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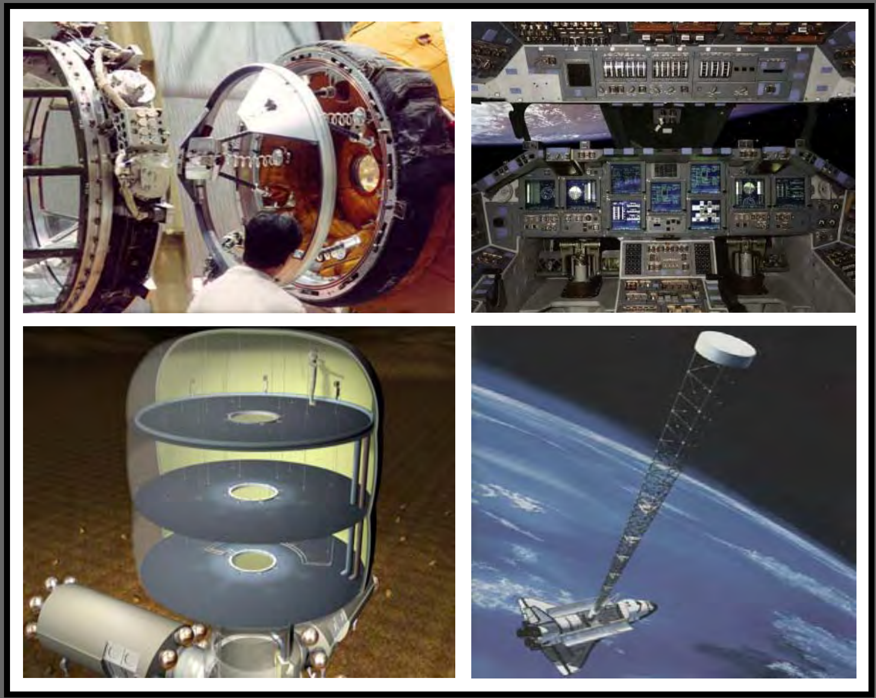
SICSA SPACE ARCHITECTURE
SEMINAR LECTURE SERIES

PART I: SPACE STRUCTURES AND SUPPORT SYSTEMS



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

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.

The SICSA Space Architecture Seminar Lecture Series is divided into two general Lecture Groups :

GROUP ONE:

Part I : Space Structures and Support Systems

Part II : Human Adaptation and Safety in Space

Part III : Space Transportation, Propulsion and Pathways

Part IV : Space Mission and Facility Architectures

GROUP TWO:

Part V : The History of Space Architecture

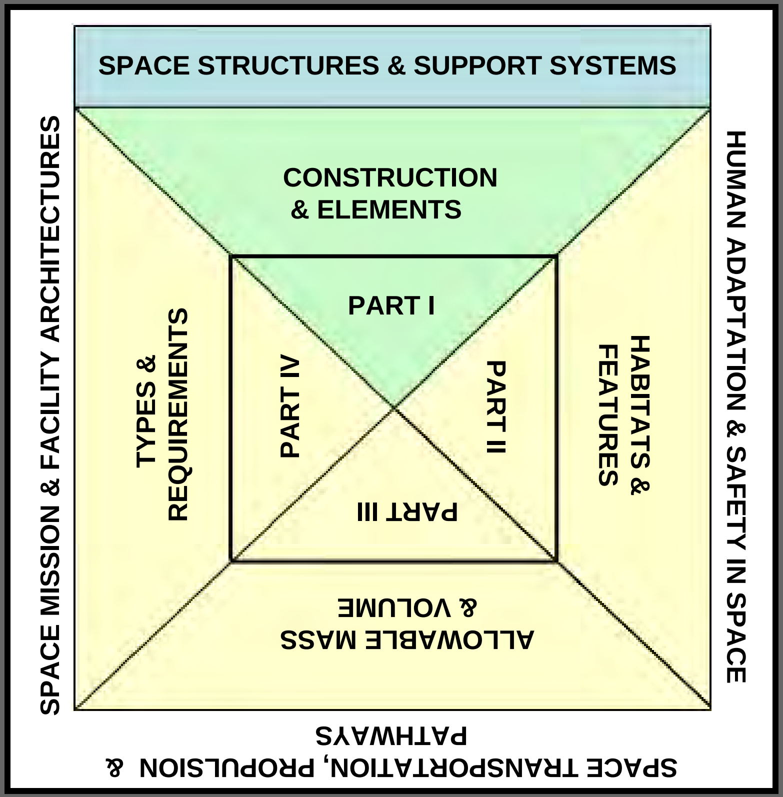
Part VI : The Nature of Space Environments

Part VII : Environmental Planning and Systems

Part VIII : Shelter Design and Construction

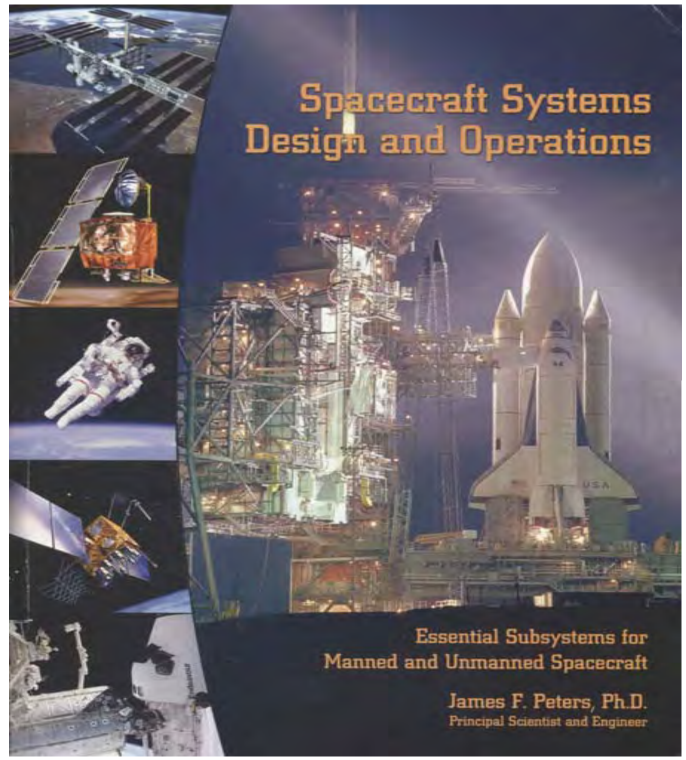
This lecture series provides comprehensive information, considerations and examples to support planning of human space missions and facilities:

- Part I (this report) presents a general anatomy of space habitats and vehicles as a foundation for understanding relationships to topics discussed in other three parts:
  - Module types, elements and construction influence Human Adaptation and Safety (Part II) by determining habitat options and features (including life support and other systems).
  - Habitat structures must be designed to comply with launch and transfer capacities of Space Transportation, Propulsion and Pathways (Part III) with regard to allowable payload mass and volume.
  - Selection and planning of all space structures and support systems must be responsive to Space Mission and Facility Architectures (Part IV) that are determined by program goals and objectives.



Key Relationships to Other Lectures

We are very grateful to Dr. James F. "Jim" Peters who has generously made a large body of material he has developed and collected available to us. This report draws extensively from his work. Much additional material can be obtained from his book, "Spacecraft Systems Design and Operations", which can be obtained from the Kendall/Hunt Publishing Company, 4050 Westmark Drive, Dubuque, Iowa 52202. This excellent publication is used as a primary text for the SICSA MS-Space Architecture curriculum, and is highly recommended as a valuable reference document for students and professionals at all career stages.



Key Reference Book

"Human Space Flight: Mission Analysis and Design" is a comprehensive and substantial book that should be in the library of any organization and individual involved in space project management, research, design or operations. The document was edited by Wiley J. Larson of the US Air Force Academy and Linda K. Pranke of LK Editorial Services as part of a Space Technology Series through a cooperative activity of NASA and the US Department of Justice. Text materials were contributed by 67 professional engineers, managers and educators from industry, government and academia. It is available through the Higher Education Division of McGraw-Hill.

Important Resource Book

SPACE STRUCTURES AND SUPPORT SYSTEMS

SPECIAL CREDITS

It would be difficult or impossible to find anyone more knowledgeable about the subject of his book, “Space Stations and Platforms”, than Gordon Woodcock from Boeing. “Gordy” has enormously broad experience and expertise, and we are all fortunate he has made the effort to share it. As noted by Edward Gibson in the book’s forward, “Over the coming years, this work should become a classic space station reference. It has high value for those who desire to understand, appreciate or contribute to our first permanent settlement in New Earth”. It can be obtained through the publisher: Orbit Book Company, Inc., 2005 Township Road, Malabar, Florida 32950.

Important Resource Book

SPACE STRUCTURES AND SUPPORT SYSTEMS

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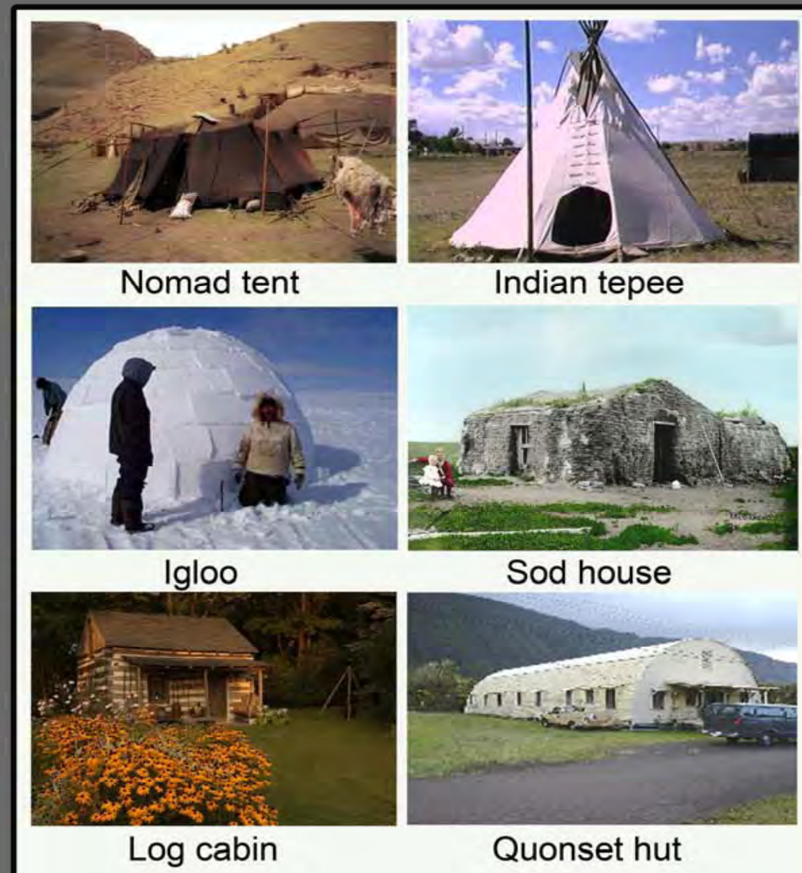
SECTION A: BACKGROUND

Human survival has always depended upon abilities to adapt shelters to different environmental settings:

- Transportable tents carried by desert nomads.
- Tepees constructed by early Native Americans.
- Ice igloos built by northern latitude Inuits.
- Sod housed excavated by North American prairie settlers.
- Log and stone cabins constructed in the American West.
- Portable Quonset huts used by polar explorers and workers.



Shelter Precedents

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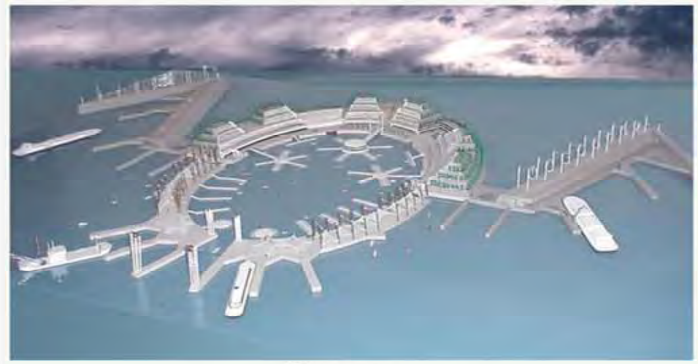
Technology is providing new ways to create habitats in extreme and challenging environments:

- Offshore surface submersible ocean facilities for industry and research.
- Polar research stations and bases for military and energy resource operations.
- Modular and constructed shelters for survivors of natural and man-made disasters.



Ocean

Polar

Special and Extreme Environments

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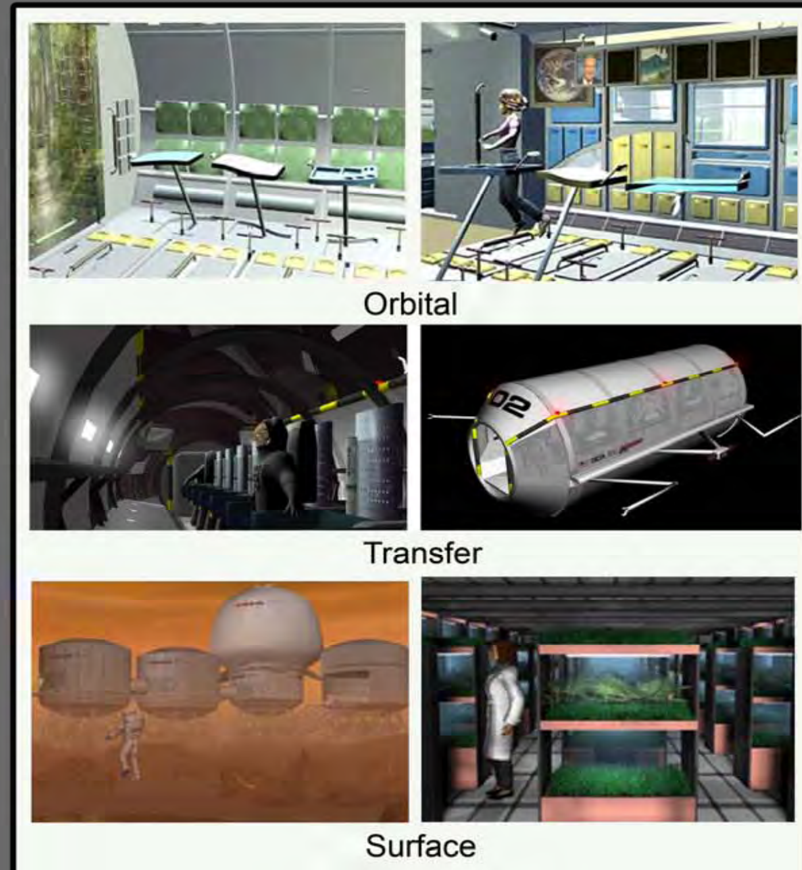
Space architecture extends the ability of humans to live and work beyond Earth:

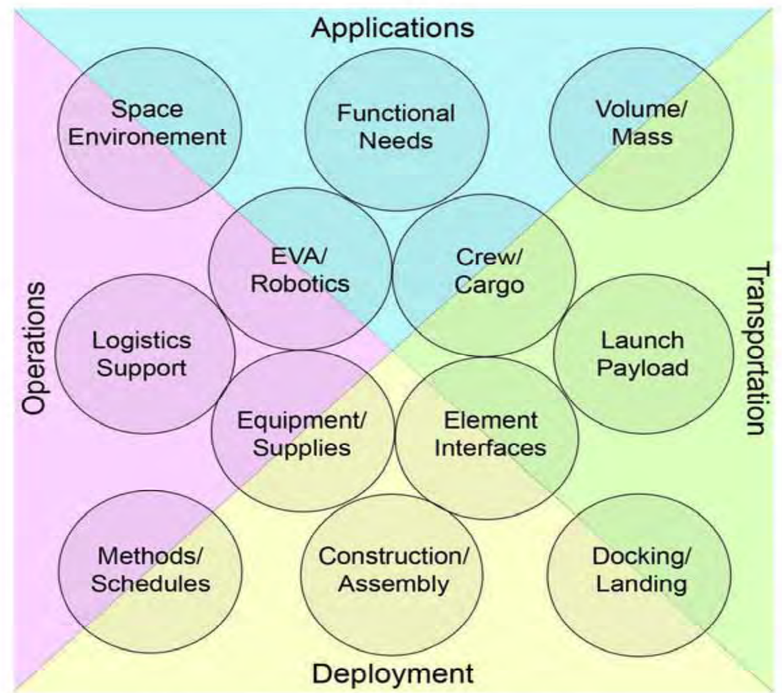
- Weightless and possible artificial gravity orbiting space habitats and laboratories.
- Vehicles and habitats to transfer crews and cargo between Earth and distant destinations.
- Future modules and settlements on the surfaces of the Moon and Mars.



Space Habitat Applications

Astrotectonics embodies a variety of inter-related planning considerations:

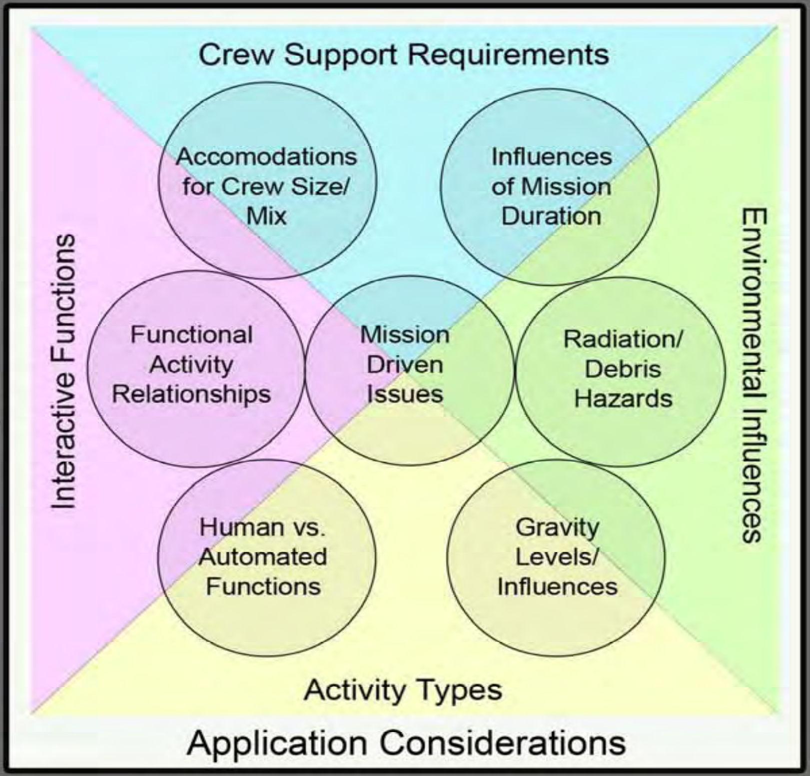
- Requirements imposed uopn elements and support systems by mission applications and environments.
- Transportation constraints determining allowable launch volume/mass and docking/ surface landing options.
- Means and support requirements to deploy and check out the elements and systems for use.
- Comprehensive operational demands and circumstances that will influence utility and versatility.



Key Planning Considerations

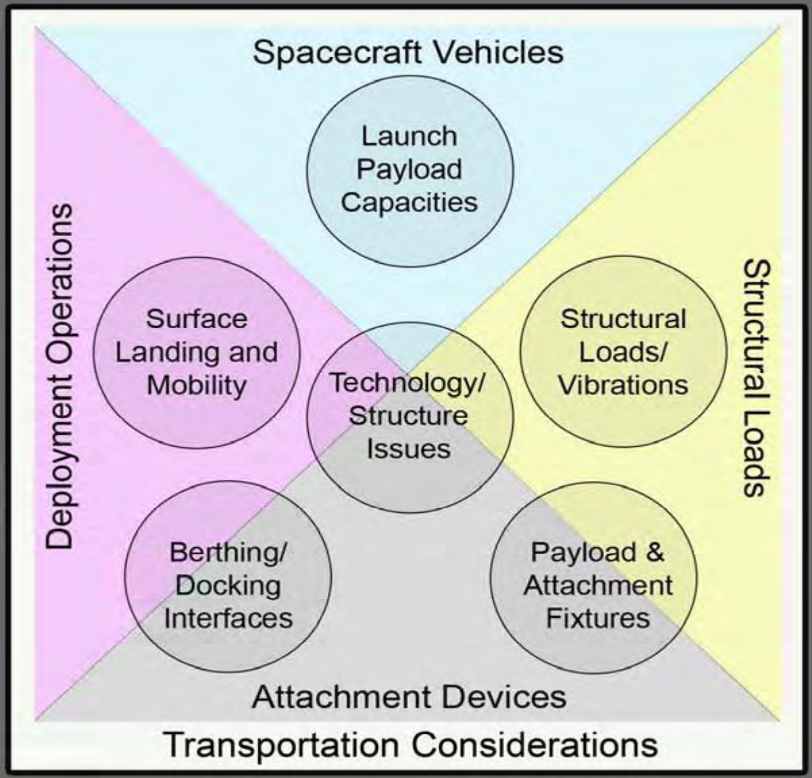
Planning/design of habitat and ancillary structures must respond to mission-specific conditions and priorities:

- Essential crew living and support accommodations.
- Influences of mission lengths upon crew health and expandable supplies.
- Measures to protect humans and equipment from space radiation and debris.
- Influences of reduced/artificial gravity upon crew health and equipment design.
- IVA and EVA human, telerobotic and automated operations/systems.
- Element configurations and layouts to optimize interactive functions.



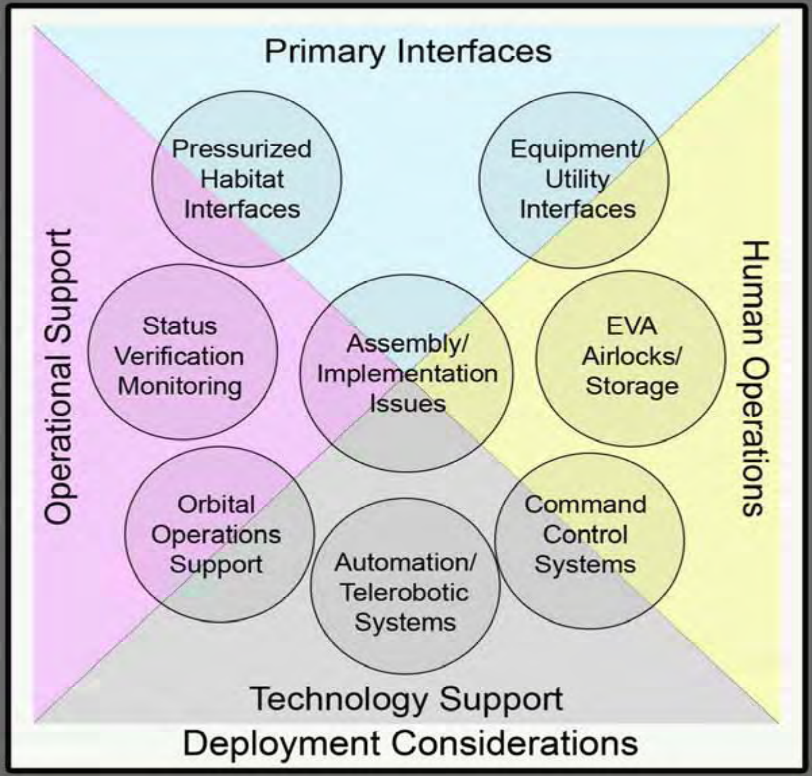
Transportation technology systems and related mission operations impose importantplanning and design considerations:

- Correlation of volume/mass with launch payload capacities.
- Induced loads/vibrations during launch, transfers and landings.
- Means to safely secure people/equipment for accelerations/impacts.
- Orbital and surface docking/berthing locations/fixtures.
- Structural accommodations for surface landings/mobility.



