PART I: SPACE STRUCTURES AND SUPPORT SYSTEMS

LARRY BELL, SASAKAWA INTERNATIONAL CENTER FOR SPACE ARCHITECTURE (SICSA)
GERALD D.HINES COLLEGE OF ARCHITECTURE, UNIVERSITY OF HOUSTON, HOUSTON, TX

www.sicsa.uh.edu
The Sasakawa International Center for Space Architecture (SICSA), an organization attached to the University of Houston’s Gerald D. Hines College of Architecture, offers advanced courses that address a broad range of space systems research and design topics. In 2003 SICSA and the college initiated Earth’s first MS-Space Architecture degree program, an interdisciplinary 30 credit hour curriculum that is open to participants from many fields. Some students attend part-time while holding professional employment positions at NASA, affiliated aerospace corporations and other companies, while others complete their coursework more rapidly on a full-time basis.

SICSA routinely presents its publications, research and design results and other information materials on its website (www.sicsa.uh.edu). This is done as a free service to other interested institutions and individuals throughout the world who share our interests.

This report is offered in a PowerPoint format with the dedicated intent to be useful for academic, corporate and professional organizations who wish to present it in group forums. The document is the first in a series of seminar lectures that SICSA has prepared as information material for its own academic applications. We hope that these materials will also be valuable for others who share our goals to advance space exploration and development.
Habitable pressure vessels can be constructed in a variety of types and forms:

- Conventional types represent the standard approach, offering design simplicity and pre-integration of equipment and utility systems.

- Telescoping types are possible using a “gelatin capsule” approach which can expand internal volume and afford some pre-integration benefits.

- Inflatable (“soft”) types of structures have pliable layered envelopes that can be compactly packaged for launch.

- Hybrid Inflatable types combine hard and soft elements to gain special advantages afforded by each.
Conventional modules apply construction methods that have been proven effective throughout the history of human spaceflight:

- They are simplest to design and deploy, and offer immediate operational capabilities.
- They offer good structural integrity and reliability, using materials that have been demonstrated in harsh space environments.
- They enable utility and equipment systems to be installed and checked out prior to launch.
- They afford the easiest and surest integration of windows, hatches/berthing ports and external attachment fixtures.
Conventional modules have versatile applications, but also present certain limitations when compared with other possible approaches:

- Internal capacity expansion can only be accomplished by adding other modules.
- Habitable volume in each module is constrained to conform within diameter and length dimensions allowed by the launch vehicle.
- Utilization of smaller limited volume modules can require more launches, rendezvous and assembly operations to achieve desired functional capabilities.

**Types of Pressure Structures**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Description</th>
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<tbody>
<tr>
<td>Monocoque</td>
<td>The Monocoque structure is essentially a “can” which is lightest and easiest to build, but is least resistive to structural load forces.</td>
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<tr>
<td>Semi-Monocoque</td>
<td>The Semi-Monocoque structure incorporates ring frames to increase the outer skin’s ability to resist buckling forces.</td>
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<tr>
<td>Skin Stringer</td>
<td>The Skin Stringer structure design is the most rigid to resist axial and bending loads, but adds mass.</td>
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Typical modules have “primary structures” that provide structural integrity and attachment functions:

- Longerons are used to increase stiffness and load-carrying capabilities of pressure shell panels.
- Ring frames provide attachment points for longerons and shell panels.
- Shell panels contain atmosphere pressurization loads.
- Window and hatch/berthing port frames provide pressure-tight interfaces.
- Integrated trunnions secure the overall module within the launch vehicle.
Telescoping modules offer a means to expand deployed volume using relatively conventional technology:

- One hard section would slide into another to shorten the undeployed length during launch.

- The inner section would have utility systems and equipment pre-integrated and checked out prior to launch.

- Following deployment in orbit or on a surface, the vacated outer section can be used for activities requiring a larger open volume, or can be outfitted for equipment using extendable/modular utility lines originating from the other section.
While offering some special benefits, telescoping modules also present certain constraints and disadvantages:

- Unlike inflatable modules which expand both in diameter and length, telescoping enlargement is limited to the linear dimension with much less volume advantage.

- Telescoping and pressure seal clearance requirements will restrict viewports and docking ports to endcap locations in order to avoid structural interferences.

Life and Biological Sciences (LaBS) Facility

SICSA Concept
Inflatable structures offer the ability to launch and deploy habitats that greatly exceed the internal volume offered by conventional and telescoping modules:

- Some systems have been demonstrated in space, and several more are in various stages of design and testing.
- Pressure walls are invariably comprised of specialized pliable layers, each providing essential features.

Possible inflatable system applications include lunar/planetary facilities as well as smaller elements such as airlocks and transfer tunnels.

NASA Lunar Base Concept
The USSR demonstrated an inflatable airlock on its Voskhod-2 spacecraft in March, 1965:

- Soviet space program founder, Sergei Korolev recognized the importance of enabling people to work outside the spacecraft without depressurizing the ship.

- A miscalculation in the pressurized size of Alexi Leonov’s EVA suit nearly resulted in tragedy when he experienced great difficulty reentering through the airlock’s small hatch.

The inflatable airlock functioned well but the hatch was too small.
The Goodyear Aerospace Corporation (GAC)* developed various inflatable module prototypes under contract with the NASA Langley Research Center during the 1960s:

- The largest was a 24 foot outside diameter torroidal space habitat structure (1960).
- The 2,300 cubic ft. deployed volume system could be packaged in an 8ft diameter launch volume.
- Module weight was approximately 4oz/ft$^2$ of surface area.

