

The economic feasibility of creating and supporting future settlements on the Moon or other planetary bodies will demand effective use of extraterrestrial resources to offset enormous transportation costs. Some of these materials, including volatiles such as oxygen for cryogenic rocket fuel, may be exported to power vehicles and support crews on even more distant interplanetary voyages. Metals and other materials obtained from the Moon or asteroids may be used in the construction of some of those or supporting spacecraft.

While the establishment of early phases of a lunar base camp would very certainly depend upon habitats brought from Earth, it is reasonable to expect that evolutionary industrialization stages might make increasing use of in-situ resources for site development and facility expansion. Samples obtained from nine Apollo landing sites and information revealed by remote sensing observations indicate that the Moon contains abundant construction materials. The dark mare plains have basalts that are rich in iron, magnesium and often, titanium. Highly-cratered highland areas contain substantial quantities of aluminum and calcium-rich rocks.

Bulk lunar soil (regolith) and its major mineral fractions can be heated and molded to form a variety of structural building elements and systems. Slow cooling of the material can cause crystallization in the form of cast basalt. Rapid cooling can produce glass, which under the anhydrous conditions of the Moon is mechanically and physically superior to many metals. These melts can be extruded through fine dies to make glass fiber cloth, glass wool and multi-stranded cables for diverse purposes.

Anthrosite materials found at Apollo sites appear to be a good source of calcium oxides (19% by weight) to produce lunar cement. Aggregates made from lunar rocks, locally-produced oxygen, and hydrogen from Earth, could provide necessary ingredients for creating concrete.

* In *Lunar Bases & Space Activities of the 21st Century.* Lunar & Planetary Institute, Houston, TX.

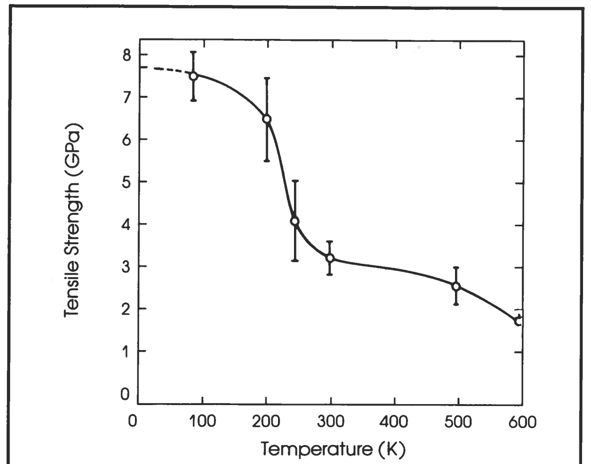
Physical Properties

Compressive Strength	4000-5000 kg/cm^2
Tensile Strength	250-350 kg/cm^2
Bending Strength	400-450 kg/cm^2
Hardness	8-9 MOH's

Thermal Properties

Thermal Expansion	78x10^{-7} cm/cm/°C
Thermal Conductivity	0.8-0.9 cal/m^2/mhr°C
Specific Heat	0.2 cal/gm/°C

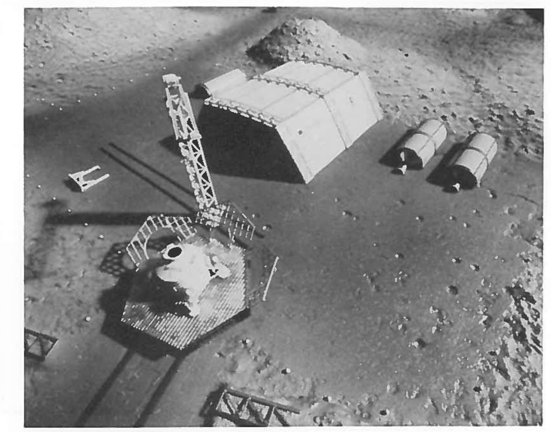
Properties of Cast Basalt
Design of a Lunar Colony. NASA Grant NGT 44-005-114



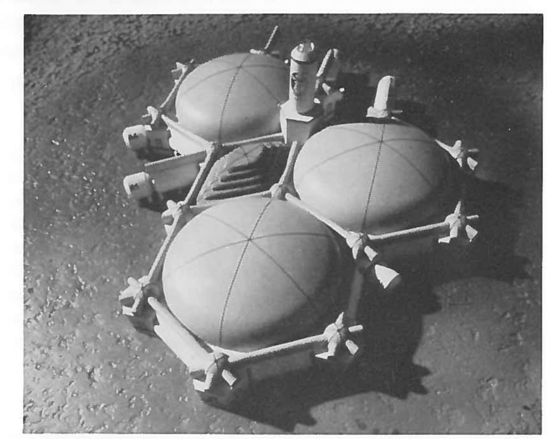
Strength of Glass in Lunar-Like Conditions
Ernsberger, F.M. 1969. Phys. Chem. Glasses, 10, 240-245. Cited in Blacic, J. 1985. "Mech. Properties of Lunar Materials...."*