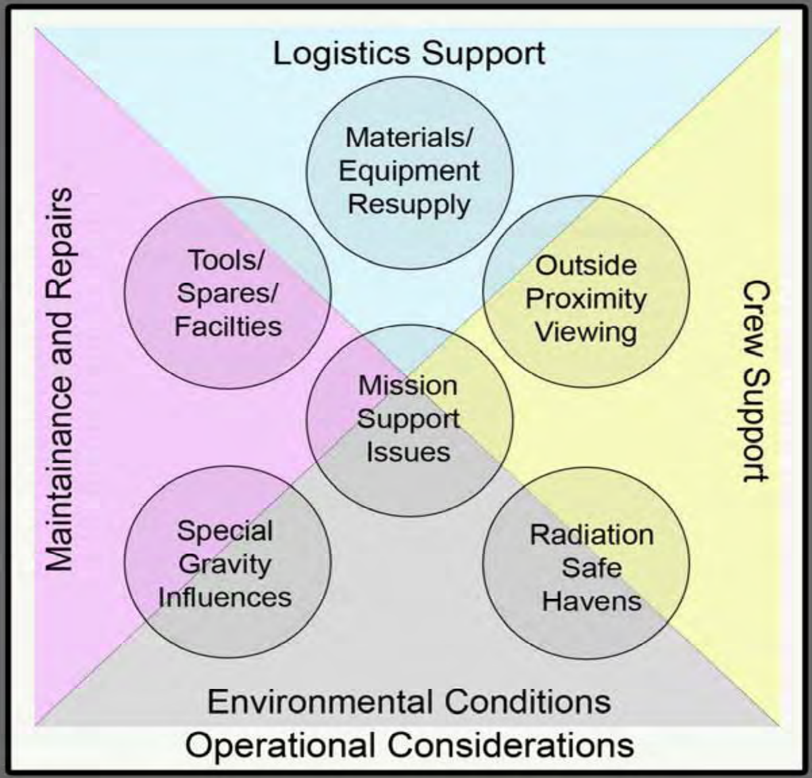
Deployment considerations address systems and activities associated with making structures operational:

- Establishing pressurized connections/seals between habitats/elements.
- Accomplishing and verifying electrical, fluid and atmosphere interfaces.
- Providing EVA access/egress and equipment stowage.
- Ensuring necessary crew command/control systems.
- Minimizing IVA and EVA operations using automated/telerobotic devices.
- Accommodating/utilizing orbital facility resources for implementation.
- Affording continuous remote and on-site safety status monitoring.



Planning and design must provide for immediate and evolutionary operational requirements, including:

- Means for accessing and stowing resupply materials and equipment.
- Outside viewing for operational control, activity support and recreation.
- Radiation storm shelters to protect crews during hazardous solar events.
- Restraint systems and mobility aids for reduced/artificial G.
- Tools, spares and facilities for routine/ emergency maintenance.



Earth Structures	Space Structures
Live Loads:	Acceleration Loads:
• People/Activities	• Launch
• Equipment Operations	• Reentry/Landing
Static Loads:	Static Loads:
• Equipment/Structures	• Pressurization (Tensile)
•Snow and Ice	• Artificial/Low Gravity
Environmental Loads:	Environmental Loads:
• Wind	• Thermal Stresses and Structure Deformation
•Earthquakes	
Vibration/Impact Loads:	•Vibration/Impact Loads:
• Equipment Systems	• Equipment /Structures
• Machinery Operations	• Flight Operations

Earth - Space Load Comparisons

- **Transportation to/from Orbit:**
  - -Orient structures to optimize G-force load vectors.
  - -Provide stiffness and structural isolation to minimize vibrations.
  - -Secure elements to avoid damage to spacecraft and structures.
- **In Orbit and on Lunar / Planetary Surfaces:**
  - -Design structures for maximum docking impact forces.
  - -Dampen/ isolate fragile systems from impact forces.
  - -Shield vulnerable areas from impact damage.
  - -Design for maintenance repair of pressurized elements.
  - -Shield/ insulate vulnerable structures from thermal extremes.
  - -Select materials that resist vibration and thermal fatigue.
- **Strength :** Ability to carry stress (forces per area without failure)
- **Stiffness :** Resistance to deflection under loads ("Young's Modulus"........stress/strain)
- **Coefficient of Thermal Expansion** : Change in deformation due to change in temperature

Space Load Considerations and Definations

Structural Loads

BACKGROUND

ASTROTECTONICS

- **Requirements for People:**
  - Interior volume and layout requirements to support activities.
  - Integration of windows and other structural elements.
  - Safe havens and multiple means of egress.
  - Airlocks for EVA access / egress.
- **Requirements for Construction & Operations**
  - Integrated and separate energy supply systems.
  - Means for heat rejection and active thermal control.
  - Structural design for safe/ reliable operations.
  - Ancillary structures such as attachment trusses and enclosures.

Structure Application Considerations in Space

- **Influences of Space Environment on Materials:**
  - Temperature extremes and fatigue due to changes
  - Exposure to molecular oxygen and ultraviolet light degradation.
  - Pitting and penetrations from micrometeoroids and space debris
  - Radiation effects on electronic systems.
- **Influences of Material Selection on Human Health and Safety:**
  - Protection from primary and secondary radiation emissions.
  - Insulation from heat and thermal changes.
  - Safe pressure containment.
  - Toxic offgassing avoidance.
  - Fire and smoke retardant.

Material Durability and Safety Considerations

Requirements and Influences

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- **Access to Critical Areas:**
  - Visual inspection for problem detection / maintenance.
  - Physical access for periodic maintenance / emergency repairs.
  - Adequate servicing space for people, tools and gloved hands.
  - Use of EVA mobility aids and external monitors/ sensors.
- **Maintenance Constraints and Operations:**
  - Quick/ easy disconnects and replacements.
  - Standardization of parts and tools.
  - Modularization of components for rapid change outs.
  - Accommodations for microgravity conditions.
  - Avoidance of hazardous processes/ materials.

Maintenance and Repair Conditions

Size/ Weight Limitations:

- Imposed by Launch
- Imposed by Landing

Form Imposed by Structures:

- Interior volume/geometry
- Overall configuration
- Mass distribution (orbit)
- Debris exposure

Assembly / Deployment Requirements :

- Stages / procedures
- Support requirements
- EVA time
- Robotic applications
- Evolutionary changes
- Maintainabilty

General Structural Design :

- Circulation interfaces
- Utility locations
- Window attachments
- Radiation protection
- Distortion under pressure
- Debris Protection

Summary Design Influences

Summary Considerations

Additional information relevant to this section can be found in Part IV, Section A of this SICSA Space Architecture Seminar Lecture Series titled Space Mission and Facility Architectures, and in SICSA Outreach Vol. 2, No. 2 “Astrotectonics: Construction Requirements and Methods in Space (1984). Both documents are available on our website: www.sicsa.uh.edu.

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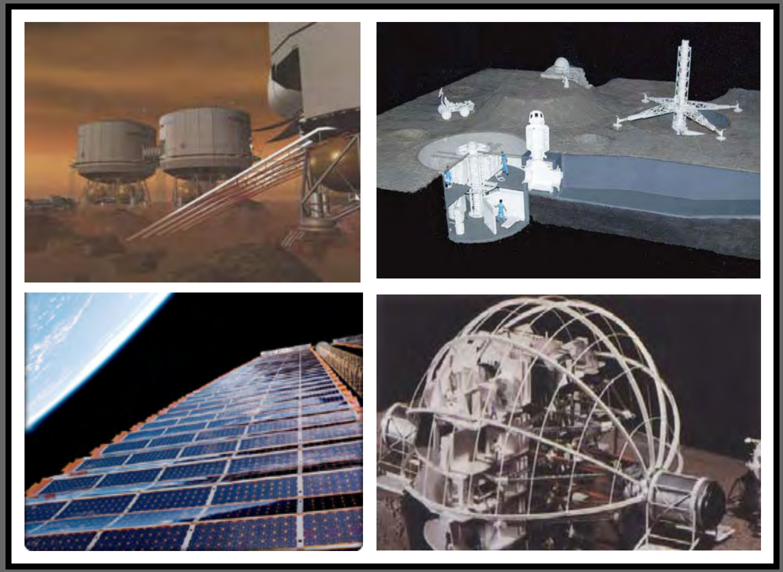
SECTION B: SPACE STRUCTURES & APPLICATIONS



Structures and materials used in space are typically subjected to a variety of harsh and destructive conditions that present design challenges:

- Structural design must stiffen and attach elements to avoid damage during rapid velocity changes and docking maneuvers, dampen/isolate vibrations, accommodate internal pressures, and prevent thermal fatigue stresses.
- Design and material selection must protect people and equipment from radiation, debris penetrations, and other space environment hazards.

Loads/Stresses	Space Environment
Dynamic Forces: •Launch/Landing •Docking/Berthing •Vibrations	Radiation Effects: •Cosmic Radiation •Solar Radiation •Nuclear Sources
Pressure Forces: •Habitat Vessels •Airlocks/EVA Suits •Interface Seals	Debris Hazards: •Micrometeoroids •Man-made •Surface Ejecta
Thermal Extremes: •Orbit Phases •Vehicle Reentry •Planetary Surfaces	Material Degradation: •Atomic Oxygen •UV Radiation •Dust/Contaminants

Operational and Environmental Issues

Structures must be designed to mitigate effects of launch, orbital docking and reentry/landing loads as each application demands:

- External and internal elements should be designed, secured and oriented to avoid damage during high-g force accelerations/decelerations.
- Support attachments should properly align equipment along the load path.
- The structures should be sized and engineered for necessary stiffness to avoid deleterious bending and axial frequency vibrations.

Quasi-static launch thrust and staging loads:

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

Structural dynamic loads from engine vibration transmitted through vehicle:

Shuttle (average)	5-35 hz	0.75 g
Ariane (average)	5-7 hz	7.7 mm
	7-15 hz	1.5 g
	15-100 hz	1.0 g

Launches impart lateral/axial loads and engine vibration loads to payload structures which must be accommodated.

Source: Agriwal . 1986, Design of Geosynchronous Spacecraft, Prentice Hall.

Launch, Docking and Reentry Loads

Structural vibrations induced by orbital maneuvers and operations can interfere with the flight vehicle's control system and produce high structural loads:

- Docking maneuvers can produce inertial impacts that cause large appendages such as solar arrays to flex and oscillate.
- Frequencies of different connected elements combine into "coupled modes" that complicate control recovery.
- Onboard equipment such as centrifuges and thrusters are additional vibration sources.

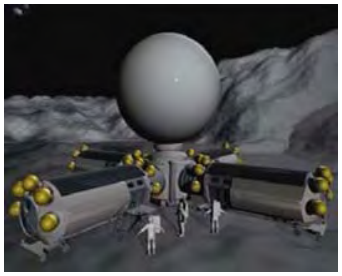
Flexation of long structures and appendages during orbital operations presents troublesome some flight control problems.

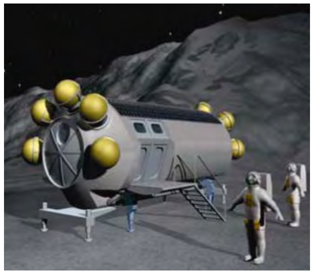
Solar Panel

Vibration Sources and Problems

All habitable structures in the hard vacuum of space must be capable of containing internal pressure loads of 0.6-1.0 atmosphere without leaking:

- Pressurized structures, regardless of materials used, are predominantly circular cross-section vessels that can include spherical, tubular "sausage" or torroidal "innertube" geometries.
- Pressure vessel penetrations for windows, hatches between modules, orbital docking ports, utility pass-throughs and other interfaces present special leak seal priorities.

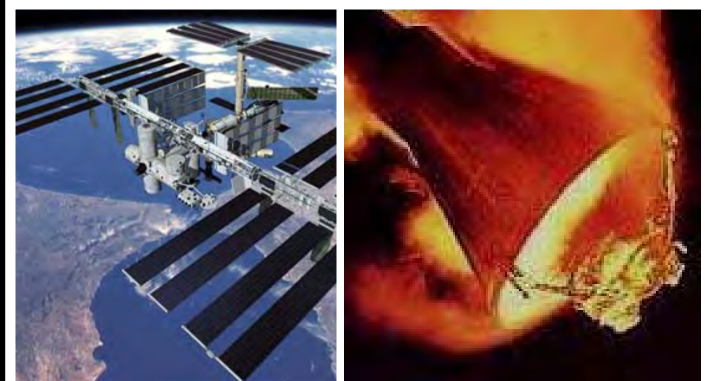

Spherical Structure


Standard Module


Stanford Torus

Pressurized Habitat Forms

NASA



Space Station in Orbit   Reentry Capsule

Spacecraft temperature fluctuations caused by alternate exposures to solar radiation and dark space as well as aerodynamic heating during atmosphere reentry maneuvers produce thermal stresses on structures and equipment:

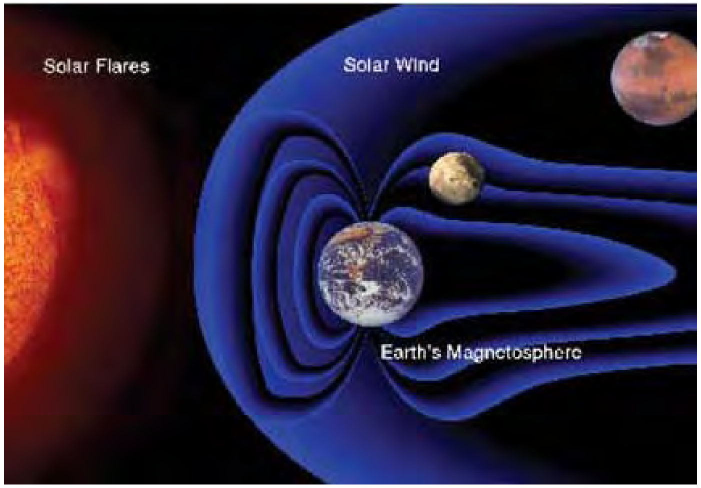
- External materials must be selected to avoid structural fatigue and thermal degradation.
- Exposed structures, equipment and utility interfaces require thermal hardening.
- Heat shields, insulating blankets and surface coatings can dissipate and reflect heat.

External walls and surfaces experience extreme and abrupt temperature changes when transitioning from sunlight to shade and during deorbit reentries into an atmosphere.

Thermal Loads and Interventions

Space structures must shield crews and equipment from harmful radiation produced from various sources:

- Galactic Cosmic Radiation (GCR) is primarily protons with very low flux density and high energy that can pass through most shields.
- The Van Allen Belts that surround Earth are the most hazardous region in our Solar System, comprised of trapped protons and electrons.
- Large solar flares which occur with different frequencies over 11 year cycles can elevate radiation levels to lethal intensities.



Trapped protons and electrons create hazards within the van Allen Belts, beyond which cosmic radiation and large solar flares present risks to people and equipment.

The Natural Radiation Environment

SPACECRAFT SYSTEMS DESIGN & OPERATIONS

Radiation dose exposures are important factors that significantly influence allowable crew mission periods and spacecraft system life:

- High radiation levels such as those that occur during large solar storms can increase long-term cancer and mortality risks, or even produce near-term illnesses and deaths.
- Radiation degrades spacecraft solar arrays and other electronic devices as well as lubricants and materials.

Dose Equivalent in REMs = Dose in RADs x QF

Where: QF = 1-5 x-ray,gamma-ray,electrons,and beta particles
(2-20) for neutrons,20 for alpha,20+ for iron ions

Dose Equivlent in REMs

Effect on Humans	Dosage (REM)
Blood count changes in population	15-20
Vomiting “effective threshold”*	100
Mortality “effective threshold”*	150
LD_{50}** with minimal supportive care	320-360
LD_{50}** with full supportive medical treatment required	480-540

*Lowest dosage affecting atleast 1 member of the exposed population

**LD_{50} is a lethal dosage in 50% of the exposed population.

Radiation Effects on Humans

HUMAN SPACEFLIGHT

Material	Damage Threshold (gray)
Humans and animals	$10^{-1} – 10^{0}$
Electronics	$10^{0} – 10^{4}$
Lubricants, hydraulic fluid	$10^{3} – 10^{5}$
Ceramics, glasses	$10^{4} – 10^{6}$
Polymeric materials	$10^{5} – 10^{7}$
Structural metals	$10^{7} – 10^{9}$

Typical Sensitivities to Radiation Doses

Radiation Effects on Crews and Equipment

Protecting humans and equipment from hazardous radiation levels can apply a variety of countermeasures:

- Select structural materials that resist degradation and penetration of types of radiation that may be encountered.
- Provide external and/or internal shielding including appropriate thickness of pressure vessel walls and insulating barrier materials such as internal water stowage bladders.
- Place structures between the crew and sensitive electronics to minimize doses and dose rates.
- Oversize electronic systems with a safety margin and provide redundancy.

Shielding Depth (cm Al)	Dose (GY)
0.5	4.68
1.0	1.95
1.5	1.02
2.0	0.59
2.5	0.37

Radiation dose units termed “gray” (GY) are defined as one J/kg of penetrating energy.

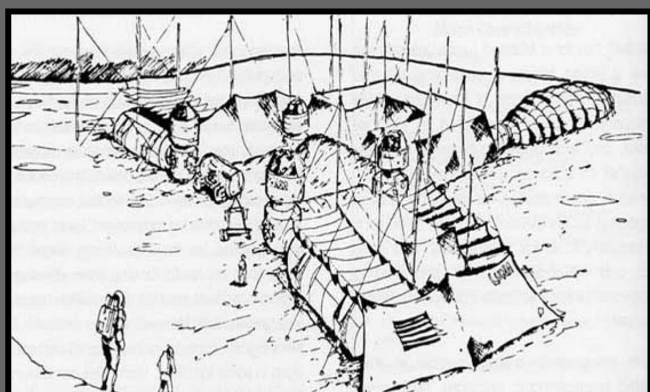
Radiation Doses from a Very Large Solar Storm

The amount of energy deposited in a material depends upon the type of radiation and material. Grays (GY) are associated with potential biological damage. Electrons moving near the speed of light penetrate farther than protons, and produce secondary radiation x-rays that can be more damaging than primary radiation that caused it.

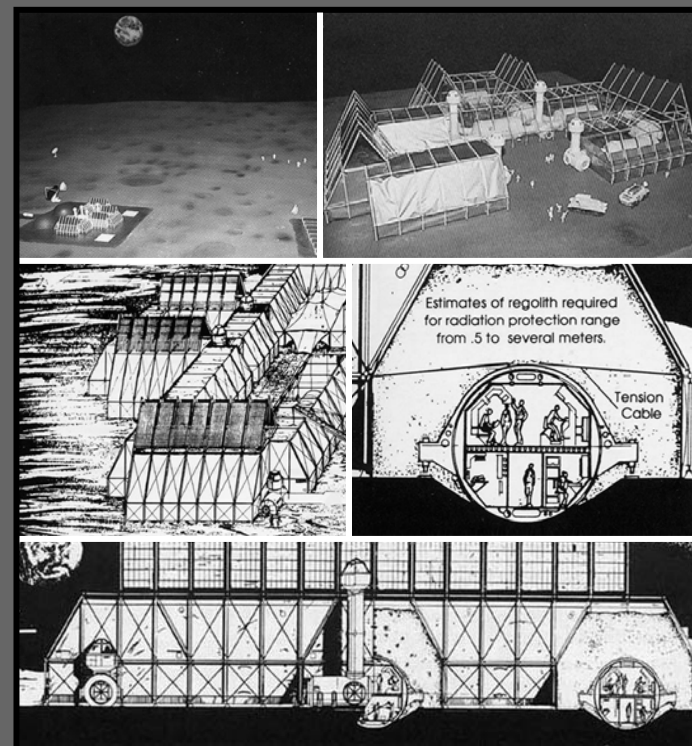
Radiation Protection

A concept using lunar regolith for solar radiation shielding over conventional habitat modules:

- Outer structure contains regolith in place.
- Flexible tunnels connect modules.
- Power is provided by photovoltaics.



SICSA's First Lunar Outpost (FLO) Concept

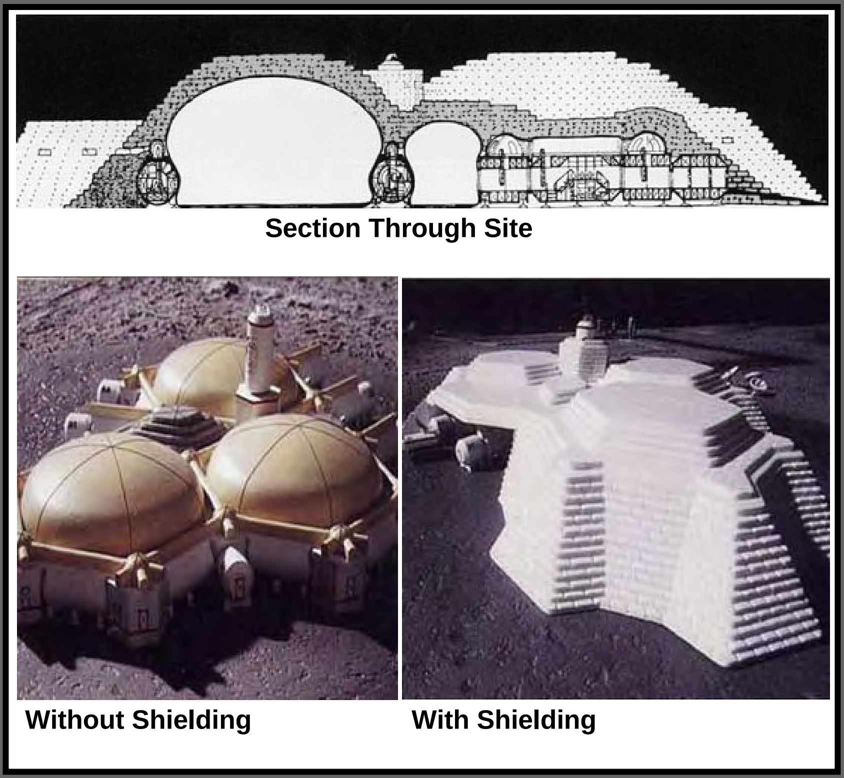


Lunar Soil as a Radiation Barrier

A concept using bags of lunar regolith for solar radiation protection:

- Helps to control dust.
- Enables a steeper slope angle to require less materials than for loose particles.
- Can facilitate robotic stacking operations.