* GAC was purchased by the Loral Systems Group.
In 1965, GAC developed a lunar shelter which was designed to support a crew of two people for periods of 8-30 days:

- The outer and inner layers of materials were polyaramid nylon fabric bonded by polyester adhesive to provide micrometeoroid protection.
- A middle layer was a closed cell vinyl foam for radiation protection and thermal insulation.
- The total module and airlock volume was 515 ft³.

Construction: 3-layer laminate consisting of nylon outer cover, closed-cell vinyl foam, and inner nylon cloth bonded by polyester adhesive layers. Internal volumes of shelter and airlock were 410 cubic and 105 cubic feet, respectively. Weight, 126 pounds/ft² (total, 326 pounds). Designed for 5 psi pressure.

Early GAC Developments
GAC developed a larger space module prototype for a proposed 110 ft. long lunar base habitat in 1968:

- The outer surface was covered with a nylon film-fabric laminate covered with a thermal control coating.
- The innermost layer was a 1/6 inch thick gas bladder made from 2 inch wide Dacron yarn dipped in a polyester resin bath, and sealed by a polyvinyl chloride (PVC) foam.
- The middle layer was a 1 ¾ inch flexible polyurethane foam.
GAC fabricated two expandable crew transfer tunnels for space:

- The first was 12 ft. long, developed for the Air Force Propulsion Laboratory in 1966 to connect a Gemini capsule to Skylab’s Manned Orbital Laboratory (MOL) crew quarters.
- The second was a 14.2 ft. long flexible section to connect the Orbiter’s crew cabin and the Spacelab module that was developed in 1979 under contract with McDonnell Douglas for the NASA Marshall Space Flight Center.

Construction: 2 plies of Nomex unidirectional cloth fabric coated with Viton B-50 elastomer wrapped around steel beads made from wraps of 0.0307 inch diameter wire. Debris shields constructed of kevlar 29 covered the surface. The 170.5 inch length compressed to 20.5 inches. Total weight 756 pounds.
GAC developed a 6.2 ft. long inflatable airlock through a joint NASA-Department of Defense venture in 1967 that was designed to be mounted on a Skylab-type vehicle:

- The structural layer used a 3.6 mil filament-wound wire for tensile strength.
- Flexible polyurethane foam provided a micrometeoroid barrier, and a fabric-film laminate afforded thermal control.
The filament-wound ribbon construction used for Moby Dick enabled the structure to be twisted and compressed through a reduction procedure called “necking down”. Longitudinal wraps of Dacron 52 yarn tape were looped around aluminum circumferential rings spaced along the pressure hull to ensure uniform folding. The entire structure could be packaged in a 12.5 foot diameter, 2 foot high cylinder.

The flex section for crew transfer between the Orbiter crew cabin and Spacelab module used unidirectional fabric plies wrapped around rings of steel wire to minimize interface section loads resulting from axial, lateral, torsional and rotational displacements caused by installation, thermal gradients and maneuvering. Fillets added to outer diameters of the wire rings ensured a smooth transition and avoided fabric abrasion.
GAC’s experimental tests involving the lunar shelters, Moby Dick and the proposed Skylab airlock demonstrated compact packaging, easy deployment, low leak rates and good structural integrity, but did not meet upgraded NASA fire safety requirements:

- In 1970, GAC designed and successfully tested a nonflammable wall using a 2 inch thick “XTC-4” combination of laminated layers.

- The wall incorporated an “XPB-14A” flame/gas barrier that met the new standards.
GAC qualified a flexible fabric consisting of Nomex unidirectional cloth coated with Viton B050 elastomer for Orbiter-Spacelab tunnel construction:

- The combination also offers potential applications for habitats.
- Nomex/Viton structural layers can be laminated together to obtain desired strength, and a flexible cable can serve as a bead to ensure structural integrity during deployment and inflated conditions.
- An inner aluminum foil flame barrier can be added along with other shielding.

<table>
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<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Strip tensile strength</td>
<td>1074 lb/inch</td>
</tr>
<tr>
<td>Weight after cure</td>
<td>46.13 oz/yd²</td>
</tr>
<tr>
<td>Thickness after cure</td>
<td>0.040 inch</td>
</tr>
<tr>
<td>Peel adhesion after cure</td>
<td>29.7 lb/inch</td>
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Nomex/Viton Properties (Per Ply Average Values)
It may be necessary in some inflatable space structure applications to provide means to rigidize the systems so that volumes are retained after inflation gases are gone:

- Rigidization might be accomplished by incorporating a flexible mesh core material impregnated with a gelatin-resin between membranes of a sealed structure which expands to harden the core when the wall cavity is vented to space vacuum during structure deployment.

- GAC investigated different chemicals and selected a reversible-type gelatin with a Scott foam mesh.
ILC Dover was a leader in developing advanced technology inflatable systems, including a hyperbaric chamber that has similarities to space habitats:

- The 0.8 meter diameter, 2.1 meter long structure included a bladder layer to retain pressure, and a restraint layer to support structural loads.

- The bladder was comprised of a urethane-coated polyester, and the restraint was a series of polyester webbings stitched to a polyester fabric substrate.

- System operating pressure was 203 Kpa with a factor of safety of 3 over ultimate.
In 1989 the Lawrence Livermore National Laboratory in Berkley, California began to study the feasibility of using an inflatable module to create a low cost space station through a contract with ILC Dover:

- Study investigations included structural analysis, materials evaluation, producability, redundant pressure containment systems, safety and reliability, mass analysis, consumables, reparability and cost.

- It was decided early that the module should be compartmentalized so that safe operations could continue in the event of a penetration causing pressure loss in one location.