	Lunar Highlands Soils (%)	Lunar Low Titanium Mare Soils (%)	Lunar High Titanium Mare Soils (%)
SiO_2	45.0	46.4	42.0
TiO_2	0.5	2.7	7.5
Al_2O_3	27.2	13.5	13.9
FeO	5.2	15.5	15.7
MgO	5.7	9.7	7.9
CaO	15.7	10.5	12.0
Total	99.3	98.3	99.0

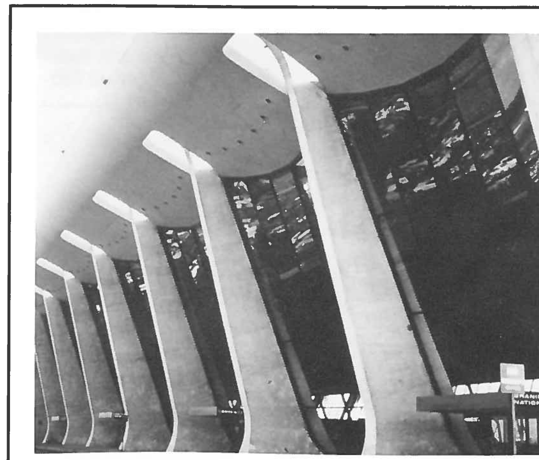
Major Element Composition of Lunar Soil
Allton, J.H., et al. 1985. "Guide to Using Lunar Soil and Simulants For Experimentation." *



Sintered Roads and Building Areas
SICSA Lunar Base Concept- Photo by Jim Olive



Potential Glass Fiber Use in Inflatable Domes
SICSA Lunar Base Concept- Photo by Jim Olive



Concrete Columns and Roof
Dulles International Airport by E. Saarinen.

Sintered and Cast Basalt Components

Basalt, a hard dense volcanic rock abundantly present in lunar regolith, can be transformed into a variety of useful building components by sintering or casting. Sintering, which increases particle adhesion by moderate heating, can create paved surfaces to provide launch pads and roadbeds using simple microwave equipment. Casting, which involves melting the material and pouring it into molds, can produce tiles, blocks, bricks, pipes and other building components. Construction applications might include building foundations, equipment shelters, regolith retaining walls and storage vaults for volatile materials.

Glass Building Products

Glass materials on Earth are strongly degraded by the presence of water in the atmosphere. The anhydrous environment on the Moon can enable the creation of far superior glass materials for versatile construction applications.

Lunar glass might be cast to form solid beams and plates, serving functions usually associated with metal structures. Glass cords and stranded cables might be used for internal reinforcement of lunar concrete elements. Glass fibers and cloths might be impregnated with resins to create pressure-tight inflatable habitats for lunar agriculture and other purposes.

Concrete Structures

Lunar-derived concrete offers interesting possibilities for construction of individual building elements and complete structures. Versatility of cast shapes matches benefits afforded by basalt melt products without requiring comparable power for heating.

An offsetting disadvantage of lunar concrete is the need for precious water in the mixing process. This requirement might be reduced by adding carbon dioxide waste produced by humans as a supplementary reactant. Techniques might also be implemented to collect and recycle water released during the drying period.

SICSA Background

SICSA is a nonprofit research, design and education entity of the University of Houston College of Architecture. The organization's purpose is to undertake programs which promote international responses to space exploration and development opportunities. Important goals are to advance peaceful and beneficial uses of space and space technology and to prepare professional designers for challenges posed by these developments. SICSA also works to explore ways to transfer space technology for Earth applications.

SICSA provides teaching, technical and financial support to the **Experimental Architecture** graduate program within the College of Architecture. The program emphasizes research and design studies directed to habitats where severe environmental conditions and/or critical limitations upon labor, materials and capital resources pose special problems. Graduate students pursue studies which lead to a Master of Architecture degree.

SICSA Outreach highlights key space developments and programs involving our organization, our nation, our planet and our Solar System. The publication is provided free of charge as a public service to readers throughout the world. Inquiries about SICSA and Experimental Architecture programs, or articles in this or other issues of *SICSA Outreach*, should be sent to Professor Larry Bell, Director.

Dr. Alan Binder and Larry Toups of Lockheed

Special thanks is extended to Dr. Alan Binder and UH Experimental Architecture alumnus Larry Toups for their ongoing technical contributions to SICSA including valuable inputs to this report. Both are with the Advanced Programs Department at the Lockheed Engineering and Management Services Company, Houston.

Readers seeking additional information about a broad range of space construction topics are urged to include two books in their survey of references. *Engineering, Construction, and Operations in Space*; edited by S. Johnson and W. Wetzel (1988) presents the proceedings of "Space '88", a conference sponsored by the Aerospace Division, American Society of Civil Engineering. *Lunar Bases & Space Activities of the 21st Century*, ed. W. Mendell presents papers from a NASA sponsored symposium hosted by the Lunar & Planetary Institute in 1985.

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