SICSA's "Project LEAP" Lunar Concept



Section Through Site

Without Shielding

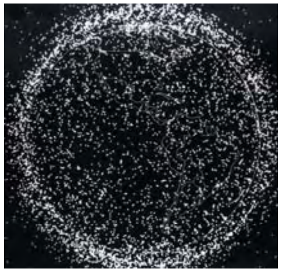
With Shielding

Bags of Lunar Soil as a Radiation Barrier

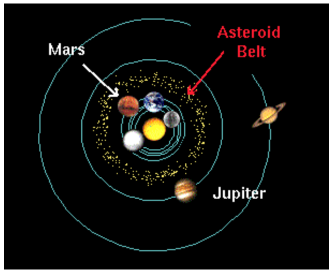
SPACECRAFT SYSTEMS DESIGN & OPERATIONS

The "vacuum" of space is populated by natural and man-made particles of widely ranging size and destructive potentials:

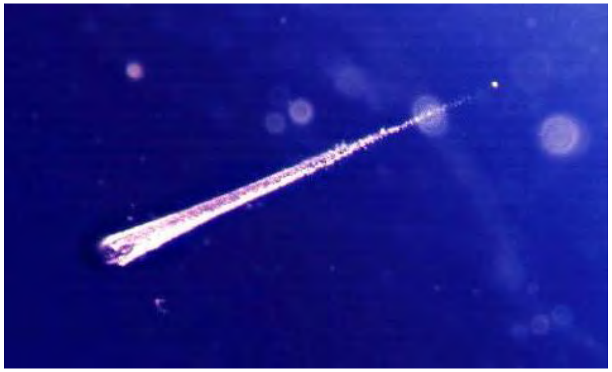
- Spacecrafts operating in Earth orbits can be expected to eventually encounter micrometeoroids, and possibly small fragments pf exploded rocket debris traveling at highly energetic hyper velocities.
- More than 7,000 asteroids have been identified in our Solar System, most between Mars and Saturn, and it is expected that the number of smaller ones is vastly greater.
- Rock ejecta produced by lander thrusters interacting with the surfaces of the Moon or Mars can present projectile hazards.



Space Debris in Earth Orbit



Asteroid Belt Between Mars and Jupiter

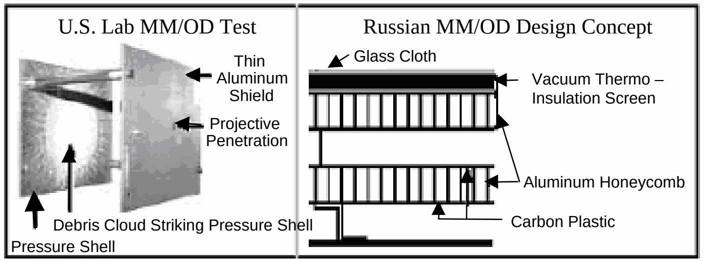


Meteoroid Photo from the EURECA Spacecraft

Space Debris Hazards

MM/OD shields include different design types and applications:

- Shielding used on US International Space Station (ISS) elements consists of a 0.05 inch thick sheet of aluminum separated from the pressure shell by a 4 inch gap.
- Debris protection blankets are mounted beneath the shields in particularly critical areas for added protection.
- Debris shielding shutters are provided to protect windows and to offer atomic oxygen, UV and thermal protection.
- The Russian segment design combines a variety of materials.



Comparison of US and Russian MM/OD Systems

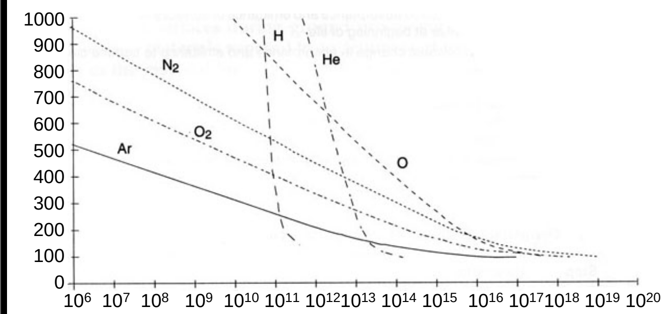
Micrometeoroid Orbital Debris (MM/OD) shields are attached to the outside of spacecrafts to absorb projectile energy and break the particles into much smaller fragments before they reach the critical pressure shell. The “debris cloud” that reaches the shell distributes remaining energy over a much broader area to reduce penetration risks.

Space Debris Protection

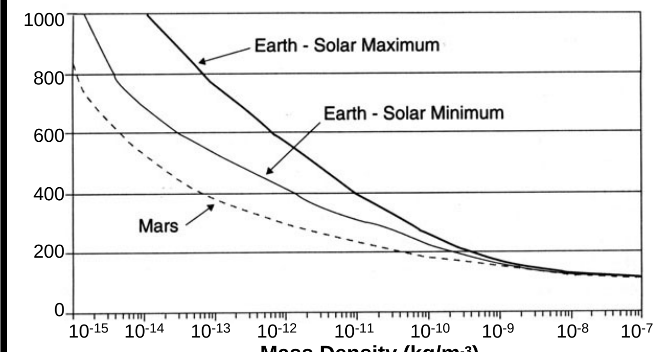
HUMAN SPACEFLIGHT

At Low Earth Orbit (LEO) altitudes, atomic oxygen, which makes up most of the thin atmosphere, produces drag on spacecrafts, causing orbits to decay. It can also erode the surface materials:

- Atomic oxygen (AO) is very reactive chemically, and degrades some materials through "sputtering" to effect thermal, optical and structural properties.
- The density of the atmosphere is influenced by levels of solar activity which change over 11 year cycles.
- The amount of surface erosion that occurs is determined by the cumulative "flux" (energy) that is received per time unit, and the material's "reaction efficiency".



Earth's Atmosphere below 1000 km Altitude



Atmospheric Mass Density as a Function of Altitude

Material Degradation / Atomic Oxygen

HUMAN SPACEFLIGHT

The deleterious effects of atomic oxygen can be avoided or reduced through proper design:

- Choose exterior spacecraft materials that are resistant to sputtering and erosion.
- Shield sensitive surfaces from AO sputtering and erosion and configure/orient low-altitude vehicles to minimize atmospheric drag and orbital decay rates.
- Select protective coatings that have acceptable reaction efficiencies.

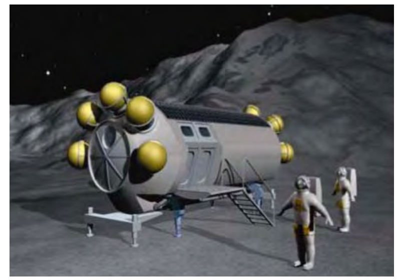
Material	Reaction Efficiency (10^{-24} cm^3/atom) Range	Best Value
Aluminum	-	0.00
Carbon	0.9-1.7	-
Epoxy	1.7-2.5	-
Fluoropolymers		
- FEP Kapton	-	0.03
- Kapton F	-	<0.05
- Teflon,FEP	-	<0.05
-Teflon	0.03-0.50	-
Gold	-	0.0
Indium Tin Oxide	-	0.002
Mylar	1.5-3.9	-
Paint		
Polyimide	0.75-4.50	-
-Kapton	1.4-2.5	-
- Kapton H	-	3.04
Silicones		
- RTV560	-	0.443
-RTV670	-	0.0
Silver	-	10.5
Tedlar		
-Clear	1.3-3.2	-
- White	0.05-0.6	-

Efficiency of Reactions between Atomic Oxygen and Other Materials.

Reducing Atomic Oxygen Effects

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 Type

Telescoping Type

Inflatable Type

Hybrid Inflatable Type

Fixed and Deployable Approaches

Habitat Module Types

Conventional modules apply construction methods that have been proven effective throughout the history of human spaceflight:

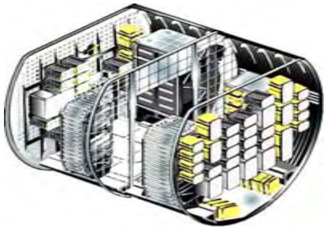
- They are simplest to design and deploy, and offer immediate operational capabilities.
- They offer good structural integrity and reliability, using materials that have been demonstrated in harsh space environments.
- They enable utility and equipment systems to be installed and checked out prior to launch.
- They afford the easiest and surest integration of windows, hatches/berthing ports and external attachment fixtures.


ISS US Lab Module


Skylab Orbital Facility


Russian Service Module


Mir Space Station Modules

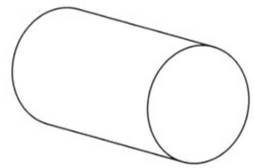
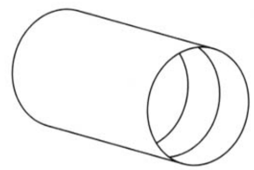
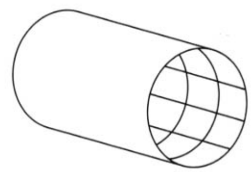

SPACEHAB Module


SICSA Lunar Modules

Conventional Module Examples

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.

 Monocoque	The Monocoque structure is essentially a "can" which is lightest and easiest to build, but is least resistive to structural load forces.
 Semi - Monocoque	The Semi- Monocoque structure incorporates ring frames to increase the outer skin's ability to resist buckling forces.
 Skin Stringer	The Skin Stringer structure design is the most rigid to resist axial and bending loads, but adds mass.

Types of Pressure Structures

Typical modules have "primary structures" that provide structural integrity and attachment functions:

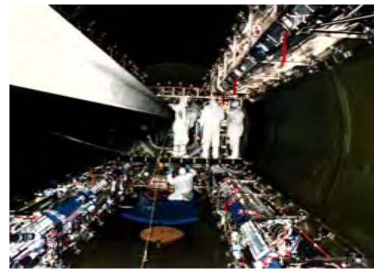
- Longerons are used to increase stiffness and load-carrying capabilities of pressure shell panels.
- Ring frames provide attachment points for longeorns and shell panels.
- Shell panels contain atmosphere pressurization loads.
- Window and hatch/berthing port frames provide pressure-tight interfaces.
- Integrated trunnions secure the overall module within the launch vehicle.

Primary Structure of a Typical Module

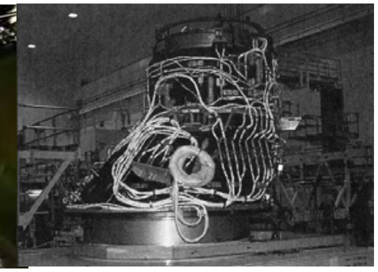
Primary Habitat Module Structures

Internal and exterior secondary structures transfer their loads to the primary structures, and include:

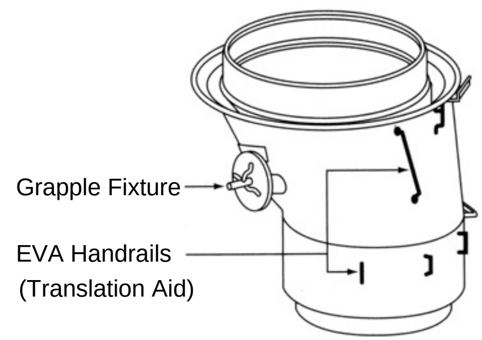
- Standoffs that provide attachment points for racks and passageways for electrical cabling, fluid lines and air distribution.
- Meteoroid debris shielding and window shutters.
- Crew and payload translation aids include internal and EVA handrails.
- Grapple fixtures for connections to other spacecraft elements.



Standoffs Inside the US lab
Internal Structure



Pressurized Mating Adaptor
External Structure



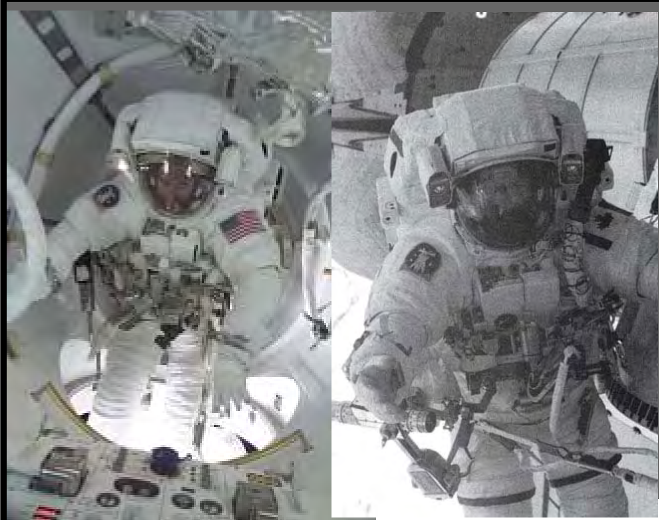
Handrails and translation aids are used by EVA crews, and grapple fixtures are used by robotic arms to install or move elements.

Pressurized Mating Adaptor

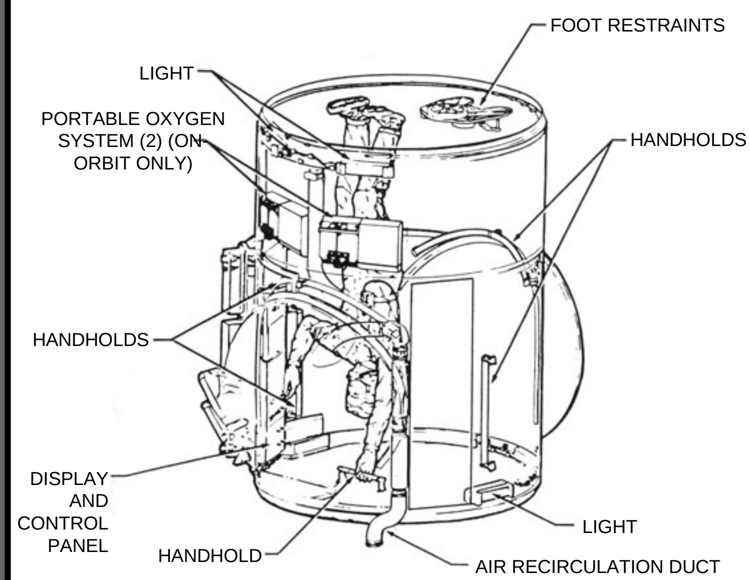
Secondary Habitat Module Structures

NASA

Airlocks are pressure vessels that can be located either inside or outside of other habitable structures. They must be sized to accommodate suits and equipment for all EVA applications.



ISS Airlock (Inside and Exterior)



Space Shuttle Orbiter Airlock

Airlock

Telescoping modules offer a means to expand deployed volume using relatively conventional technology:

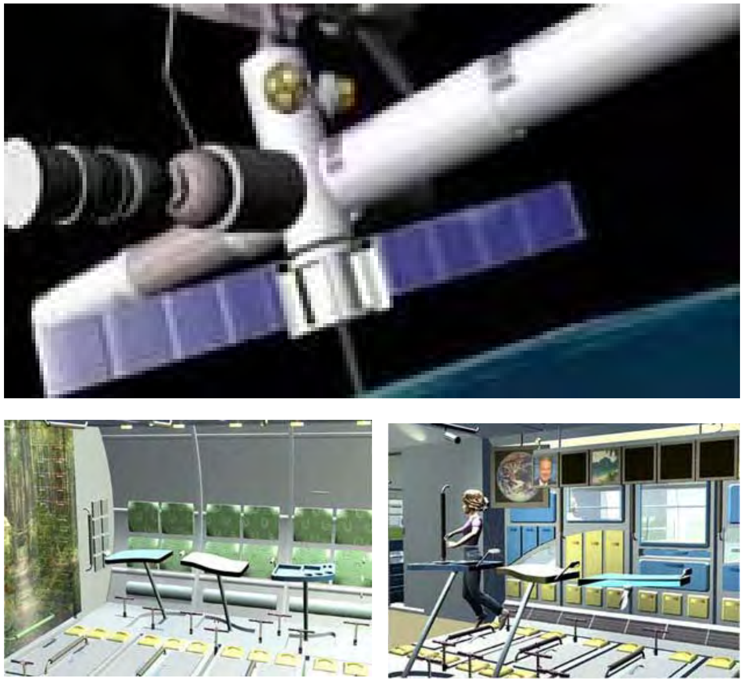
- One hard section would slide into another to shorten the undeployed length during launch.
- The inner section would have utility systems and equipment pre-integrated and checked out prior to launch.
- Following deployment in orbit or on a surface, the vacated outer section can be used for activities requiring a larger open volume, or can be outfitted for equipment using extendable/modular utility lines originating from the other section.

SICSA Concept

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.



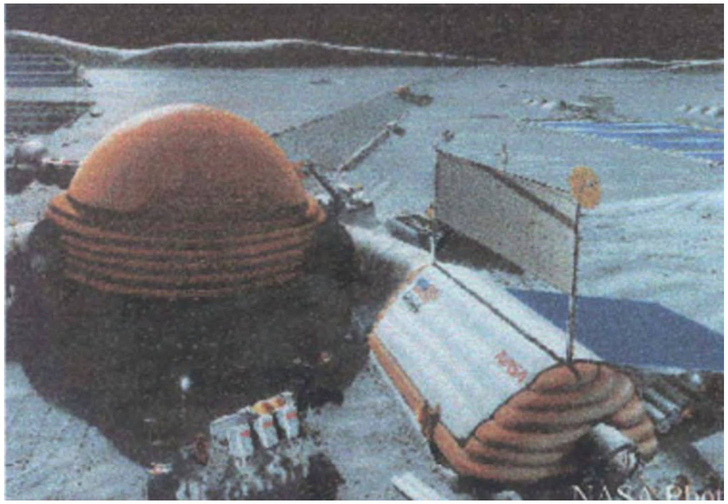
Life and Biological Sciences (LaBS) Facility

SICSA Concept

NASA

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.



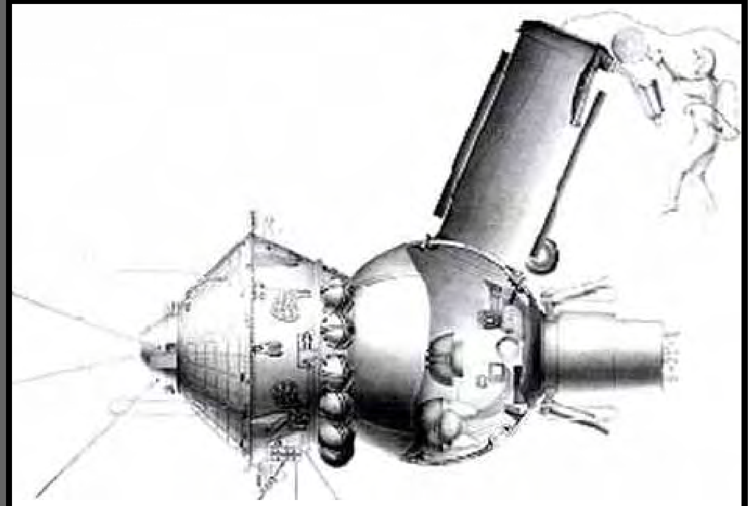
Possible inflatable system applications include lunar/ planetary facilities as well as smaller elements such as airlocks and transfer tunnels.

NASA Lunar Base Concept

Benefits and Applications

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.

Russian Voskhod-2 Inflatable Airlock

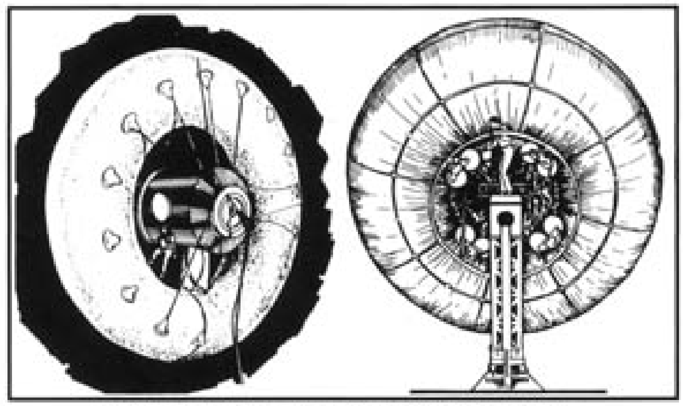
Russian Airlock Demonstration

GOODYEAR AEROSPACE CORPORATION

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.



24 Foot Diameter Toroidal Structure

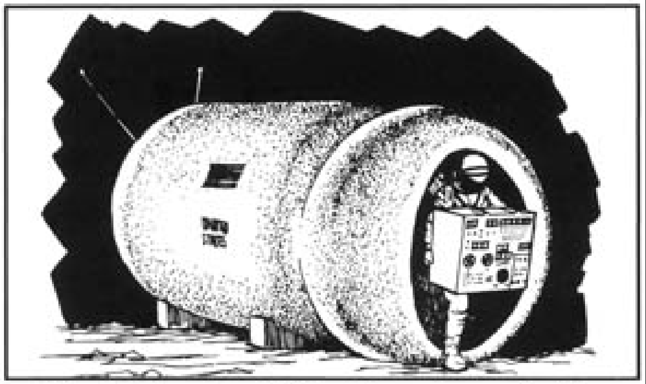
Construction: Meriodonally-wound Dacron filaments with a Butyl rubber binder and internal bladder of Butyl-impregnated nylon for gas retention packaged in an 8 foot diameter hub for launch with deployed volume 2,300 cubic feet. Weight approximately 4 oz/ft^2 of surface area. Designed for 5 psi pressure.

Early GAC Developments

GOODYEAR AEROSPACE CORPORATION

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 ft^3.



7 Foot Diameter, 15 Foot Long Lunar Shelter

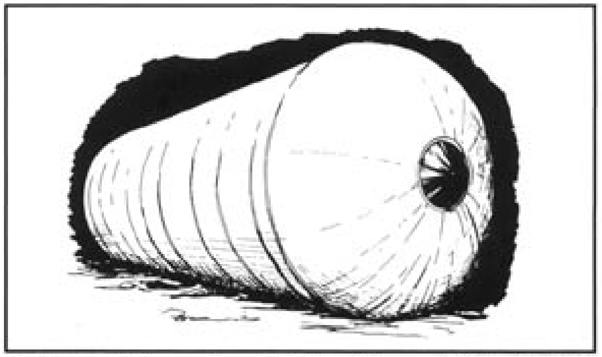
Construction: 3-layer laminate consisting of nylon outer cover, closed-cell vinyl foam, and inner nylon cloth bonded by polyester adhesive layers. Internal volumes of shelter and airlock were 410 cubic and 105 cubic feet, respectively. Weight.126 pounds/ft^2 (total, 326pounds). Designed for 5 psi pressure.

Early GAC Developments

GOODYEAR
AEROSPACE
CORPORATION

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.



12.8 Foot Diameter, 37.5 Foot Long "Moby Dick"

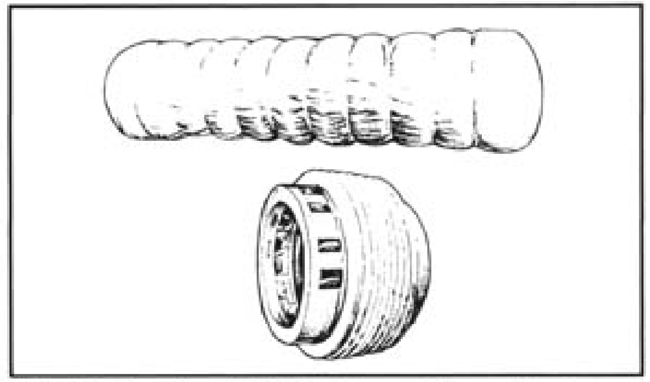
Construction: 1/6 inch thick gas bladder made from 2 inch wide Dacron 52 yarn dipped in a polyester resin bath. The bladder was sealed by a polyvinyl chloride (PVC) foam and the entire structure was covered by a 1-3/4 inch flexible polyurethane foam, over which was placed a nylon film-fabric laminate painted with a thermal control coating. The 1622 pound structure was designed for 5 psi pressure.

Early GAC Developments

GOODYEAR
AEROSPACE
CORPORATION

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.