Livermore Habitat Module

A redundant pressure containment system would be redundant:

- The secondary (outer) envelope would be pressurized at 17.2 KPa to maintain geometry.
- Habitation Spaces would be pressurized at 51.7 KPa.
The Livermore studies investigated two different structure options:

- One option investigated was a system with rigid composite end plates that separated compartments within the module.
- A second option proposed a flexible composite system with stacked torroidal internal elements.
- Both systems were 5 meters in diameter and approximately 17 meters long with a 1 meter diameter central corridor.
- The flexible portion of both utilized a Kevlar-type scrim laminate with each layer coated on each side with urethane for a strong, low-permeation bladder.
In 1996, the NASA Johnson Space Center began to study a possible return mission to the lunar surface that envisioned use of an inflatable habitat to support human check-out activities before a permanent habitat was sent:

- Again, ILC Dover was contracted to study various configuration options and sub-assemblies including bladder, restraint layer and Thermal and Micrometeoroid Cover (TMC).
- The system was envisioned to sit atop a landing craft and expand to full volume on the surface.
Numerous concepts were investigated for the lunar surface module’s construction:

- One bladder possibility was a dual-walled self-sealing silicon-coated Vectran fabric with film laminates which afforded simplicity, cold temperature deployment properties and a robust nature.

- Several restraint layer concepts were also investigated, including coated single-layer fabrics, layers with circumferential and axial webbing over coated fabric, and structures with circumferential torroidal webbing over an internal axial layer.
The selected wall system presented the following elements:

- A restraint layer that applies an outer Kevlar 4082 Kg layer overlaying a structural 710 denier, 45 x 45 count plain weave. (The structural layer was slightly oversized to create a quilted effect to reduce pressure loads transmitted through the fabric.)

- A multi-layer overall assembly wall scheme was able to meet diverse operational and environmental requirements.
During the late 1990s, NASA-JSC began to develop designs for an inflatable space module comprised of several specialized layers:

- Gas retention would be achieved by a double-redundant bladder assembly with laminated layers of nylon, ethylene vinyl alcohol (EVOH) and polyethylene film.

- Structural restraint utilizes interwoven Kevlar webbings that form a shell capable of withstanding 101 kPa pressure loads.

- Debris protection was provided by a series of 1.5 mm thick Nextel layers separated by foam spacers, and metalized exterior films were used to reflect radiation.

TransHab was designed to be packaged around a central utility core for launch. It would expand to a 7.6 meter diameter, 9.1 meter length, a volume equivalent to 2 conventional ISS modules.
A program of prototype manufacture and design involving ILC Dover as a member of the Integrated Project Team (IPT) was initiated by NASA:

- The first unit was inflated to twice the operational load without failure to validate pressure retention.

- Following some design modifications, a second unit was hydrostatically tested to a safety factor of 4 times.

- A third unit was developed for vacuum chamber tests to evaluate leakage, structural rigidity and deployment.
Bigelow Aerospace, a Las Vegas company, is developing inflatable modules intended primarily for space tourism applications:

- The company is providing half of a $50 million “America’s Space Prize” to the first spacecraft company that can service the orbital Bigelow facilities. (The winner will also be guaranteed 1st right on an ongoing service contract.)

- A key objective is to encourage development of a commercial launch vehicle that can deliver 5-7 astronauts at a time by the end of this decade.

- The company also hopes to provide NASA with technology for the Moon and Mars.
Bigelow Aerospace is working with NASA and a variety of contracting organizations:

- The company holds 2 license agreements with NASA:
  - an exclusive license for 2 TransHab patents;
  - a license for radiation shielding with exclusive and non-exclusive contracts.

- Bigelow is developing ways to fold/package soft materials around a module's aluminum core to ensure that creases and critical seals such as windows don’t leak when pressurized.

Module Inflation
The 7 layer module wall will be pressurized at 10psi (compared with 14.7psi for ISS).
A planned 22 ft. diameter, 45 ft. long “Nautilus” module will have 2.75 times the internal volume of standard ISS modules:

- Unmanned test operations are planned by 2008 using a Russian Proton-class booster.
- Two 1/3 scale “Genesis” modules are planned to be launched prior to Nautilus in 2005 and 2006 (one on a Space X Falcon V, the other on a Russian “Dneper” commercial version of the SS-18 ballistic missile).
- The first Genesis will use a nitrogen atmosphere, and the second will use an oxygen-nitrogen mixture.
SICSA has studied and conceptualized inflatable space structures over a period of more than two decades. One proposed design deploys interior floors automatically:

- An axial “web” of tension cables support floor membranes that are integrated and folded within the inflatable enclosure package prior to launch.

- Vertical cables, in combination with the horizontal web, restrain the deployed envelope shape and provide attachment points for utility systems and equipment.
Central tension rings accommodate vertical circulation between interior levels and offer attachment fixtures for utility risers and equipment. Turnbuckles enable tension chords to be adjusted in order to minimize floor “trampoline” effects.
Hybrid modules offer combined advantages of inflatable and conventional elements:

- Soft inflatable sections provide relatively large internal volumes to optimize habitability features.

- Hard sections enable pre-integration of utility and equipment systems and can readily accommodate integral viewports, docking interfaces and other structures.

- SICSA’s SpaceHab which was proposed in the 1980s illustrates an example.
HABITABLE STRUCTURES HYBRID MODULES

SICSA SpaceHab Concept
HABITABLE STRUCTURES

SICSA SpaceHab Concept

HYBRID MODULES
SICSA’s LunarHab project conceived in the 1980s proposed an inflatable 70 ft. diameter spherical habitat comprised of a composite pressure bladder, two hard airlocks, and an internal erectable structure:

- The inflatable section would be placed over an appropriately shaped and sized surface cavity, possibly created by pyrotechnics.
- A main internal truss frame would be attached between the airlocks to span the cavity prior to full inflation of the pressure envelope.