4 Foot Diameter, 14.2 Foot Long Spacelab Tunnel

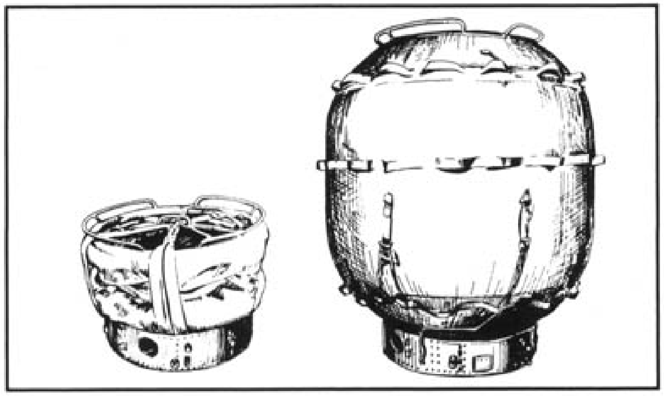
Construction: 2 plies of Nomex unidirectional cloth fabric coated with Viton B-50 elastomer wrapped around steel beads made from wraps of 0.0307 inch diameter wire. Debris shields constructed of kevlar 29 covered the surface. The 170.5 inch length compressed to 20.5 inches. Total weight 756 pounds.

Early GAC Developments

GOODYEAR AEROSPACE CORPORATION

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.

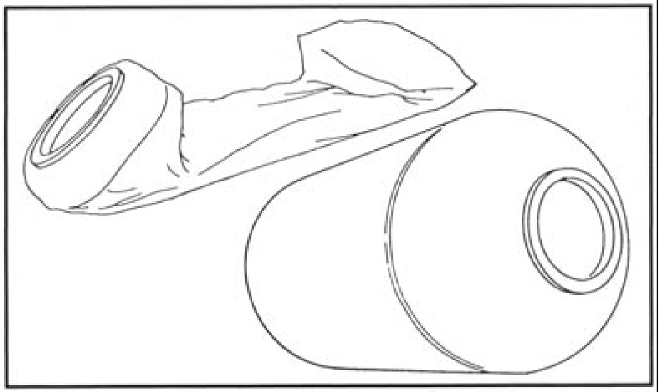


5.2 Foot Diameter, 6.2 Foot Long Airlock

Construction: Multilayered expandable material consisting of a composite bladder; filament-wound 3.6-mil steel wire structural layer; flexible polyurethane foam micrometeorite barrier; and fabric-film laminate thermal coat. The unit weighed 185.6 pounds and fit into a 4 foot diameter, 2.5 foot tall cylinder.

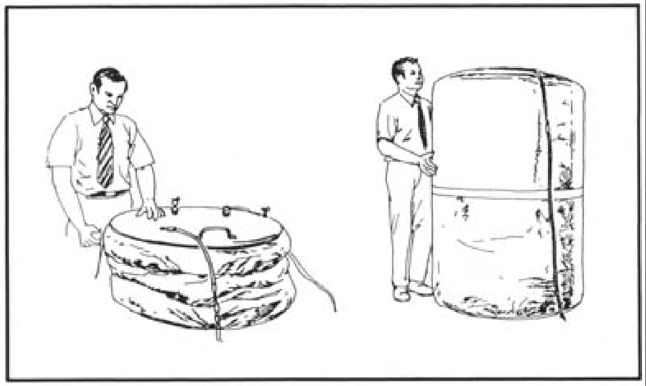
Early GAC Developments

GOODYEAR AEROSPACE CORPORATION



"Necking Down" Folding Technique

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.



"Accordion" Folding Technique

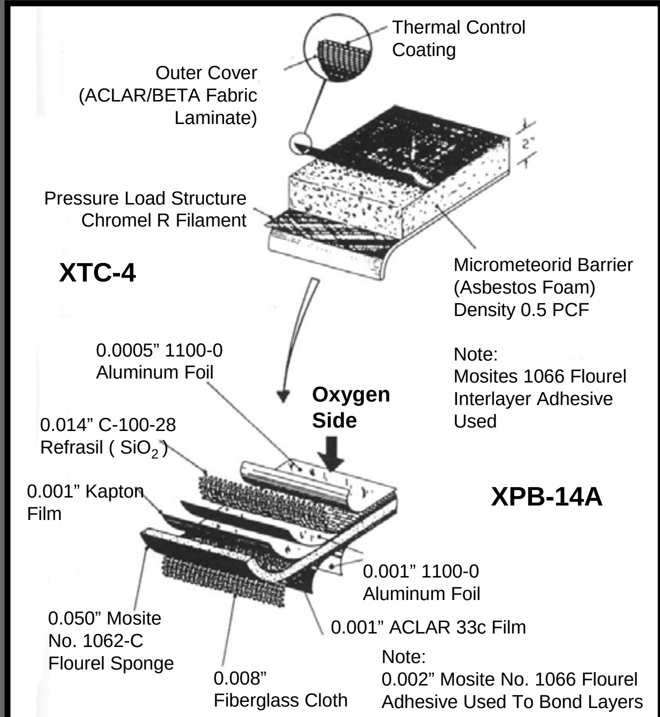
The flex section for crew transfer between the Orbiter crew cabin and Spacelab module used unidirectional fabric plies wrapped around rings of steel wire to minimize interface section loads resulting from axial, lateral, torsional and rotational displacements caused by installation, thermal gradients and maneuvering. Fillets added to outer diameters of the wire rings ensured a smooth transition and avoided fabric abrasion.

GAC Folding Techniques

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.

GOODYEAR AEROSPACE CORPORATION



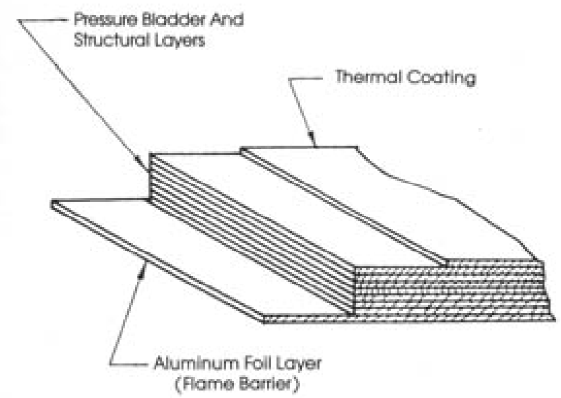
XTC-4 Nonflammable Wall System

GAC Pressure Wall Construction

GOODYEAR AEROSPACE CORPORATION

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.



Orbiter-Spacelab Tunnel Construction

• Strip tensile strength	1074 lb/inch
• Weight after cure	46.13 oz/yd^2
• Thickness after cure	0.040 inch
• Peel adhesion after cure	29.7 lb/inch

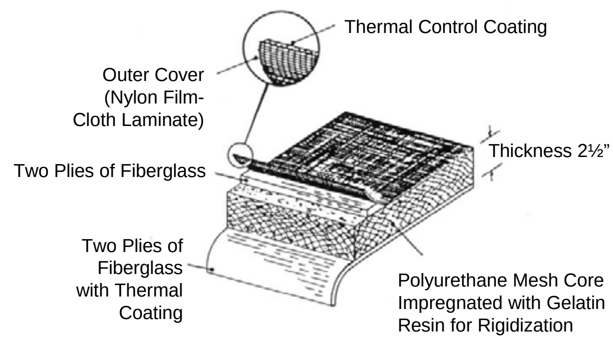
Nomex/Viton Properties (Per Ply Average Values)

GAC Pressure Wall Construction

GOODYEAR AEROSPACE CORPORATION

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.



Example Foam-Rigidized Wall System

• Outer cover and thermal coating	0.068
• 4 Plies of fiberglass	0.142
• 3 Adhesive interlayers	0.030
• Mesh core and gelatin resin	0.750
• Inner thermal coating	0.040
• Total system weight	1.030

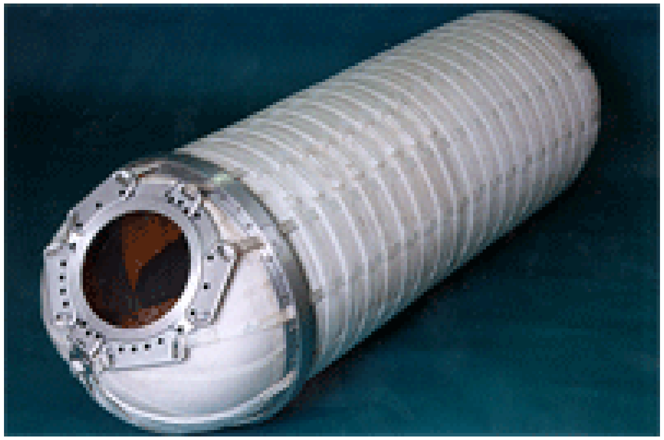
Material Weight (Pounds/Foot^2)

Foam – Rigidized Structures

ILC DOVER

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.



ILC Dover,, developer of EVA suits, also created an inflatable hyperbaric chamber for treatment of flying personnel who experience the bends during the 1980s.

ILC Collapsible Hyperbaric Chamber

Early Inflatable Development

ILC DOVER

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::

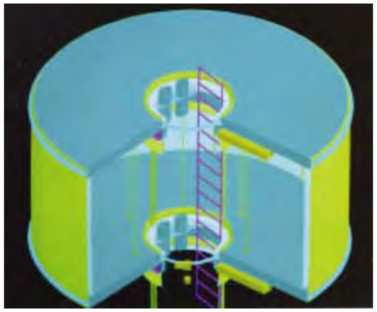
- The secondary (outer) envelope would be pressurized at 17.2 KPa to maintain geometry.
- Habitation Spaces would be pressurized at 51.7 KPa.

Lawrence Livermore Studies

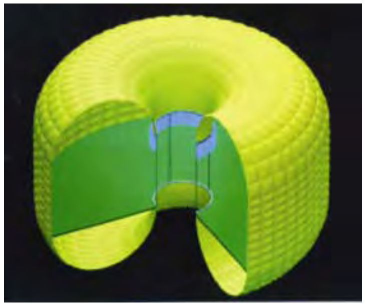
ILC DOVER

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.



Inflatable Compartment



Rigid Wall Compartment

Key Features	All-Flexible Composite	Rigid End Plates
Total System Mass (kg)	1523	1344
Total Usable Vol. (m^3)	232	196
Total Packed Vol. (m^3)	29	32

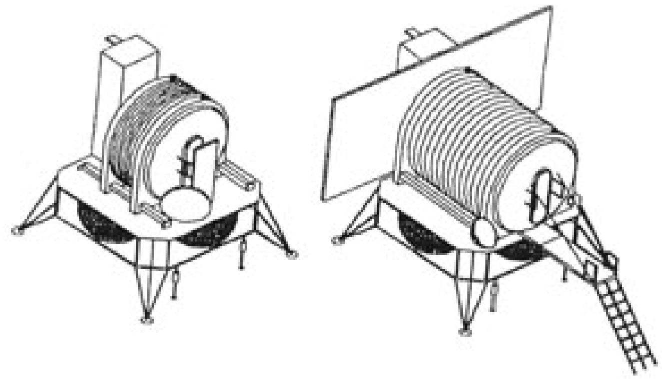
Livermore Option Comparisons

Lawrence Livermore Studies

ILC DOVER

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.



Stowed and Deployed Habitat

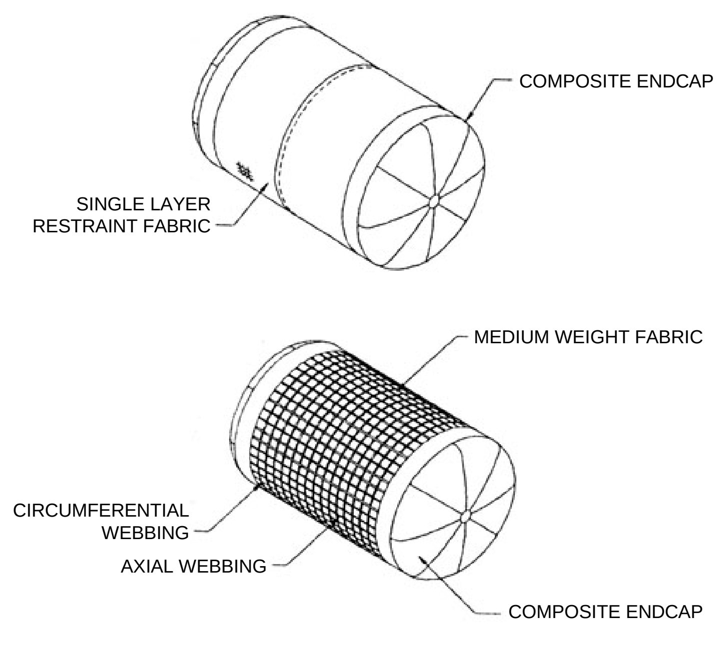
The Expandable habitat was envisioned to be a 2.3 meter diameter cylindrical structure with rigid end caps that would expand to 3.7 meters in length when deployed.

NASA-JSC / ILC Lunar Habitat

ILC DOVER

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.



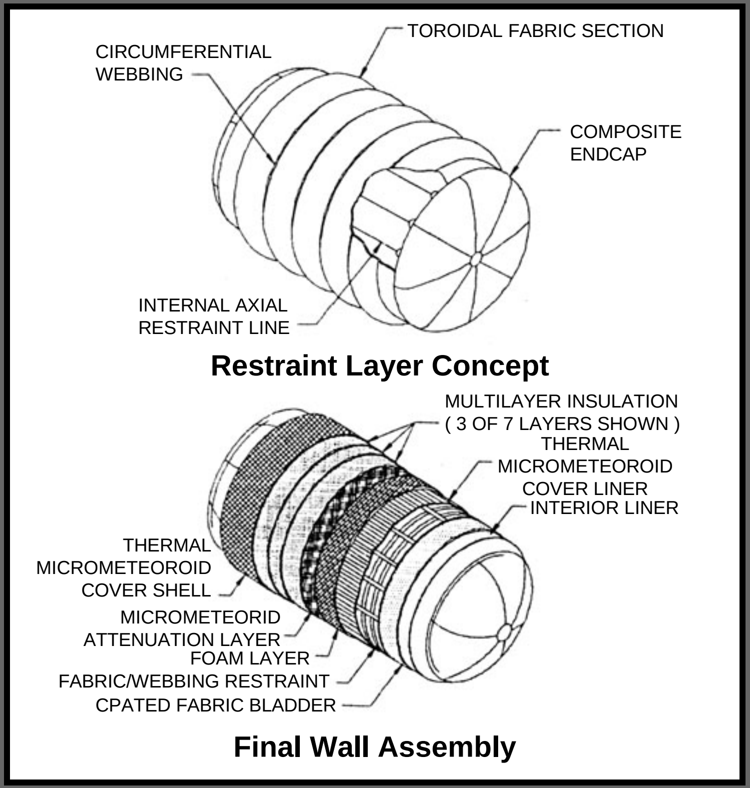
Restraint Layer Concept

NASA / ILC Lunar Habitat Construction

ILC DOVER

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.



NASA / ILC Lunar Habitat Construction

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.

NASA

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.

NASA-JSC TransHab Concept

ILC DOVER

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.

Hydrostatic tests were conducted on a full scale diameter but shortened prototype unit at the NASA-JSC Neutral Buoyancy Facility.

NASA-JSC / ILC Dover TransHab Prototype

BIGELOW AEROSPACE

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 Commercial Venture

BIGELOW AEROSPACE

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).

Bigelow Module Development

BIGELOW AEROSPACE

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.

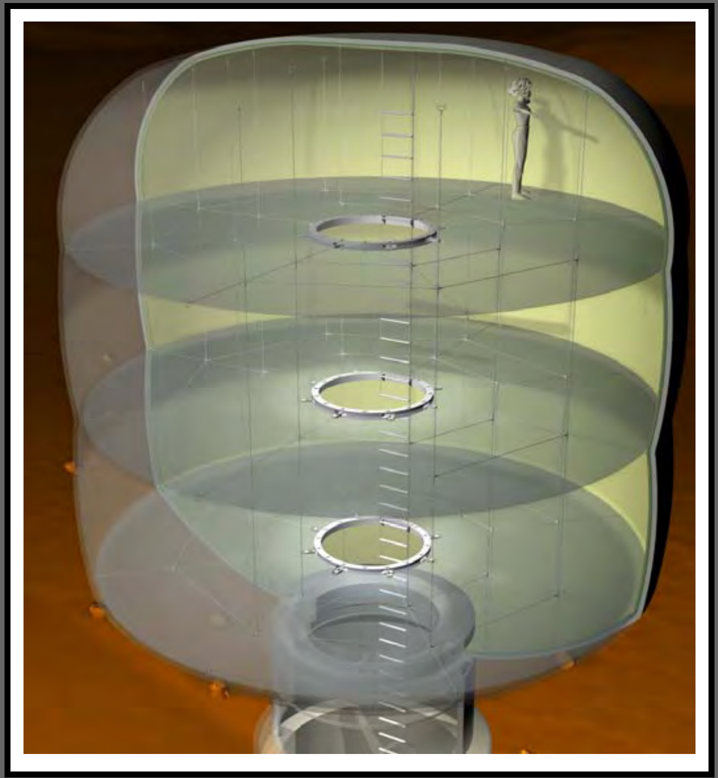
Metal Module Outfitting Simulators

A 120,000 sq.ft. development facility provides 3 full-scale metal module simulators along with a variety of other equipment.

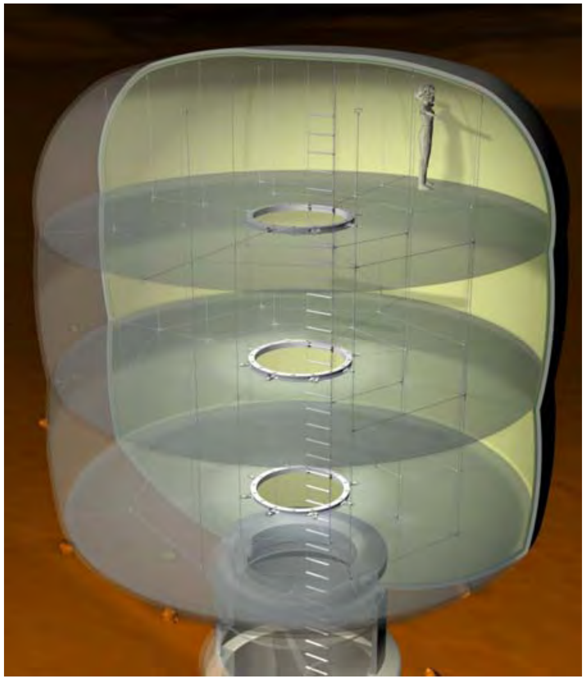
Bigelow Module Testing

SICSA has studied and conceptualized inflatable space structures over a period of more than two decades. One proposed design deploys interior floors automatically:

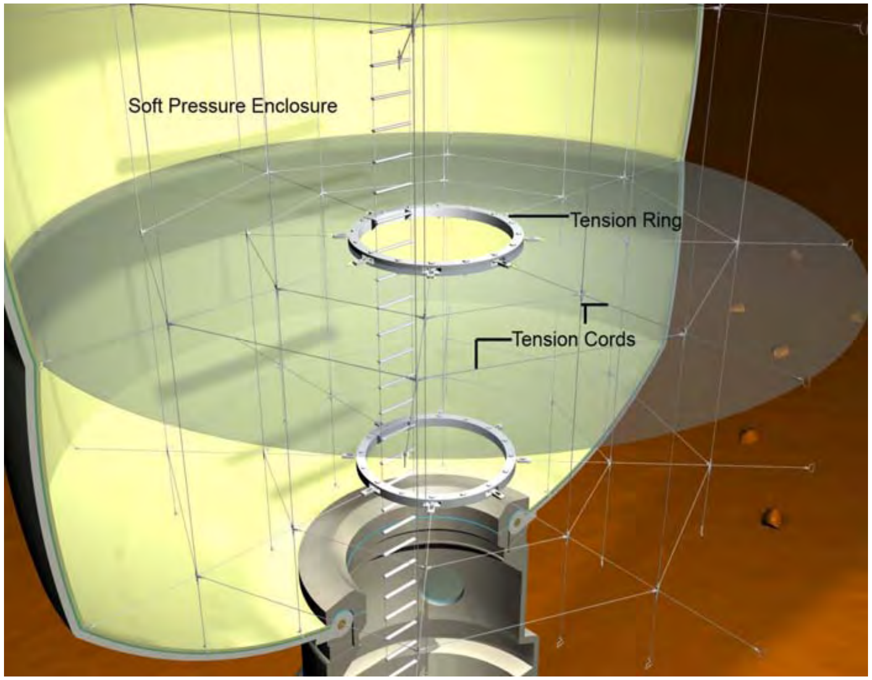
- An axial "web" of tension cables support floor membranes that are integrated and folded within the inflatable enclosure package prior to launch.
- Vertical cables, in combination with the horizontal web, restrain the deployed envelope shape and provide attachment points for utility systems and equipment.



SICSA "Pop-Out" Interior Concept

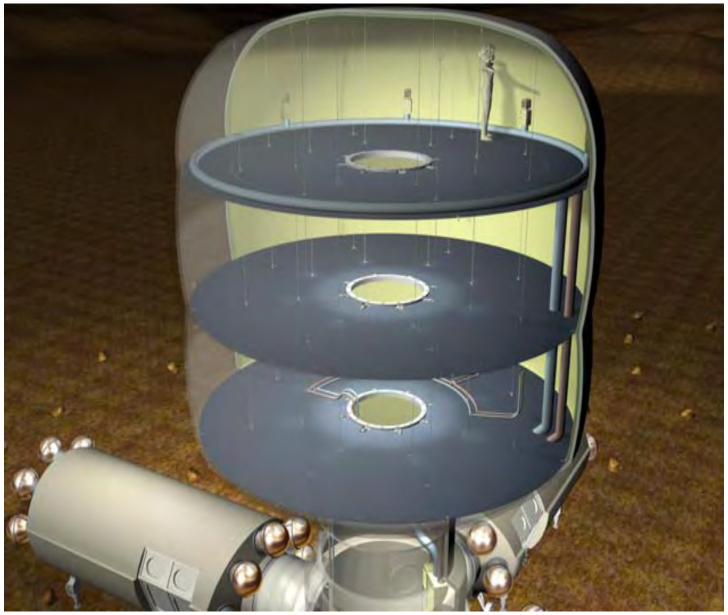


Pop-Out Internal Structure

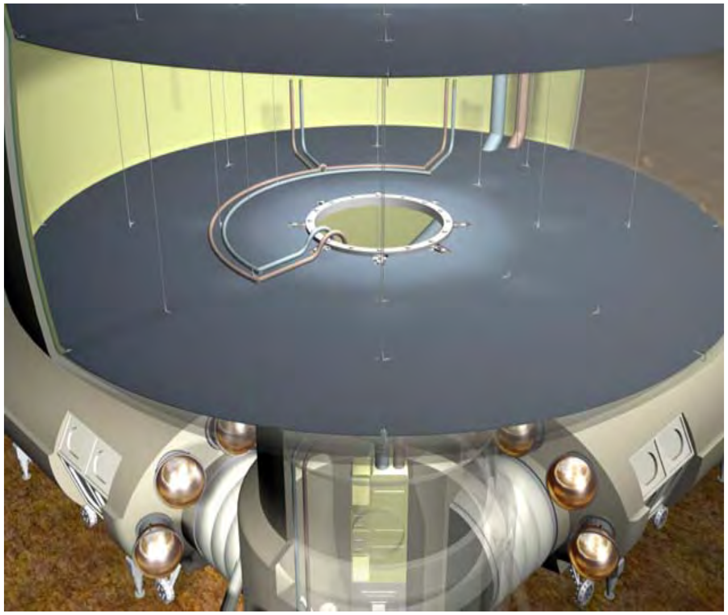


Typical Floor Structure

SICSA "Pop-Out" Interior Concept

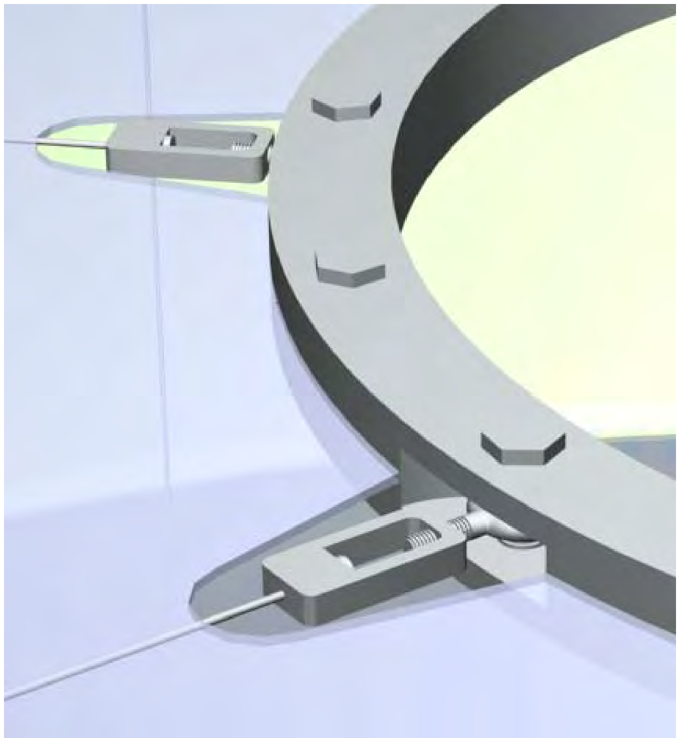


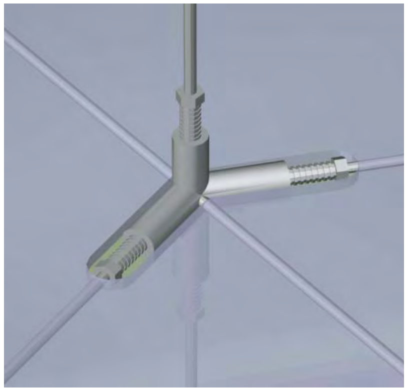
Three Level Scheme



Lower Level Structure & Utilities

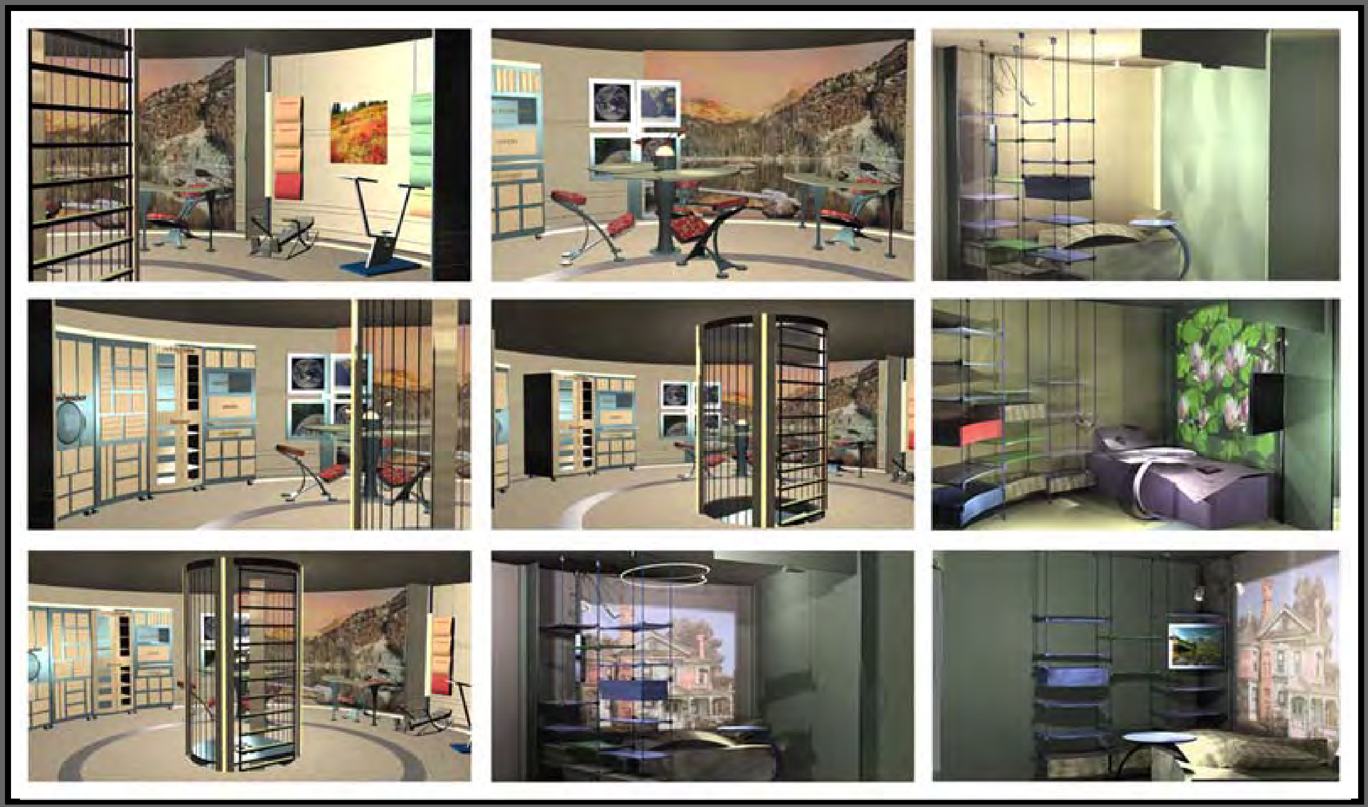
SICSA "Pop-Out" Interior Concept





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.

SICSA “Pop-Out” Interior Concept



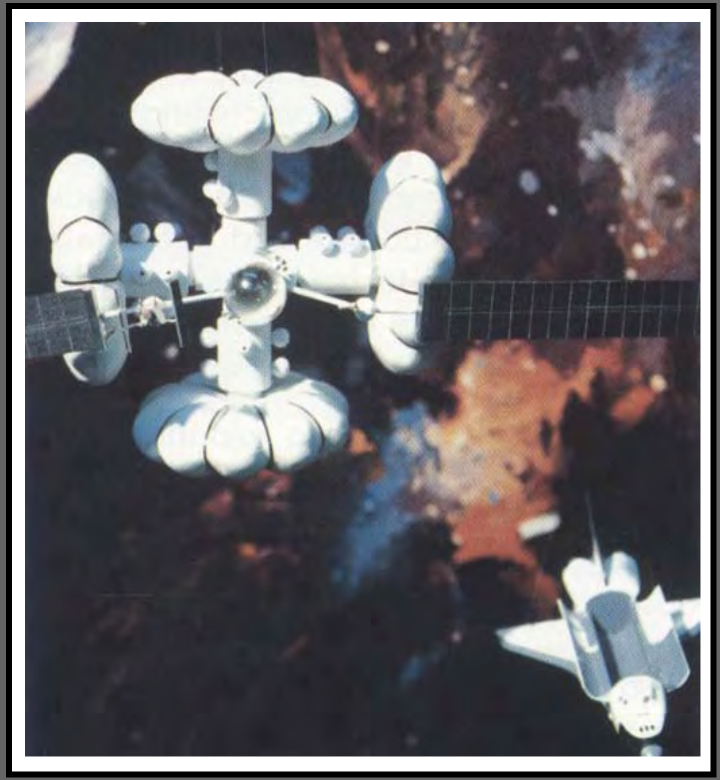
SICSA Lunar / MarsHab

HABITABLE STRUCTURES

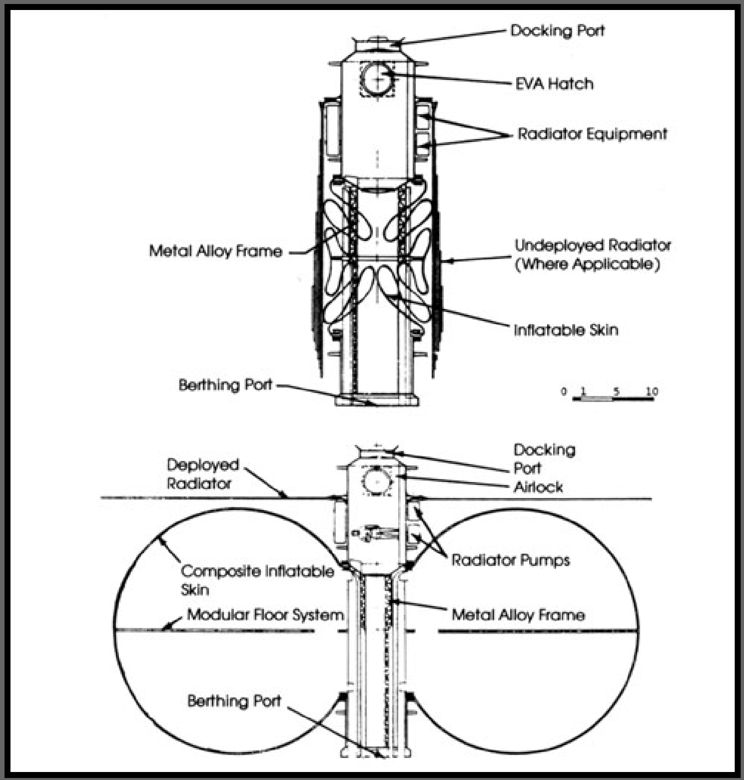
INFLATABLE MODULES

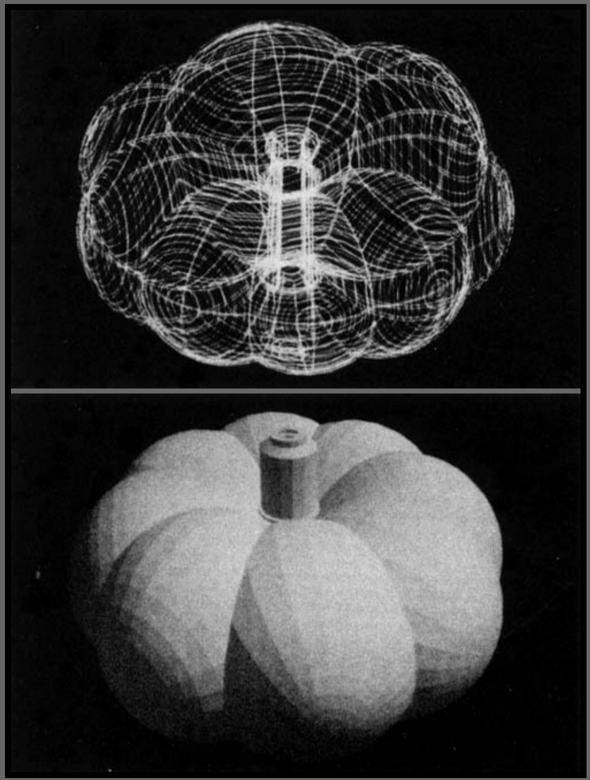
Hybrid modules offer combined advantages of inflatable and conventional elements:

- 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.



SICSA SpaceHab Concept

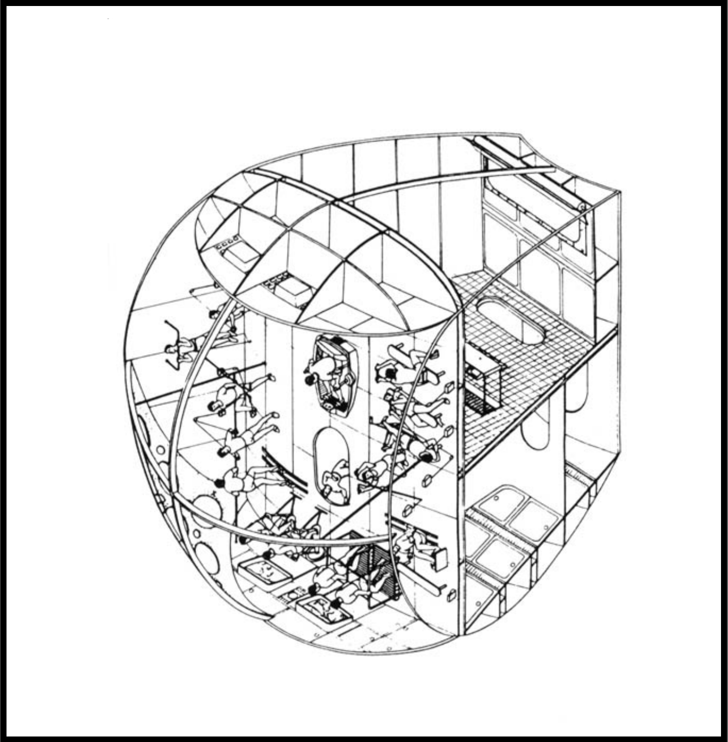


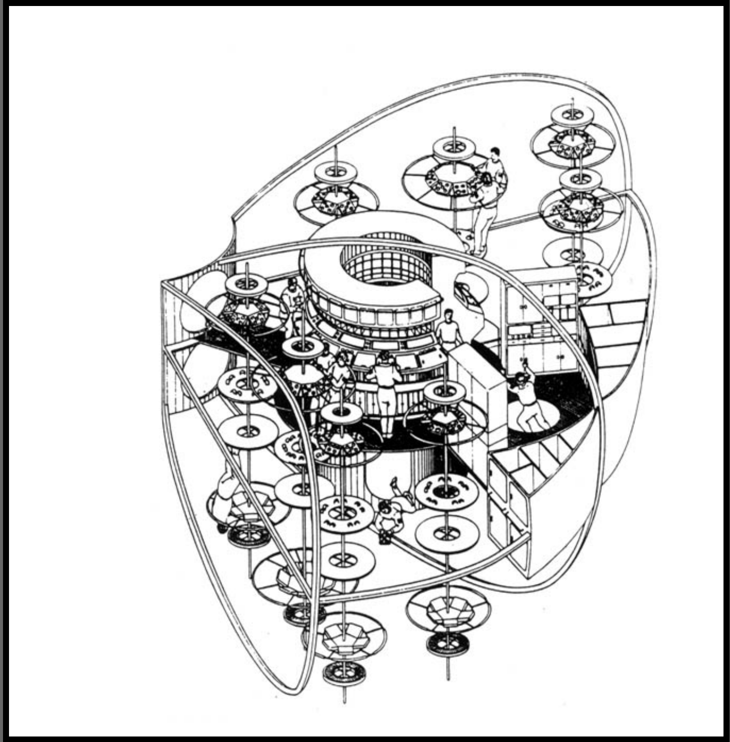


SICSA SpaceHab Concept

HABITABLE STRUCTURES

HYBRID MODULES

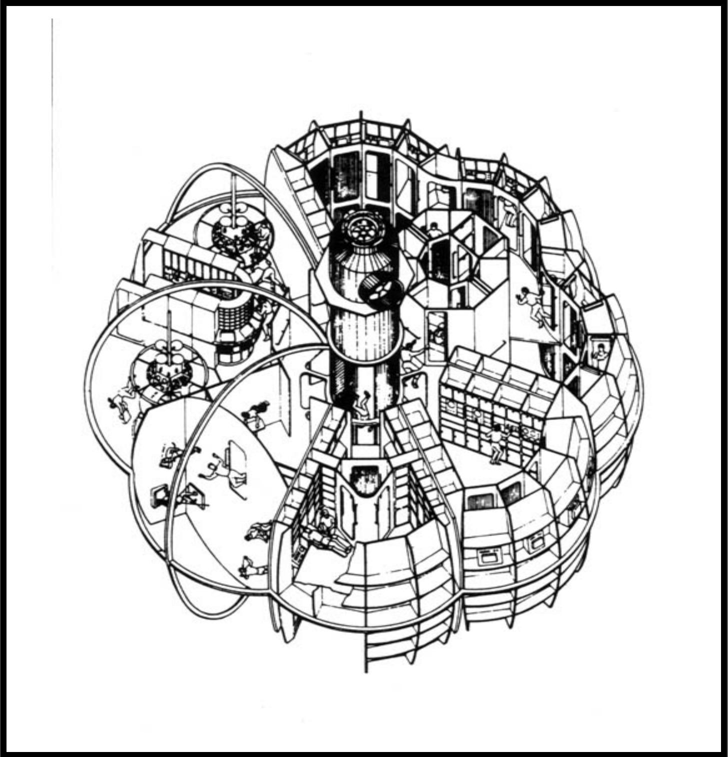


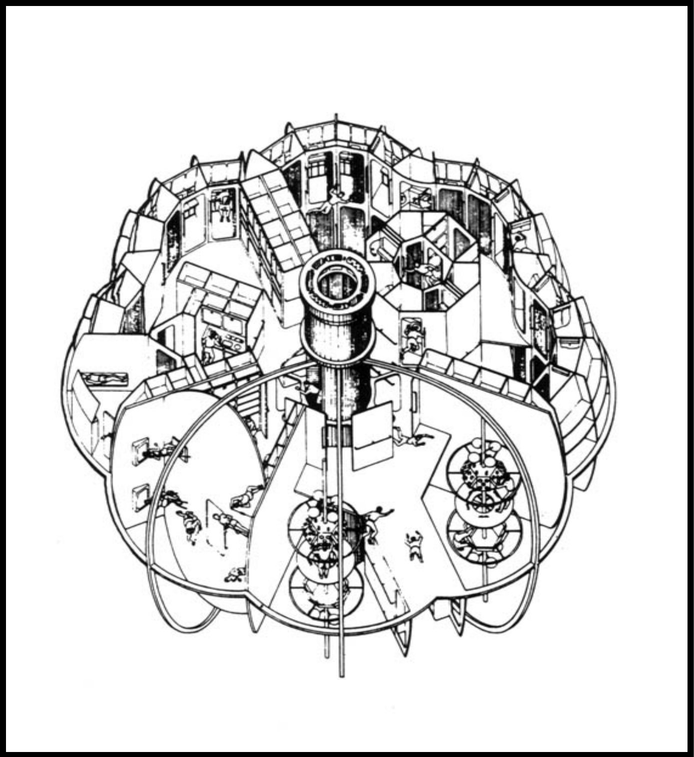


SICSA SpaceHab Concept

HABITABLE STRUCTURES

HYBRID MODULES

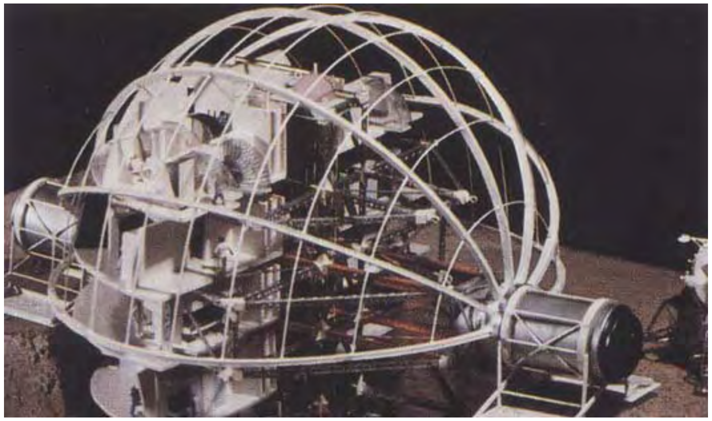


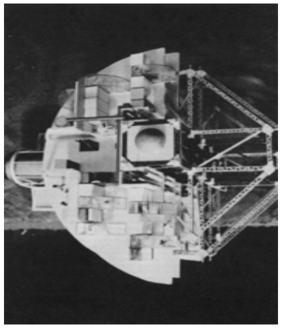


SICSA SpaceHab Concept

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.

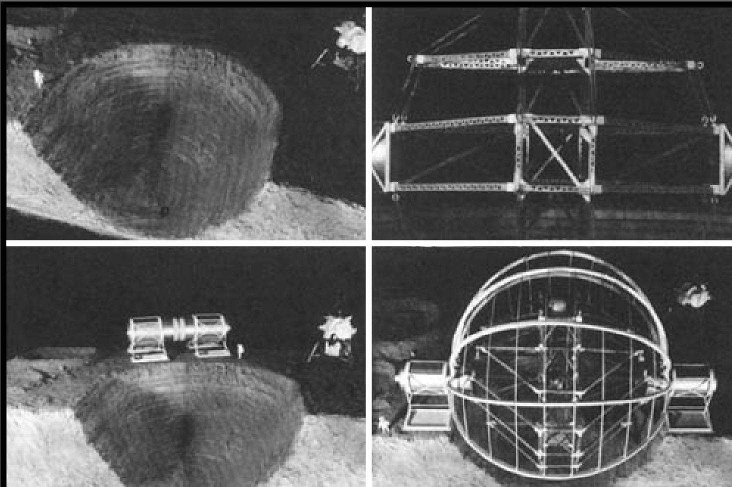




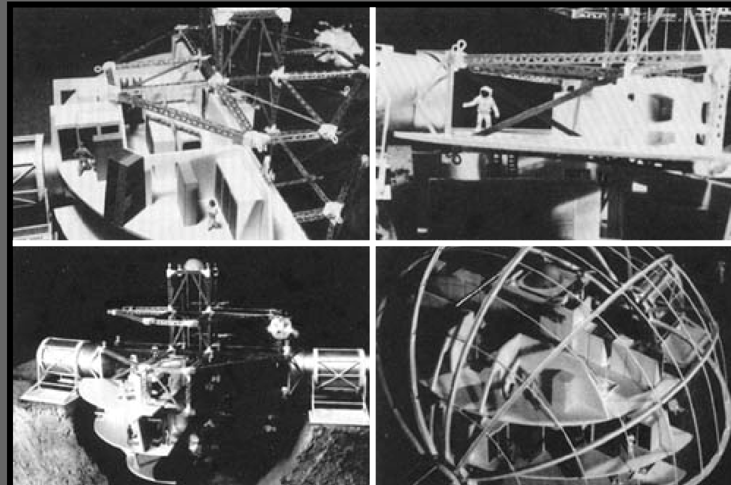
The concept incorporates 2 access/egress airlocks at opposite ends of an inflatable sphere. An internal metal structure would be assembled following envelope pressurization.

Hard and Soft Elements

SICSA LunarHab Concept



The spherical geometry would require that a surface cavity be discovered or created to accommodate the lower area and prevent in 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.