The concept incorporates 2 access/egress airlocks at opposite ends of an inflatable sphere. An internal metal structure would be assembled following envelope pressurization.

**HABITABLE STRUCTURES**

**HYBRID MODULES**

**SICSA LunarHab Concept**
The spherical geometry would require that a surface cavity be discovered or created to accommodate the lower area and prevent it from lifting when the module is pressured.

An erectable internal structure would be assembled from aluminum truss sections along with floor panels, modular utility systems and attached equipment that are delivered separately.

SICSA LunarHab Concept
A relatively large 45ft. Diameter hybrid concept was proposed by SICSA to support hydroponic plant growth and aquatic experiments for food production which would require substantial volumes:

- The module would land in a vertical orientation with the inflatable section protected within a deployable shroud.
- Following pressurization, the first crew, operating under shirt sleeve conditions, would attach internal utility and equipment systems to a pre-integrated pop-out tension cable matrix.
HABITABLE STRUCTURES

SICSA MarsLab Interior Views

HYBRID MODULES
The Lunar/Mars Hab incorporates SICSA’s pop-up internal inflatable system and external hard-soft interfaces that were developed and tested by the Goodyear Aerospace Corporation (GAC):

- Connecting ends of the soft sections where they attach to hard sections contain compressible bundles of wraparound wires to prevent fiber damage during folding and deployment.

- Connecting tunnel interfaces enable passage of utility lines between the module and other pressurized facilities.
SICSA’s Lunar Ecosystem and Architecture Prototype (Project LEAP) proposes a combination of hard and soft module types:

- Conventional hard modules provide an initial operational capability with pre-integrated utilities and equipment.
- Inflatable habitats and laboratories are added as required throughout growth stages.
SICSA’s proposed First Mars Outpost combines 45 ft. diameter MarsHab modules and hybrid MarsLab modules that would be launched to LEO by expendable Heavy Lift Vehicles (HLVs):

- MarsHabs are designed to support 8-person crews for surface missions lasting up to 500 days, and are estimated to weigh approximately 100 metric tons (including the landing system).

- MarsLab modules used for hydroponics and other functions are connected by soft tunnels to the MarsHabs, and use similar hard section construction.
SICSA’s Medium Lift Vehicle (MLV) lunar/Mars settlement scenario proposes use of hybrid modules in combination with axially-connected conventional modules:

- Equipment for hybrid module outfitting is transferred from the first arriving conventional modules by initial crews.
- As equipment and supplies are moved out of pressurized logistics carriers, they can then be utilized as laboratory modules.

Soft pressurized connecting tunnels between modules adjust for imprecise alignments under irregular surface conditions.
HABITABLE STRUCTURES

Surface Module Configuration

Inflatable Module Levels

SICSA’s Lunar / Mars Modules

MODULE COMBINATIONS
HABITABLE STRUCTURES

SICSA’s Lunar / Mars Modules

FIRST/SETUP MODULE:
Astronauts will live and work out of this module for the first few days till the habitat is set up. This module will later be used as a safe haven.

The Logistics module will be docked to the core module & equipment and storage will be transferred to other modules. A part of this module can later be used as lab space.

Astronauts will dock the core module with the first one, deploy the inflatable and get the systems in order.

INFLATABLE:
LEVEL 1: EXERCISE/STORAGE (HEAVY EQUIPMENT)
LEVEL 2: LAB/WORKSPACE
LEVEL 3: CREW QUARTERS (PRIVATE SPACE)
The importance of outside viewing has been clearly demonstrated throughout all human space missions, including:

- Monitoring and control of vehicle rendezvous/docking procedures.
- Operation of telerobotic devices through direct eye contact.
- Discovery and photographic documentation of natural events and spacecraft hazards/damage.
- Crew recreation and morale to offset boredom and psychological confinement/isolation.

Example of window attachments with a Skin Stringer waffle pattern pressure shell structure.

Window Importance
Window options include a variety of locations and types:

- They can be placed into module cylinder walls, end caps, pressure hatches and attached cupolas.
- They can be flat or domed bubble geometries.
- They can be designed for general viewing, or can incorporate special optical features for photographic and scientific applications.
- They can be outfitted with fixed or moveable UV filters and debris shields.
End Cap Turret RMS Station

End Cap Corner RMS Station

Window types and Locations

HABITABLE STRUCTURES

OUTSIDE VIEWING
Special Viewing Devices

Viewing Mirror Assembly

RMS Station Privacy Screen

HABITABLE STRUCTURES

OUTSIDE VIEWING
Attached Cupola Concepts

HABITABLE STRUCTURES

Faceted Cupola

Bubble Cupola

OUTSIDE VIEWING
Spacecraft windows add substantial structural mass, introduce pressure seal and transparency maintenance problems and can reduce wall space available for equipment and other uses:

- The size and number of windows must be correlated with launch and functional volume constraints.

- Locations must be selected for appropriate viewing orientation in relation to the vehicle’s orbital attitude and operational objectives.

- Window designs must accommodate viewing objectives and limitations.

Window Design Approaches

Early Space Station Freedom studies explored ways to enable equipment racks to be added or removed from window areas.

Window Planning and Design
The NASA Marshal Space Flight Center proposed a Common Module concept, and Rockwell proposed a smaller 6 in. diameter concept:

- Both designs provided an inner assembly with 2 panes plus an outer micrometeoroid barrier pane.
- Outer assemblies are attached for EVA removal using quick-release pins.