SICSA MarsLab Concept

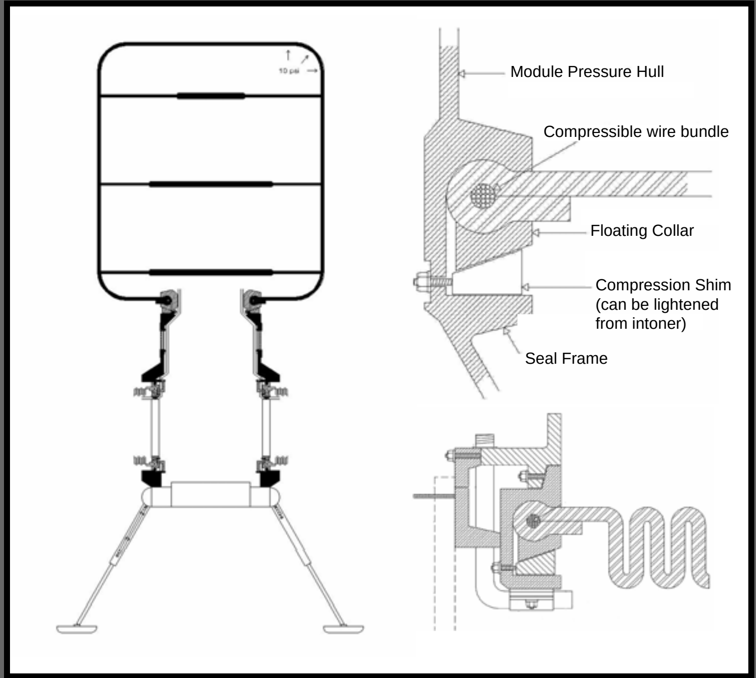
SICSA MarsLab Interior Views

HABITABLE STRUCTURES

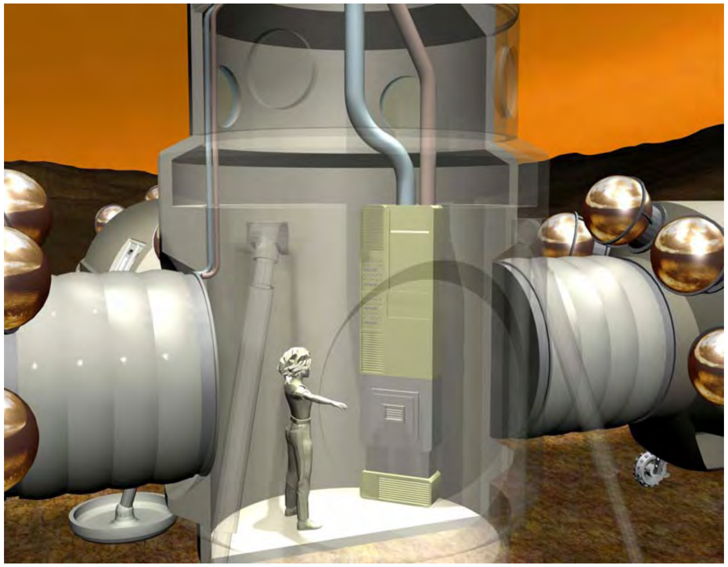
HYBRID MODULES

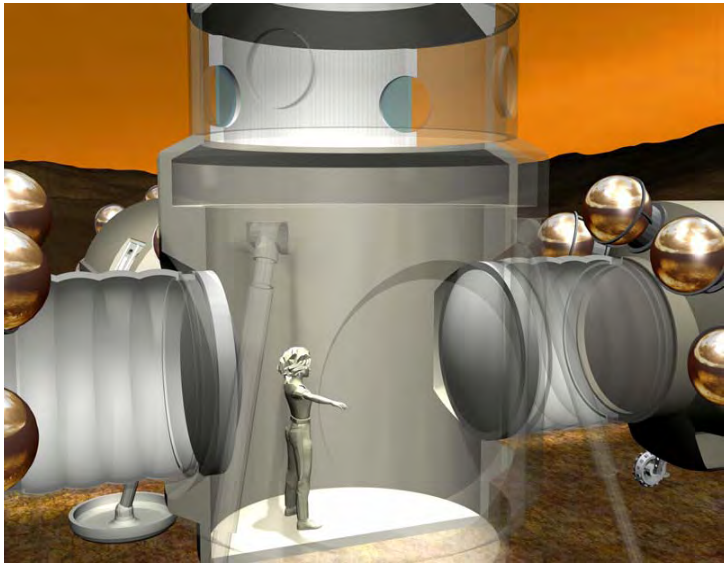
The Lunar/Mars Hab incorporates SICSA's pop-up internal inflatable system and external hard-soft interfaces that were developed and tested by the Goodyear Aerospace Corporation (GAC):

- 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 Lunar / Mars Hab


Hard Section & Utilities


Hard Section & Tunnels

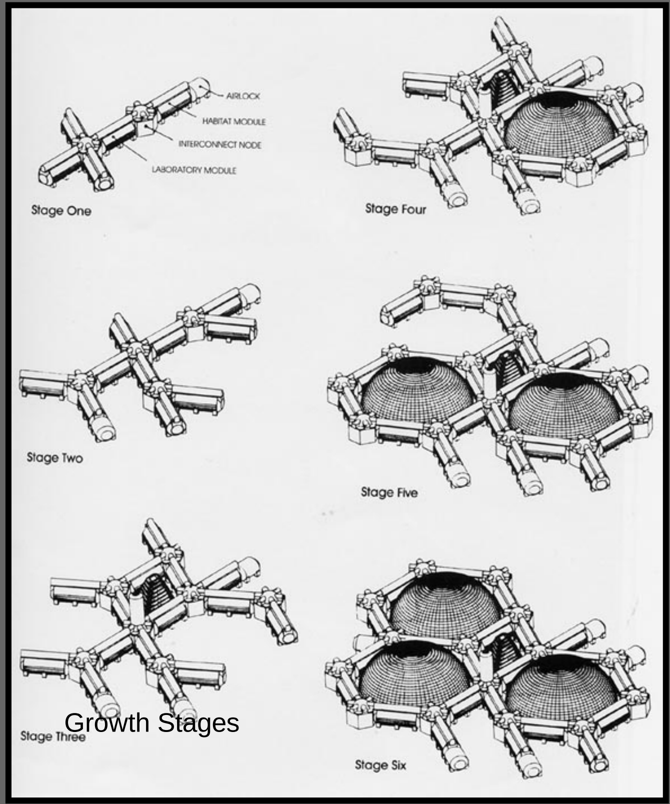
SICSA Lunar / Mars Hab

HABITABLE STRUCTURES

HYBRID MODULES

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.



Growth Stages

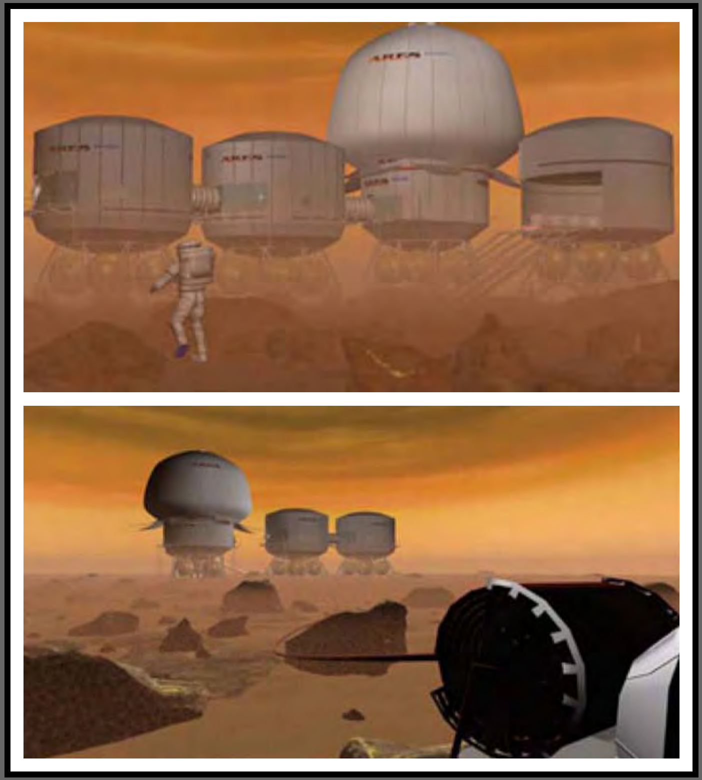
SICSA's Project LEAP

HABITABLE STRUCTURES

MODULE COMBINATIONS

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.



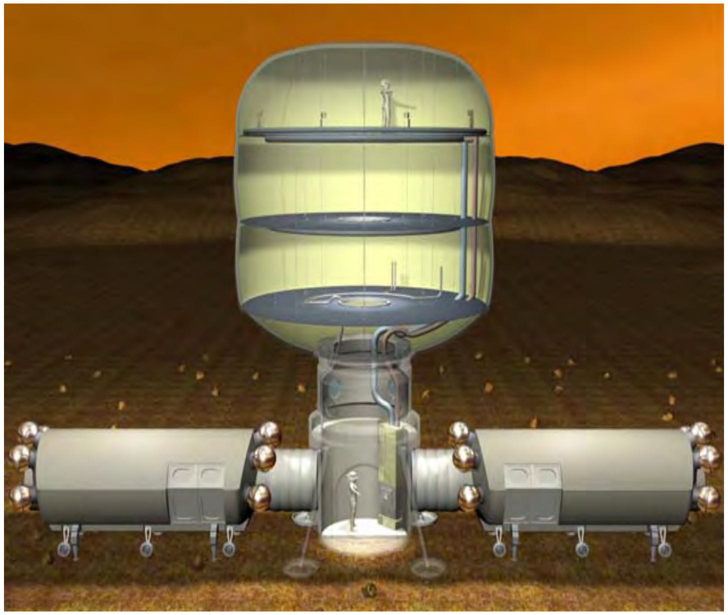
SICSA's First Mars Outpost

SICSA's Medium Lift Vehicle (MLV) lunar/Mars settlement scenario proposes use of hybrid modules in combination with axially-connected conventional modules:

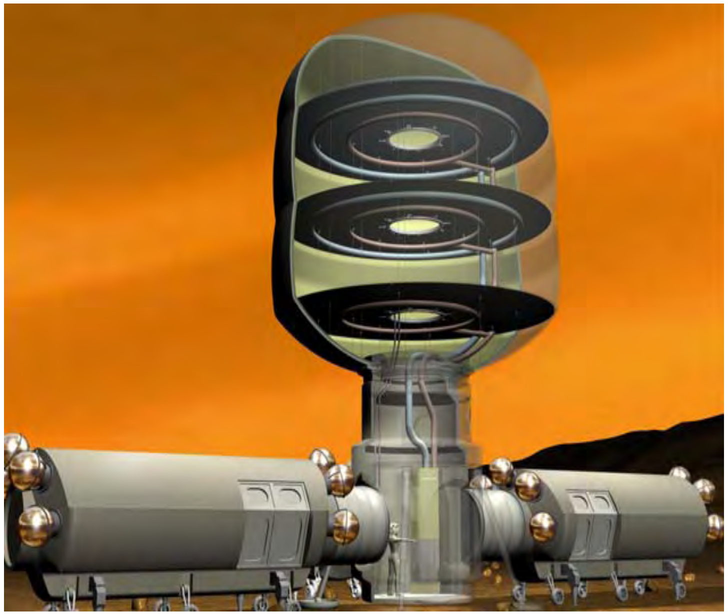
- Equipment for hybrid module outfitting is transferred from the first arriving conventional modules by initial crews.
- As equipment and supplies are moved out of pressurized logistics carriers, they can then be utilized as laboratory modules.

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

SICSA's Lunar / Mars Modules



Surface Module Configuration

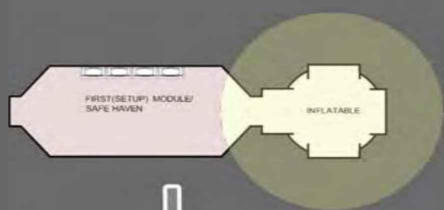


Inflatable Module Levels

SICSA's Lunar / Mars Modules

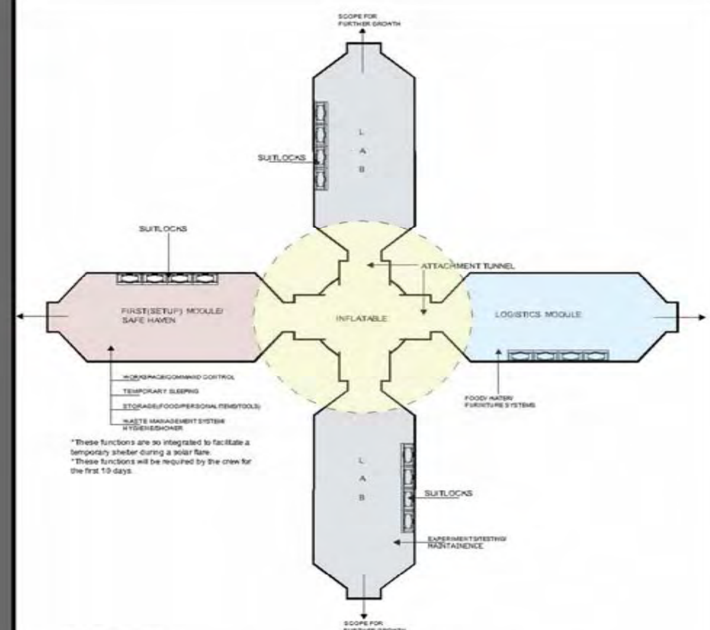
FIRST/SETUP MODULE :

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.



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

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.



INFLATABLE:
LEVEL 1: EXERCISE/STORAGE (HEAVY EQUIPMENT
LEVEL 2: LAB/WORKSPACE
LEVEL 3: CREW QUARTERS (PRIVATE SPACE)

SICSA's Lunar / Mars Modules

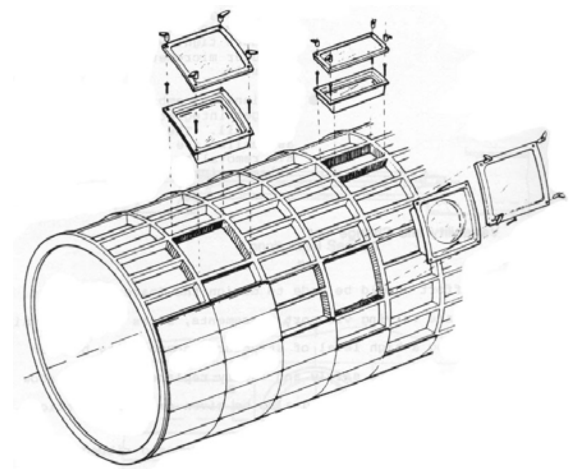
HABITABLE STRUCTURES

MODULE COMBINATIONS

BELL & TROTTI, INC

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 Integration

Window Importance

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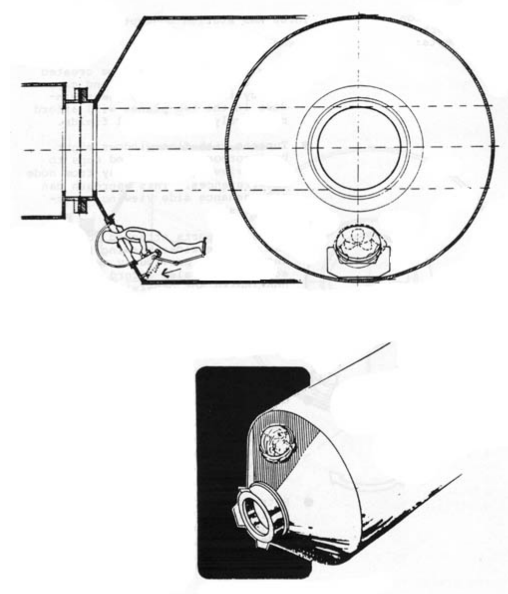
Window options include a variety of locations and types:

- 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 Domed RMS Station

Window types and Locations

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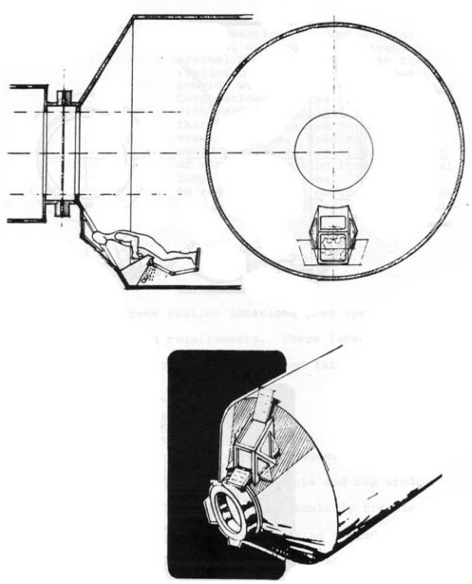
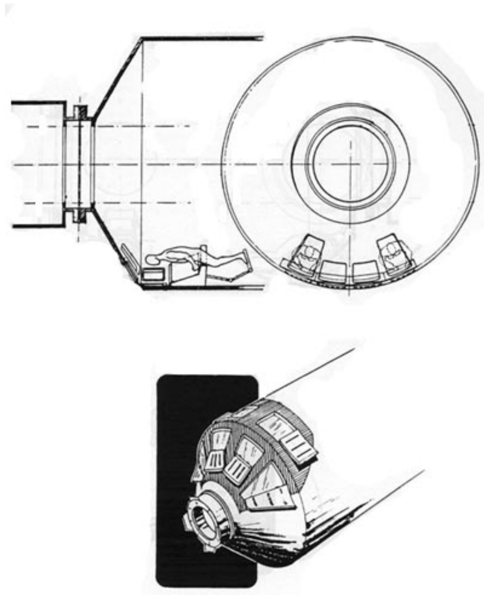


End Cap Turret RMS Station



End Cap Corner RMS Station

Window types and Locations

HABITABLE STRUCTURES

OUTSIDE VIEWING

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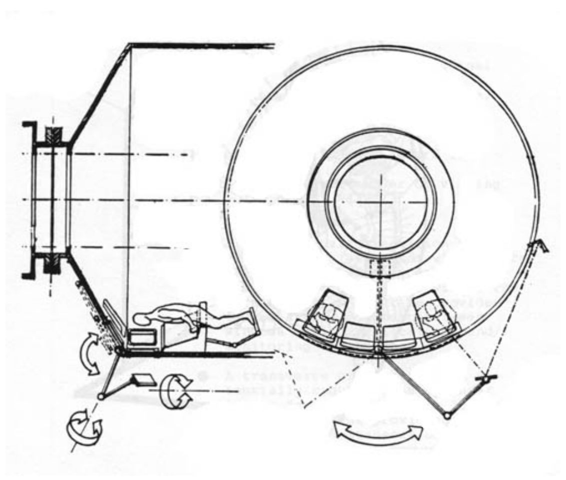

Viewing Mirror Assembly

RMS Station Privacy Screen

Special Viewing Devices

HABITABLE STRUCTURES

OUTSIDE VIEWING

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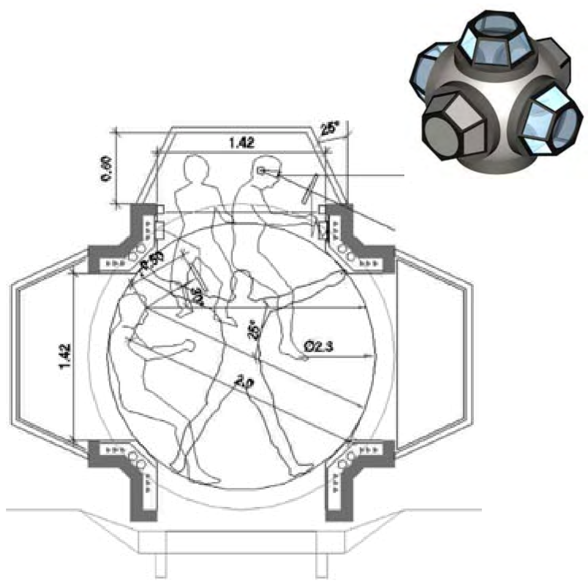
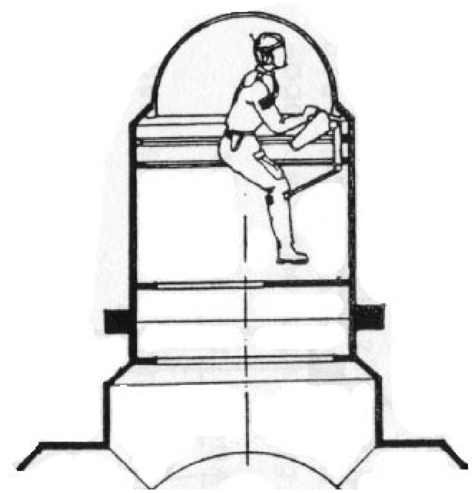


Faceted Cupola



Bubble Cupola

Attached Cupola Concepts

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.

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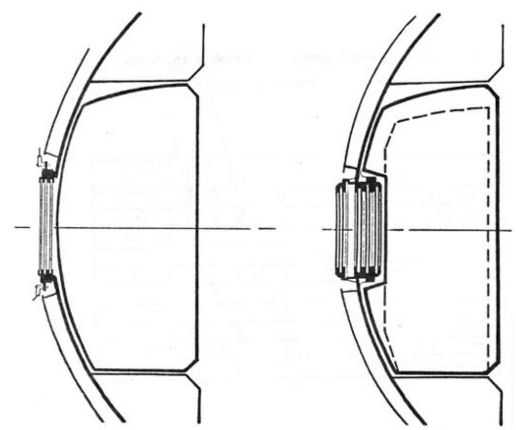

ROCKWELL VIEWPORT CONCEPT NASA-MSFC VIEWPORT CONCEPT

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

Window Design Approaches

Window Planning and Design

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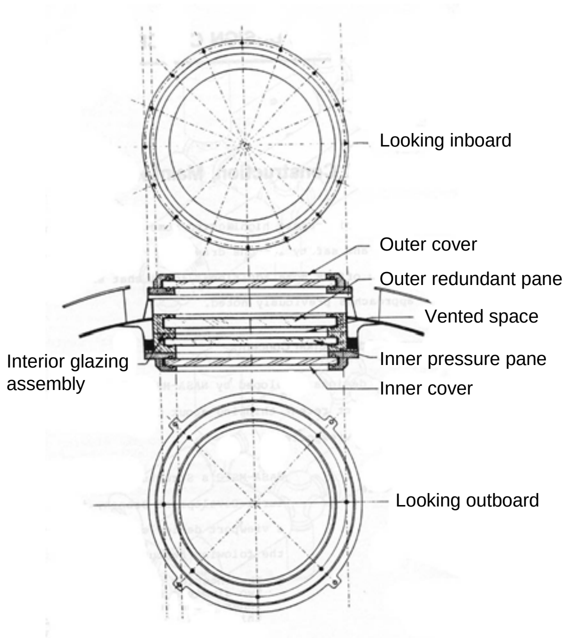
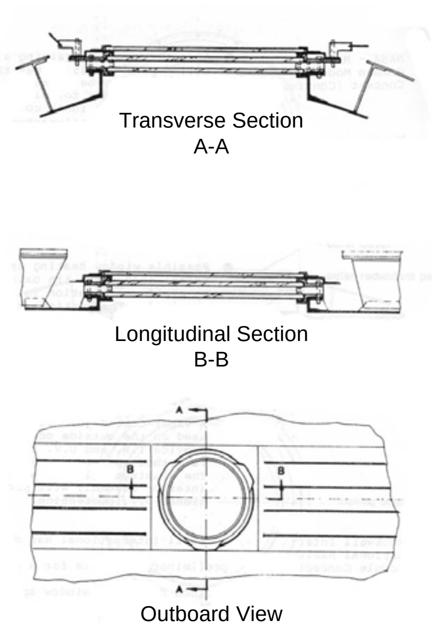


NASA-MSFC Concept

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.



Rockwell Concept

Illustrative Construction Concepts

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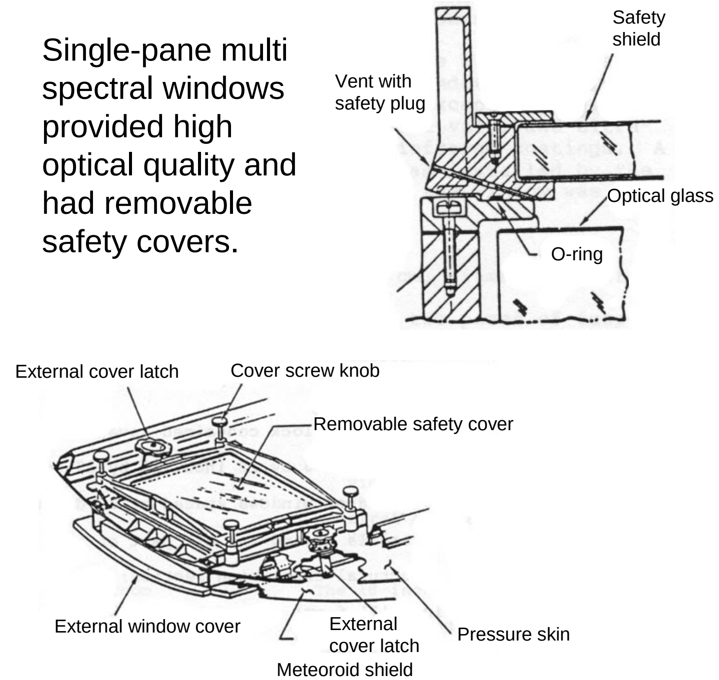
Wardroom Window

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.



Multi-spectral Windows

Skylab Windows

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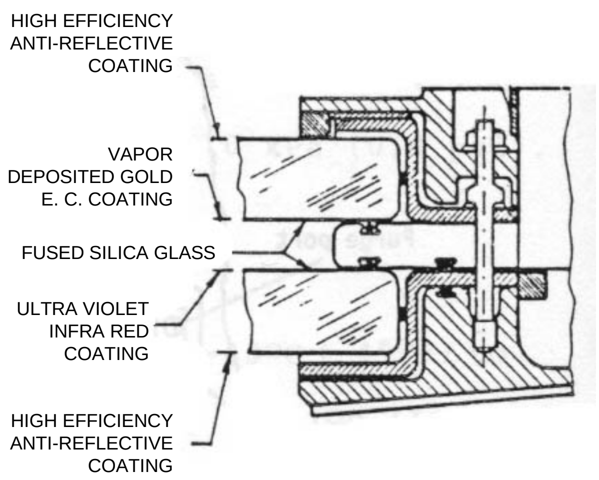
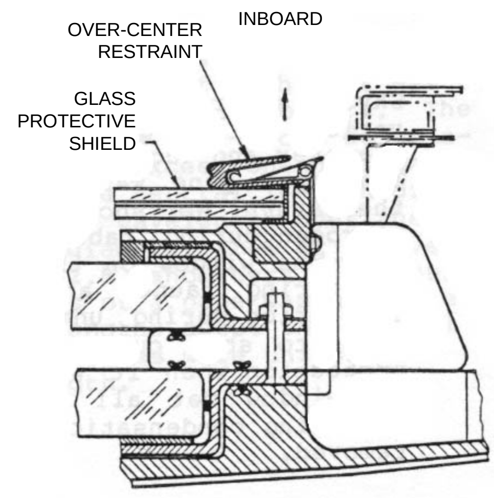


Materials



Components

Skylab Wardroom Window

HABITABLE STRUCTURES

OUTSIDE VIEWING

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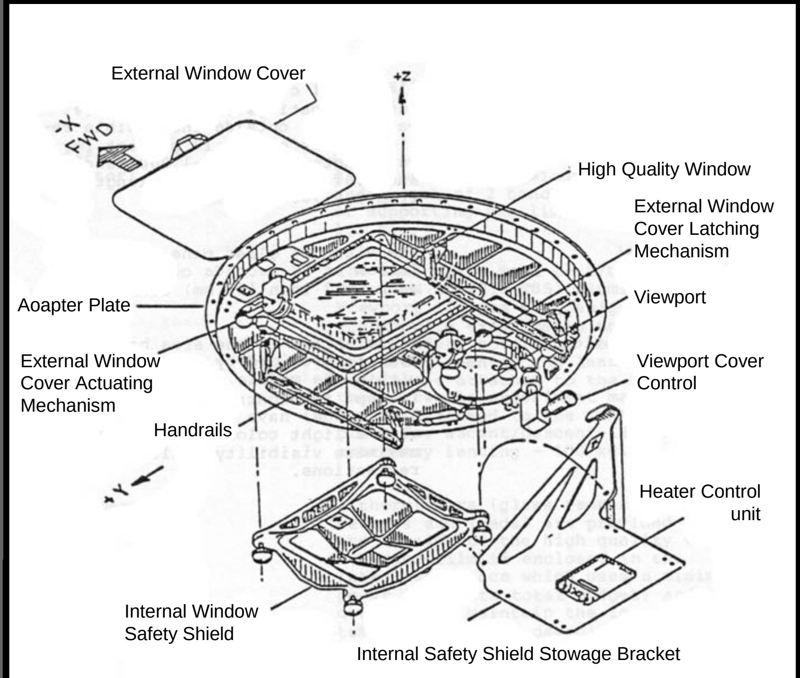
The ESA Spacelab Window Adapter Assembly (SWAA) is of special interest because it incorporated provisions for both general and scientific viewing:

- 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.



Components

ESA Spacelab Window Adapter Assembly

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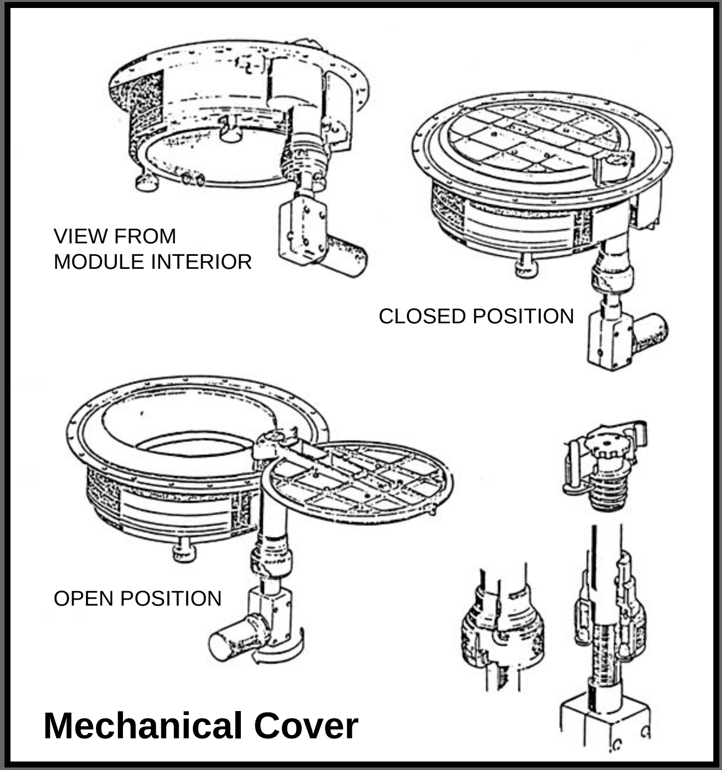
When not in use, the SWAA's glass surfaces were protected by two covers:

- 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.



ESA Spacelab Window Adapter Assembly

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.

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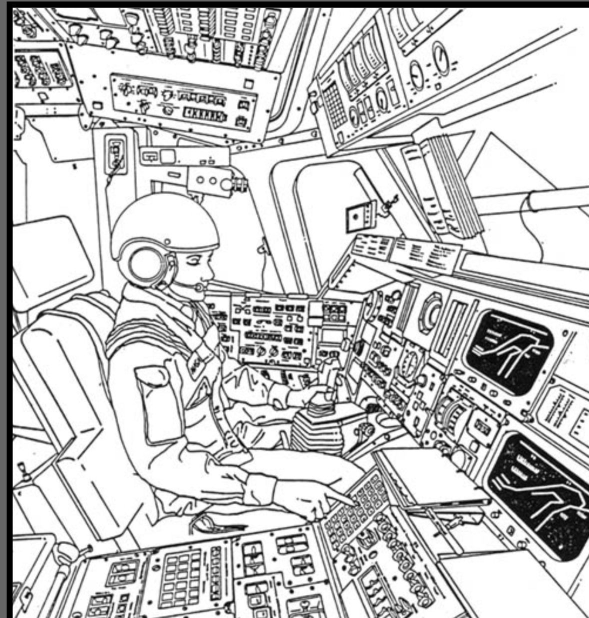


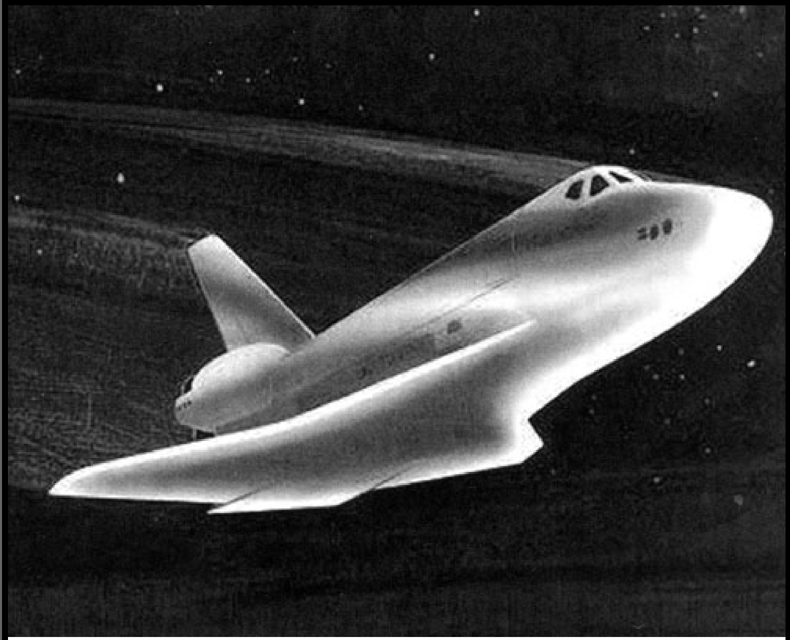
Flight Deck

Shuttle Orbiter Windows

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).

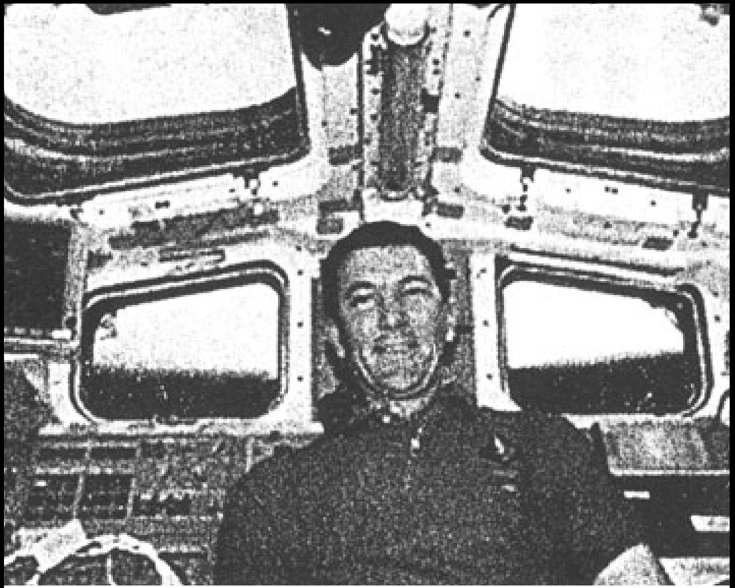
The 3 layers of material separated by atmospheric space results in a rather thick viewing aperture which has been reported to be like looking through a tunnel.



Windshield Construction

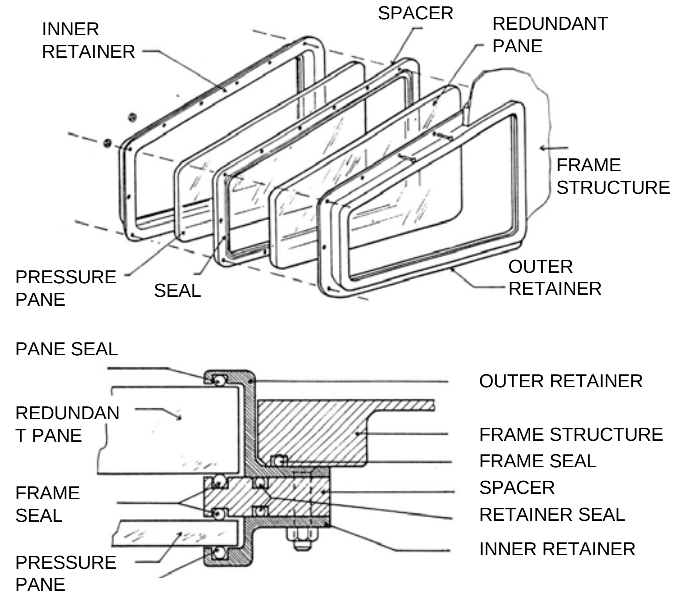
Shuttle Orbiter Windows

BELL & TROTTI, INC



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.

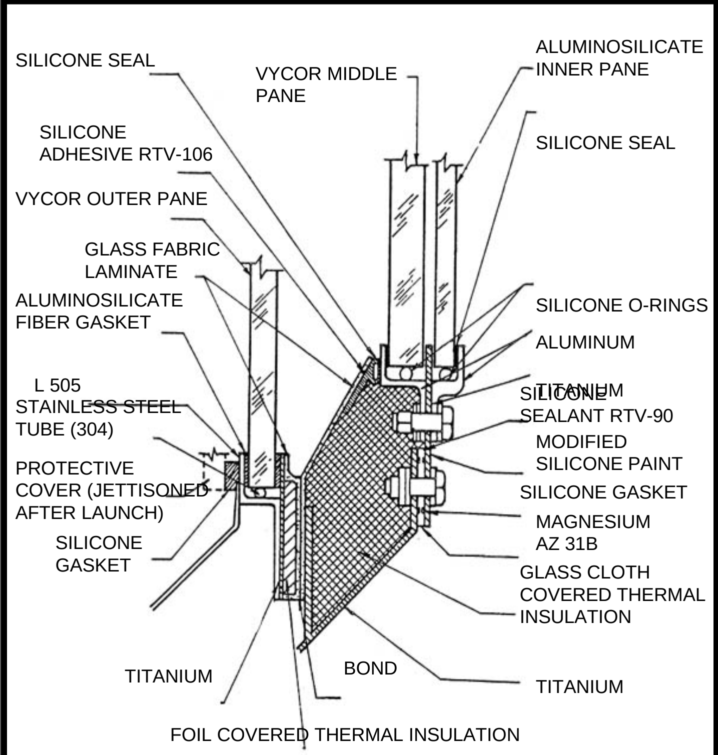
RMS Window Construction

Shuttle Orbiter Windows

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.

BELL & TROTTI, INC



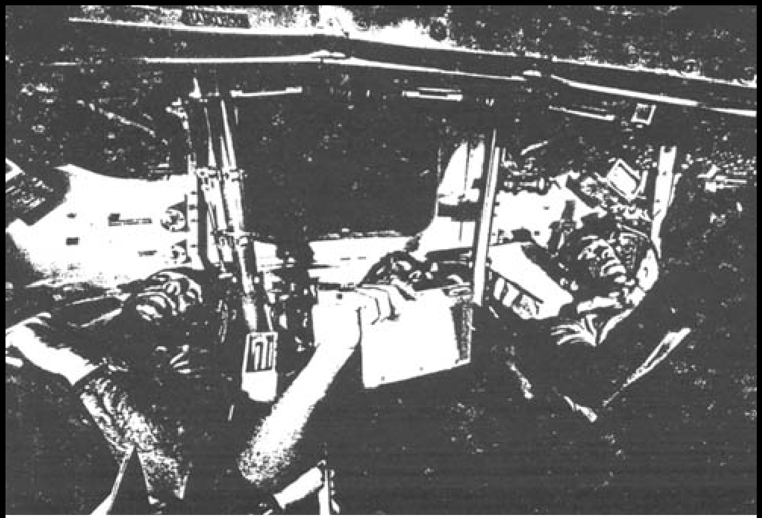
Construction

Gemini Side Window

BELL & TROTTI, INC

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.



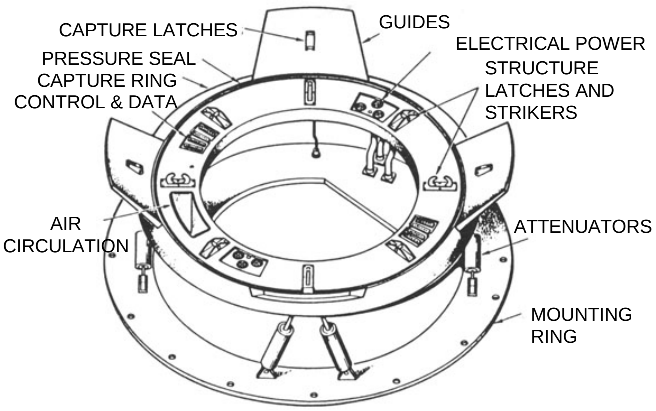
Improved visibility and broader field of view angles became important for Apollo / Soyuz and Apollo landing missions.

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.



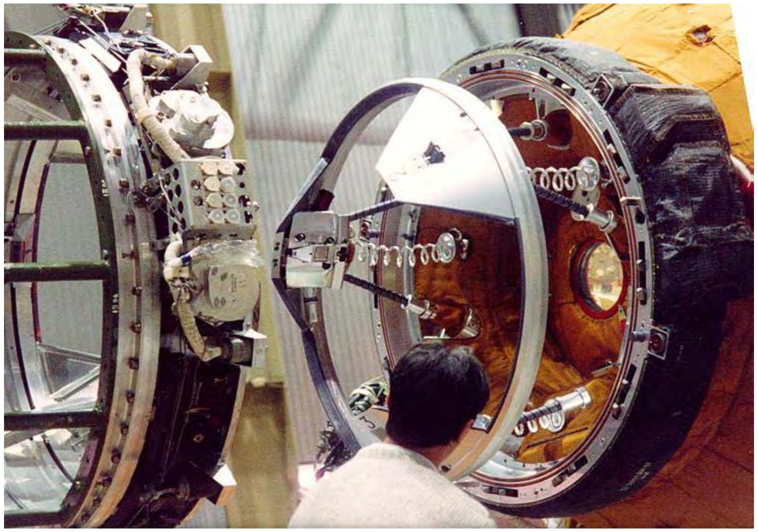
Guide vanes containing capture latches align the two elements upon contact, and they are tightly locked together by structure latches and strikers.

Rockwell Docking Concept

Docking and Berthing Systems

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.



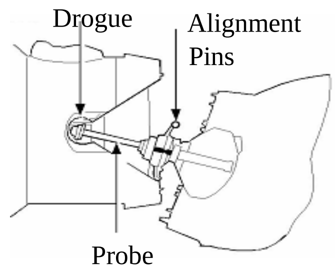
The Androgynous Peripheral Attach System (APAS) is a Russian design that is able to mate with an exact copy of itself.

Androgynous Peripheral Attach System

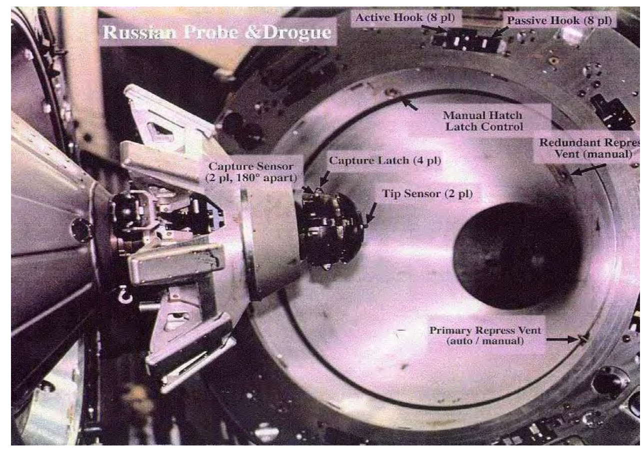
Orbiter – ISS / Mir Docking System

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.



The Probe/ Drogue Docking System for all Russian ISS Elements.

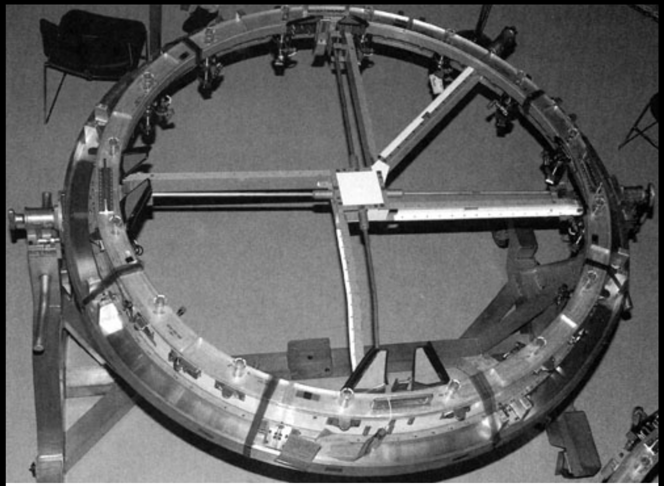


Probe/ Drogue Docking System

Russian ISS Segment Docking

ISS hatches are integrated with docking mechanisms used for mating modules together:

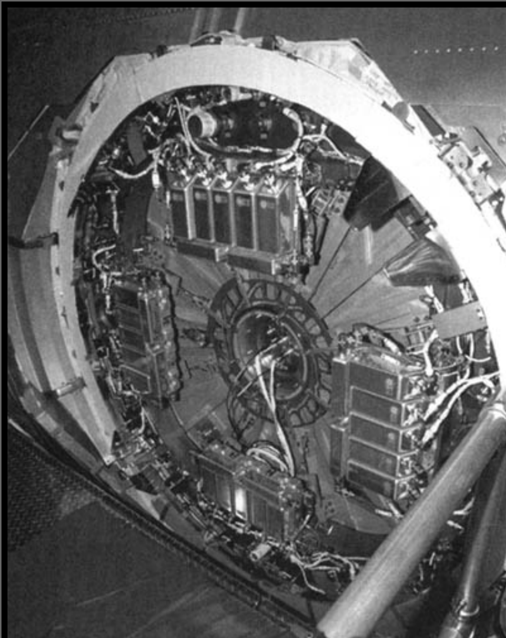
- A Manual Berthing Mechanism is located on the no.21 truss segment, and is manually operated by an EVA crew person to mate it with the passive side of a Common Berthing Mechanism (CBM).
- The CBM has both a passive and active half that connects one US module to another by means of capture latches, alignment guides, powered bolts and controller panel assemblies.