Illustrative Construction Concepts

HABITABLE STRUCTURES

OUTSIDE VIEWING
Skylab provided several windows:

- A large 18 in. diameter Wardroom window.
- Two 3 in. diameter and one 3.96 in. diameter docking adapter viewports.
- Four 8 in. x 12 in. oval airlock viewports and two 8.5 in. diameter windows in the airlock hatches.

Single-pane multi-spectral windows provided high optical quality and had removable safety covers.

**HABITABLE STRUCTURES**

**OUTSIDE VIEWING**
Skylab Wardroom Window

Materials

- HIGH EFFICIENCY ANTI-REFLECTIVE COATING
- VAPOR DEPOSITED GOLD E. C. COATING
- FUSED SILICA GLASS
- ULTRA VIOLET INFRA RED COATING
- HIGH EFFICIENCY ANTI-REFLECTIVE COATING

Components

- OVER-CENTER RESTRAINT
- GLASS PROTECTIVE SHIELD
- INBOARD

HABITABLE STRUCTURES

OUTSIDE VIEWING
The ESA Spacelab Window Adapter Assembly (SWAA) is of special interest because it incorporated provisions for both general and scientific viewing:

- An 11.8 in. diameter viewport with a single 0.98 inch thick pane afforded general viewing.
- A 16.36 x 20.55 inch high quality single-pane optical window (1.63 in. thick) was used for scientific viewing.
- The assembly was constructed of 2219-T851 aluminum, and had a total mass of 57.4 kg.
When not in use, the SWAA’s glass surfaces were protected by two covers:

- Internally, a transparent cover of comparable optical quality and a thermal dark cover offered protection.

- A mechanically-operated external cover provided protection against thermal effects, micrometeoroid impacts, contamination and other damage.

- The assembly also incorporated an electric heater unit to prevent condensation.
Space Shuttle window planning was driven by critical needs for flight maneuvering, payload manipulation, landing control viewing, and requirements to resist extreme heat and dynamic loads:

- Six windows stretch across the front portion of the flight deck cockpit.
- Two 23.3 in. x 11.3 in. aft crew station windows provide direct payload bay viewing and RMS control.
- A 15 in. diameter optical mid-deck hatch window was incorporated as a Department of Defense requirement.
Orbiter windshields are comprised of 3 panes:

- Fused silica outside thermal panes (0.6-0.7 in. thick).
- Fused silica redundant middle panes (1.3 in thick).
- Tempered aluminosilicate inner pressure panes (approximately 0.6 in. thick).

The 3 layers of material separated by atmospheric space results in a rather thick viewing aperture which has been reported to be like looking through a tunnel.
The RMS windows support telerobotic and EVA viewing functions that are directly analogous to space station applications.

**RMS Window Construction**

The Orbiter’s aft crew station windows comprised of 2 panes of fully tempered aluminosilicate material.

**RMS Window Construction**

**Shuttle Orbiter Windows**

**HABITABLE STRUCTURES**

**OUTSIDE VIEWING**
Project Gemini window design was strongly influenced by requirements imposed by thermal and dynamic Earth reentry loads:

- Window assemblies contained 3 separate glazing panels, 2 inner panels providing pressure barriers, and an outer pane acting as a thermal barrier.
- Left hand assemblies used Vycor for the outer panes, and tempered glass for the inner pane.
- Right-hand assemblies used high-optical quality Vycor for all 3 panes to offer good photography features.
Project Apollo’s orbital rendezvous/ docking and lunar landing requirements demanded window improvements over those of Project Gemini:

- Apollo Command Modules contained 2 forward windows, 2 side windows, and an optical center hatch window.

- Flight windows were constructed of 0.7 in. thick fused silica external panes, and 0.5 in. thick tempered glass inner panes, separated by 0.1 in. airspaces.

- The windows, designed to withstand heat (3,110°F melting point) and dynamic pressure loads represented the Apollo Program’s longest technical lead item.

Improved visibility and broader field of view angles became important for Apollo / Soyuz and Apollo landing missions.

Field of Vision

Apollo 14 Command Module Window
Docking and berthing mechanisms use a set of guides to position mating space elements and a set of latches to mechanically connect the elements when docked or berthed:

- Docking occurs when two elements fly together under control of propulsion and attitude control systems, therefore requiring means to absorb collision energy produced by the closing velocity.

- Berthing implies that another mechanism such as a telerobotic manipulator is used to position two elements in the berthing position.

- Both systems typically provide means to transfer data and electrical power between connected elements.

Guide vanes containing capture latches align the two elements upon contact, and they are tightly locked together by structure latches and strikers.

**Rockwell Docking Concept**
The Androgynous Peripheral Attach System (APAS) serves important ISS functions:

- It accommodates Orbiter docking and 2-way transfer of crews and supplies.
- It is used to connect the Functional Cargo Block (FGB) to the Pressurized Mating Adaptor (PMA)-1.
- An APAS is located on each of the ISS PMAs on the FGB forward side.
- The same design referred to as the Androgynous Peripheral Docking System (APDS) was also used for Shuttle/ Mir flights.

The Androgynous Peripheral Attach System (APAS) is a Russian design that is able to mate with an exact copy of itself.

Androgynous Peripheral Attach System

Orbiter – ISS / Mir Docking System
The Probe/Drogue docking system is used to mate all Russian modules together, including the Science Power Platform (SPP) segments:

- The active half contains a probe, a capture latch at the end of the probe, alignment pins, hooks, and shock absorbers.
- The passive half has a drogue, a receiving cone and a structural ring.
- When the probe enters the receiving cone, the capture latch activates as the tip enters the drogue.
- The probe retracts, bringing the 2 halves together. Then, capture hooks mate them, and the capture latch releases.
ISS hatches are integrated with docking mechanisms used for mating modules together:

- A Manual Berthing Mechanism is located on the no.21 truss segment, and is manually operated by an EVA crew person to mate it with the passive side of a Common Berthing Mechanism (CBM).

- The CBM has both a passive and active half that connects one US module to another by means of capture latches, alignment guides, powered bolts and controller panel assemblies.
HABITABLE STRUCTURES

ISS Berthing Mechanisms

Common Berthing Mechanism

Active Half
Passive Half
Attachment Bolts
Structural Rings
Capture Latches
Controller Panel Assembly
Alignment Guides
Alignment Guide

HABITABLE STRUCTURES ELEMENT INTERFACES
Orbital space stations are typically comprised of many different elements that must be connected together in a manner that provides stiffness with the least possible amount of mass. Trusses offer special infrastructure advantages for such applications:

- They can be erected or automatically deployed to create large structures which can be launched from Earth in compact packages.
- They can be designed/adapted for a wide variety of configuration requirements.
- They provide versatile element attachment and reconfiguration possibilities.

Trusses provide a light weight, strong and versatile structural approach.

Applications and Benefits
The truss backbone idea appeared in a Boeing concept created in 1983:

- The Power Tower was designed to fly Earth-oriented in a gravity gradient stable altitude.
- The power section could be expanded to provide higher levels to support evolutionary needs.
- The lower truss afforded substantial space for equipment storage and hangars.
- The structure could accommodate a variety of module configurations.
- Earth viewing would offer a clear field at the bottom.
- The transportation approach and departure corridors were open.
The Delta configuration was developed at the NASA Johnson Space Center during the early 1980s:

- Pressurized modules were located at the apexes of the delta triangular shape and were connected by tunnels to create a nearly balanced inertial configuration.

- The solar array was one of the three triangular surfaces pointed at the sun by aiming the entire vehicle.

- Later studies considering Shuttle docking/berthing and various mission accommodations exposed serious control problems that caused the design to be abandoned.

The Delta configuration was devised to provide stiffness to avoid dynamic controllability problems associated with the long, flexible Power Tower truss.

NASA Delta Space Station Concept
The “Tee” concept was also designed to be stiff, but was less so than the Delta:

- It flew in a gravity gradient-stable altitude, and did not pose the static control problems of the Delta.

- The solar array was positioned to fly in a local horizontal attitude which presented very low drag. Since it did not track the Sun, its efficiency was poor for large beta angles when the Sun was far outside the orbit plane.

- The module cluster was attached to a truss structure extending downward, which contributed to gravity gradient-stability.

The design which was conceptualized at the NASA Johnson Space Center in the early 1980s was determined not to provide adequate power generation efficiency.

**NASA Big–Tee Space Station Concept**

**Configuration Concepts**
SICSA’s Space Planetary Operations Support Terminal (Space POST) concept was proposed in 1987, and was developed in cooperation with the NASA-Ames Research Center’s Space Human Factors Office:

- The design provided a high level of gravity gradient stability with an emphasis upon accommodations for human space operations.
- The large truss would be used as an attachment fixture for equipment, tools and RMS systems to support EVA functions.
- Gimbaled solar-tracking arrays avoided pointing orientation problems associated with the Big-Tee approach.
Space frame trusses are often preferred for structures that must span considerable distances or areas with high moments of inertia to resist bending and compression loads relative to their mass:

- They can be designed to be assembled by EVA crews with or without telerobotic assistance, or to be deployed automatically.
- Graphite composites can optimize lightweight strength, but may require atomic oxygen protection.
- Common geometric arrangements include A-frame and pentahedral trusses, and hexahedral (box trusses).
Fixed and deployable tetrahedral trusses can be used to create very large and efficient structures which combine tetrahedral and pentahedral geometries:

- Representative applications include major space station element attachment performs, deployable deep space antenna systems, and possible platforms for proposed solar space satellites to beam power to Earth.

- Springs or tension cords can be incorporated to “unfurl” the systems from their compact launch packages.

 Strictly speaking, there is no such thing as a purely tetrahedral truss since its geometry does not fill in all surface spaces when tetrahedrons are joined together.

**“Tetrahedral” Trusses**
Technologies presently exist to erect or deploy truss structures in a variety of ways:

- Some systems are comprised of individual solid or tubular members and connector sockets that are assembled in “tinker toy” fashion by space-suited astronauts, or attached using teleoperated devices.

- Some are pre-assembled with hinged joints, compactly folded during launch and automatically expanded at the destination.

- Possible future methods may use “beam builders” that can form, position and weld metal strips into rigid trusses in space applying automation technology.
One of the first US space assembly experiments was the Assembly Concept for Erectable Space Structure (ACCESS) which was successfully demonstrated on the Shuttle Orbiter during November and December, 1985:

- One experiment involved 2 astronauts in foot restraints attached to a special platform in the payload bay assembling a 45 ft. long truss with 4.5 ft. bays.

- In another experiment, an astronaut worked from a foot restraint attached to the Orbiter’s RMS to evaluate its use to assist limited EVA construction and maintenance tasks.

ACCESS successfully demonstrated on-orbit construction applying current EVA and RMS technologies.
During recent years, more and more emphasis is being directed to developing telerobotic and automated assembly methods that can reduce EVA time and risks:

- During the late 1980s, the NASA Langley Research Center in Hampton, Virginia, began to explore a broad range of off-the-shelf industrial manipulators, and tested their use for space construction.

- An ultimate goal of these and other research and development activities is to eventually automate all assembly processes, elevating human roles to high level supervisory functions.

Mobile RMS devices offer the potential to eliminate human EVA roles.

**Telerobotic Assembly and Servicing**

**System Types**

**CONNECTING STRUCTURES**

**TRUSS ASSEMBLIES**
A “large unfurlable structure” called ERA was developed by Aerospatiale for the French space agency CNES, and was deployed by a French astronaut onboard the Russian Mir space station in late 1988:

- The 12.5 ft. x 11.8 ft. x 3.3 ft. structure was made up of 1.18 in. diameter carbon fiber tubes linked together by light alloy joints forming 24 prismatic-shaped sections.

- The assembly contained more than 5,000 parts, including more than 1,300 bearings which fit into a 1 ft. diameter, 2 ft. high bundle which deployed in 2.5 seconds.
Fully automated manufacturing processes may one day transfer existing terrestrial technology to the space environment:

- Beam builders might transform metal strips contained on spools to triangular truss 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 equipment to accomplish this operation might be complex and bulky, the process could be valuable to create structures using materials from the Moon, Mars and asteroids.
The ISS contains two major truss assemblies, each providing telerobotic manipulation capabilities:

- The US Integrated Truss Structure extends across the center of the station, and provides a Mobile Servicing System (MSS) which was developed through a collaboration involving NASA and the Canadian Space Agency (CSA).

- The Science Power Platform was developed to support the Russian ISS segments, and contains a European Robotic Arm (ERA) which was created by the European Space Agency (ESA) and the Russian Space Agency (RSA).

**ISS Applications**

**ERA**

**Science Power Platform (SPP)**

**And Russian Segments**

**SSRMS**

**Truss and U.S. Segments**

**JEMRMS**

**Exposed Facility (EF)**

**Special Purpose Dexterous Manipulator (SPDM)**

**Mobile Remote Servicer Base System (MBS)**

**Mobile Transporter (MT)**

**MSS External Components**
The Integrated Truss Structure (ITS) provides the ISS’s structural backbone with attachments points for external payloads:

- The truss reaches 328 ft. in length fully assembled, and is comprised of 10 individual segments which are identified by location on the illustration.
- The segments contain electrical, data, and fluid utility lines, along with rails for a mobile transporter system.
- Different component sections support specialized functions, and can be visualized as a modular “kit”.

**Types of ITS Backbone Truss Segments**

Z=Zenith, S=Starboard, P=Port

**ISS Applications**
The Russian Science Power Platform (SPP) is located on the zenith side of the Russian Service Module:

- The truss system is 25.76 ft. long and contains radiators, solar arrays, the capability for pressurized storage, and the ability to support the European Robotic Arm (ERA).
- The SPP is also equipped with thrusters to aid the Service Module with control moments along the roll axis.
- The system is comprised of 2 segments, one containing the pressurized volume, and the other containing the radiators, solar arrays, thrusters and ERA.
The Lab Cradle Assembly (LCA) attaches the ISS’s SO truss to the US Lab Module:

- The LCAs active half attaches to one of the module’s external ring frames and longerons, and is mounted into place by EVA-driven bolts and support braces. This half contains a central capture latch and 4 alignment guides.

- The LCA’s passive half contains a capture bar that slips into the active capture latch and interface alignment bars.
The ISS Common Attach System (CAS) is designed to fasten exposed payloads and logistics carriers to the ITS:

- The CAS attaches to truss longerons, and contains a capture latch and guide vanes. Payloads placed into the CAS are equipped with a capture bar and guide pins for alignment.

- Two of the unpressurized logistics carrier attach systems can remotely capture and physically attach their carrier platforms to the P3 Integrated Truss Structure, and 4 payload attach systems can remotely capture and attach to the S3 ITS segment.
Segments of the Integrated Truss Structure (ITS) are connected together using either a motor-driven Segment-to-Segment Attach System (SSAS), or a Rocketdyne Attach System (RTAS):

- The end of each truss segment has either an SSAS or RTAS mechanism attached to it.
- SSAS mechanisms have an active half containing motorized bolts, course alignment pins, fine alignment cones, and a capture latch; and a passive side containing nuts, coarse and fine alignment cups, and a capture bar.

Many of the ITS truss segments can be attached automatically, including the S3/4, S1, SO, P1 and P3/4 segments.
<table>
<thead>
<tr>
<th>Mechanisms:</th>
<th>Functions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Berthing Mechanism (CBM)</td>
<td>Connects US modules together</td>
</tr>
<tr>
<td>Lab Cradle Assembly (LCA)</td>
<td>Connects integrated truss (SO) to the Lab</td>
</tr>
<tr>
<td>Segment-to-Segment Attach System (SSAS)</td>
<td>Connects integrated truss segments together</td>
</tr>
<tr>
<td>Rocketdyne Truss Attach System (RTAS)</td>
<td>Connects integrated truss segments together</td>
</tr>
<tr>
<td>Common Attach System (CAS)</td>
<td>Connects exposed payloads and logistics carriers to the truss</td>
</tr>
<tr>
<td>Androgynous Peripheral Attach System (APAS)</td>
<td>Mates FGB and PMA1, and docks the Orbiter to the Station</td>
</tr>
<tr>
<td>Probe/ Drogue Docking System</td>
<td>Connects Russian modules together</td>
</tr>
<tr>
<td>Hybrid Docking Assembly</td>
<td>Connects Russian modules together</td>
</tr>
</tbody>
</table>

**Summary of ISS Attachment Elements and Functions**
## Comparison of Conventional Space Construction Materials

### Characteristics of Variously Used Metals and Composites.

<table>
<thead>
<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aluminum</strong></td>
<td>• High strength to weight</td>
<td>• Poor resistance to galling and wear</td>
<td>• Truss members, skins, stringers, fittings, brackets, shells</td>
</tr>
<tr>
<td></td>
<td>• Low cost</td>
<td>• High thermal coefficient</td>
<td>• Face sheets for sandwich structures</td>
</tr>
<tr>
<td></td>
<td>• Readily available</td>
<td>• Heat during welding causes reduced strength</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Easy to machine</td>
<td>• Prone to cracking</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Weldable</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Corrosion resistant</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Titanium</strong></td>
<td>• High strength to weight</td>
<td>• Difficult to machine or form</td>
<td>• Attachment fitting for advanced composites</td>
</tr>
<tr>
<td></td>
<td>• Low thermal expansion coefficient</td>
<td>• Relatively expensive</td>
<td>• Fasteners</td>
</tr>
<tr>
<td></td>
<td>• Good temperature properties</td>
<td>• Availability</td>
<td></td>
</tr>
<tr>
<td><strong>Steel</strong></td>
<td>• High stiffness and strength</td>
<td>• High mass density</td>
<td>• Fasteners</td>
</tr>
<tr>
<td></td>
<td>• Wear resistant, ductile</td>
<td>• Low buckling strength vs. weight</td>
<td>• Ball bearings</td>
</tr>
<tr>
<td></td>
<td>• Easy to machine and weld</td>
<td>• Varying corrosion resistance</td>
<td>• Structural supports</td>
</tr>
<tr>
<td></td>
<td>• Low cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Magnesium</strong></td>
<td>• High buckling strength vs. weight</td>
<td>• Poor corrosion resistance</td>
<td>• Lightly loaded structures, especially those critical for buckling</td>
</tr>
<tr>
<td></td>
<td>• Heat capacity and conductivity</td>
<td>• High thermal coefficient</td>
<td>• Light castings</td>
</tr>
<tr>
<td></td>
<td>• Easy casting</td>
<td>• Low stiffness</td>
<td></td>
</tr>
<tr>
<td><strong>Beryllium</strong></td>
<td>• High stiffness vs. weight</td>
<td>• Expensive and toxic</td>
<td>• Mirrors and optical support structures</td>
</tr>
<tr>
<td></td>
<td>• Low thermal coefficient</td>
<td>• Low ductility and fracture</td>
<td>• Precision gimbal and telescope housings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Poor cross grain properties</td>
<td>• Hinges, high temperature applications</td>
</tr>
<tr>
<td><strong>Heat Resistant Alloys</strong></td>
<td>• Strength at high temperatures</td>
<td>• High mass density</td>
<td>• Fastening hardware</td>
</tr>
<tr>
<td></td>
<td>• High stiffness and strength</td>
<td>• Low buckling strength</td>
<td>• High temperature applications (nozzles heat shields)</td>
</tr>
<tr>
<td></td>
<td>• Oxidation resistant</td>
<td>• Relatively hard to machine</td>
<td></td>
</tr>
<tr>
<td><strong>Graphite/ Epoxy Composite</strong></td>
<td>• Relatively light</td>
<td>• Brittle (no ductility), repair</td>
<td>• Truss members, antenna booms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Absorbs water, outgases</td>
<td>• Face sheet for sandwich structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Process development cost</td>
<td>• Optical benches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• UV sensitive</td>
<td>• Fuel tanks</td>
</tr>
</tbody>
</table>
Inflatable and inflation-deployed structures offer potential advantages and applications for future space structure development:

- They can be used to create large, rapidly-deployable systems that minimize launch volume/mass requirements.

- They can be created in a wide variety of geometric configurations to meet special needs.

- They can be rigidized by plastic foams or mechanical devices discussed earlier in this section.
Possible Forms

CONSTRUCTION AND MATERIALS

INFLATABLE SYSTEMS
Possible Forms

Foam-Rigidized Tubes/Bladders

Mechanically-Rigidized Structures

CONSTRUCTION AND MATERIALS

INFLATABLE SYSTEMS
Possible Applications

Airlocks and Space Habitats

Orbital Transfer Vehicle Hangars

CONSTRUCTION AND MATERIALS

INFLATABLE SYSTEMS
Possible Applications

CONSTRUCTION AND MATERIALS

INFLATABLE SYSTEMS
Space mission activities produce large quantities of trash that must be stowed until it can be returned to Earth or otherwise properly disposed of.

SICSA has proposed use of an inflatable trash holding container that attaches to a berthing port:

- Trash is inserted into a 4 cubic ft. airlock and automatically forced through shredding blades into the container.
- The deployed 15 ft. diameter spherical container provides 1,767 cubic ft. of holding volume.

Inflatable systems can be used to receive dry trash to preserve internal spacecraft volumes for productive functions.

**Shredder Unit and Containment Rod**

**SICSA Trash Management Concept**

**CONSTRUCTION AND MATERIALS**

**INFLATABLE SYSTEMS**
Containment pods attached to spacecraft berthing ports hold and isolate contamimates and bacteria from internal spaces.

Externally Mounted Containment Pod

Holding systems are detachable from shredding chambers for return to Earth by the Space Shuttle or another transport vehicle.

Receiving Chamber and Interface

SICSA Trash Management Concept

CONSTRUCTION AND MATERIALS

INFLATABLE SYSTEMS