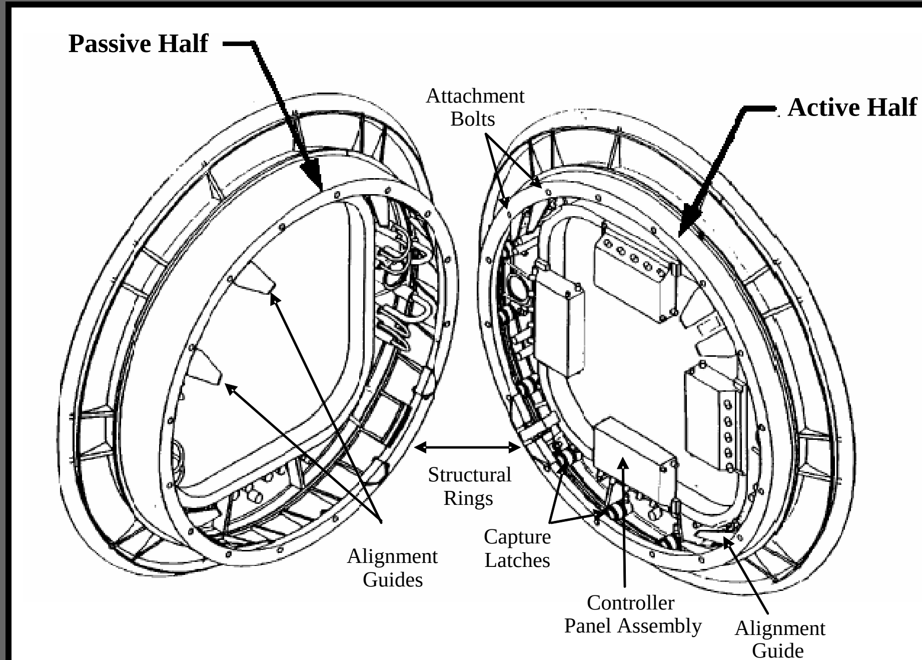
The Manual Berthing Mechanisms (MBM) serves as a temporary EVA attachment point that can mate with any passive CBM.

Manual Berthing Mechanisms

ISS Berthing Mechanisms



Active Half of a CBM

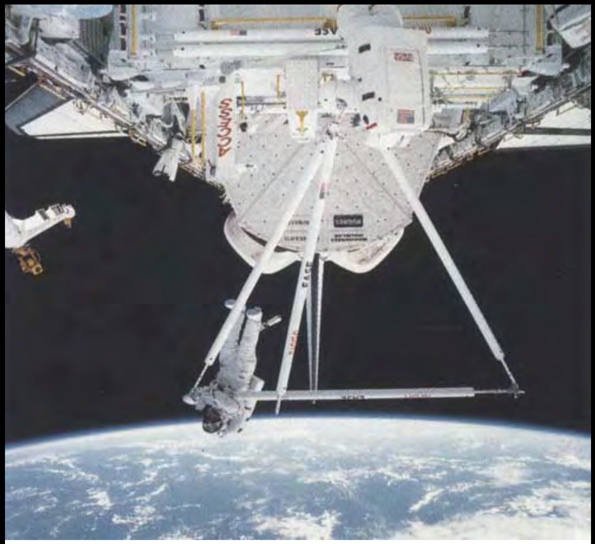


Common Berthing Mechanism

ISS Berthing Mechanisms

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.



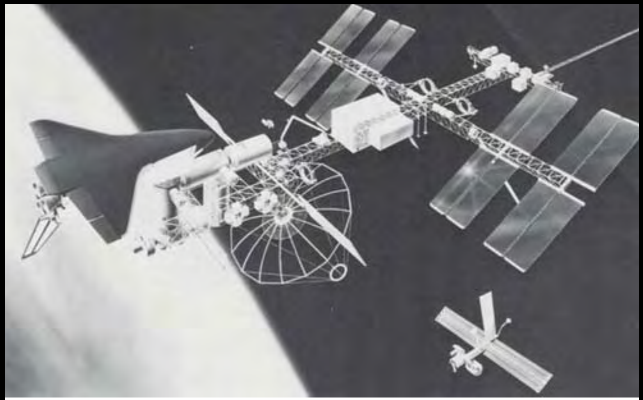
Trusses provide a light weight, strong and versatile structural approach.

Truss Construction from Orbiter

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.

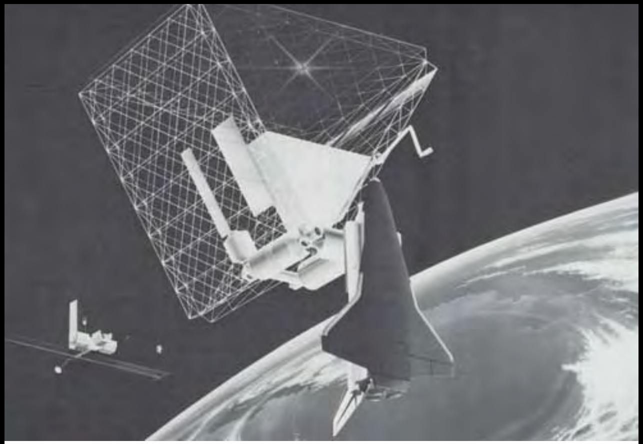


The Power Tower featured a long box truss backbone structure that could accept a variety of functional attachments, including modules, storage facilities and solar arrays.

Early NASA Power Tower Concept

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.

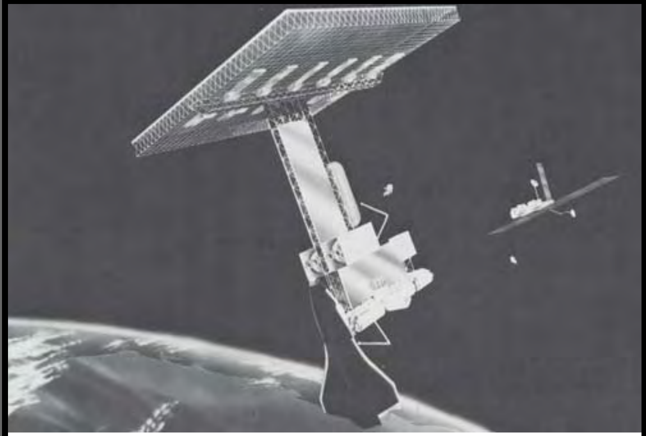


The Delta configuration was devised to provide stiffness to avoid dynamic controllability problems associated with the long, flexible Power Tower truss.

NASA Delta Space Station Concept

The “Tee” concept was also designed to be stiff, but was less so then 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.

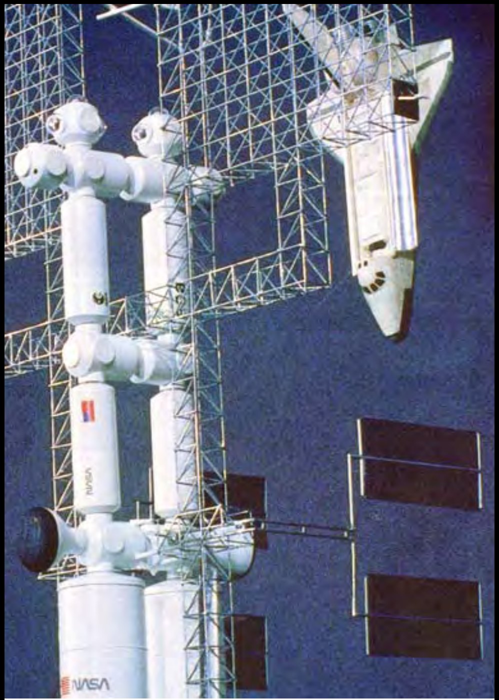


The design which was conceptualized at the NASA Johnson Space Center in the early 1980s was determined not to provide adequate power generation efficiency.

NASA Big–Tee Space Station Concept

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:

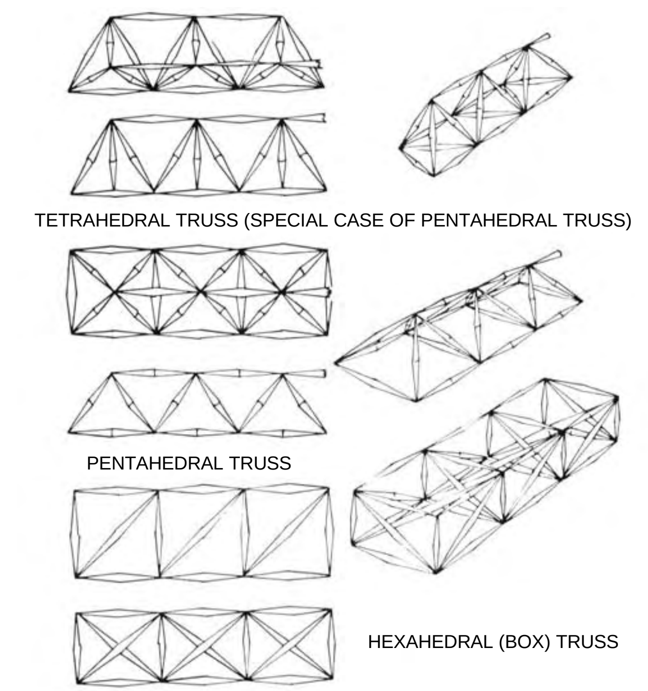
- The design provided a high level of gravity gradient stability with an emphasis upon accommodations for human space operations.
- The large truss would be used as an attachment fixture for equipment, tools and RMS systems to support EVA functions.
- Gimbaled solar-tracking arrays avoided pointing orientation problems associated with the Big-Tee approach.


SICSA Space Post Concept

Configuration Concepts

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).

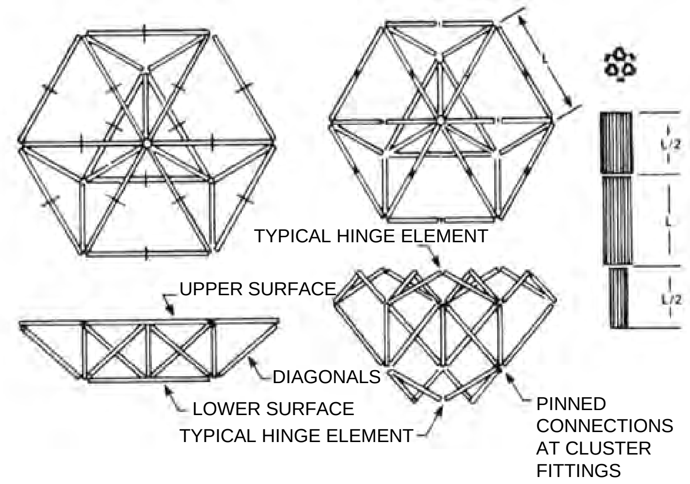


Common Truss Geometries

System Types

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

System Types

Technologies presently exist to erect or deploy truss structures in a variety of ways:

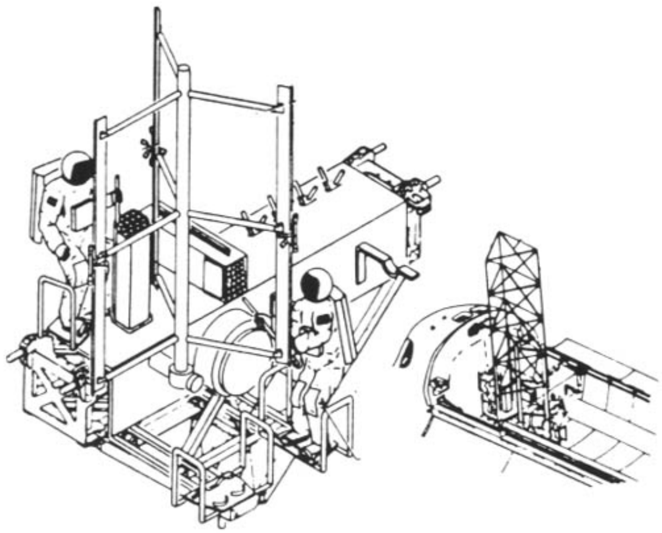
- Some systems are comprised of individual solid or tubular members and connector sockets that are assembled in "tinker toy" fashion by space-suited astronauts, or attached using teleoperated devices.
- Some are pre-assembled with hinged joints, compactly folded during launch and automatically expanded 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.

Deployable Truss Structure

System Types

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.



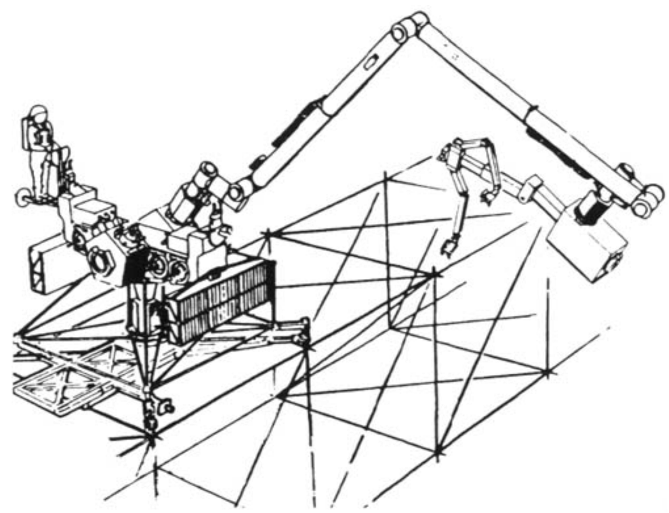
ACCESS successfully demonstrated on-orbit construction applying current EVA and RMS technologies.

ACCESS Construction Operation

System Types

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.

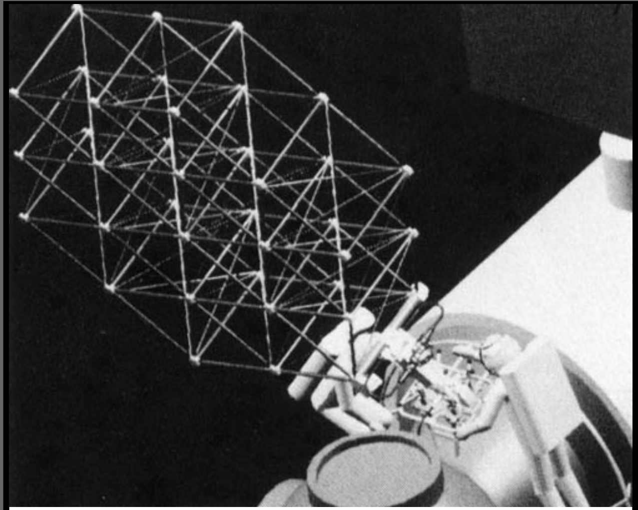


Mobile RMS devices offer the potential to eliminate human EVA roles.

Telerobotic Assembly and Servicing

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.



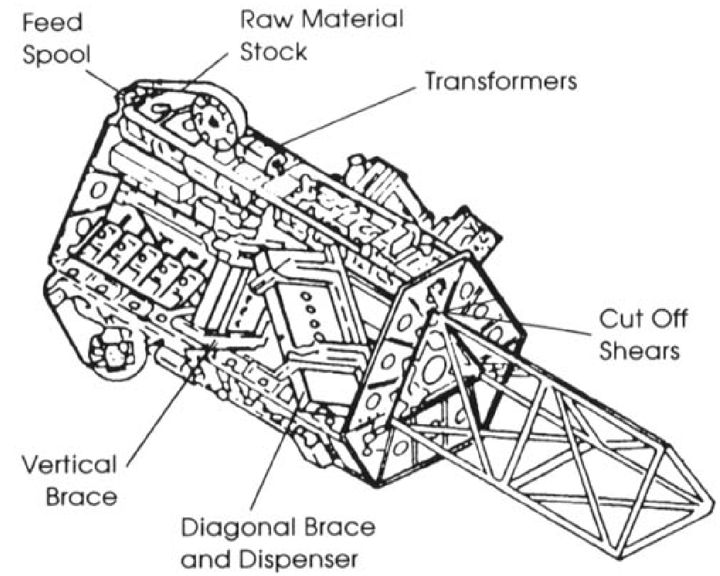
The system deployed automatically when a restraint cable was cut by a thermal knife.

ERA Unfurlable Structure

System Types

Fully automated manufacturing processes may one day transfer existing terrestrial technology to the space environment:

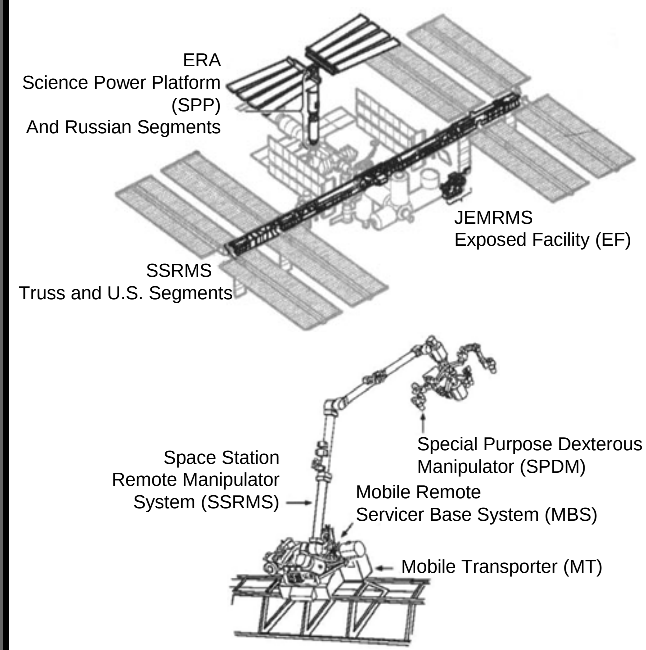
- Beam builders might transform metal strips contained on spools to triangular truss sections complete with struts and ties.
- The vertical and diagonal braces would pass through internal rolling mills, be positioned and cut to length, and then welded in place.
- While equipment to accomplish this operation might be complex and bulky, the process could be valuable to create structures using materials from the Moon, Mars and asteroids.



Automated Beam Builder Concept

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).

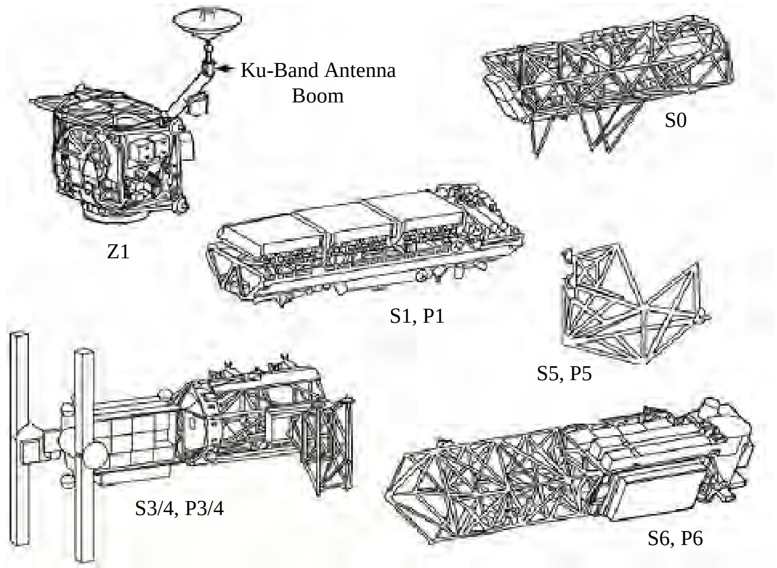


MSS External Components

ISS Applications

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".



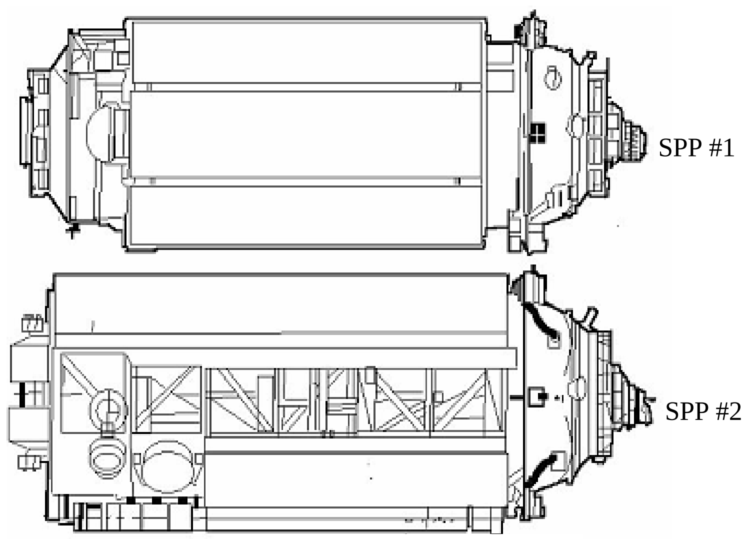
Z=Zenith, S=Starboard, P=Port

Types of ITS Backbone Truss Segments

ISS Applications

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

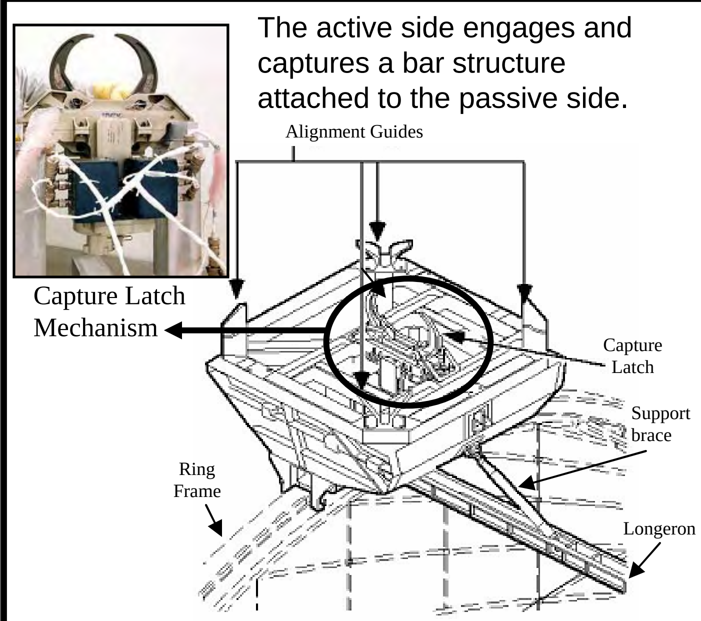
- The truss system is 25.76 ft. long and contains radiators, solar arrays, the capability for pressurized storage, and the ability to support the European Robotic Arm (ERA).
- The SPP is also equipped with thrusters to aid the Service Module with control moments along the roll axis.
- The system is comprised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



Russian Science Power Platform (SPP)

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.

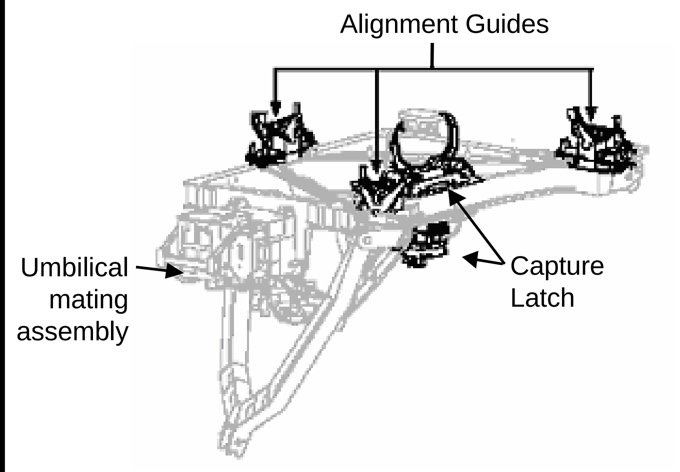


Lab Cradle Assembly (LCA)

ISS Truss – Module Interface

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.



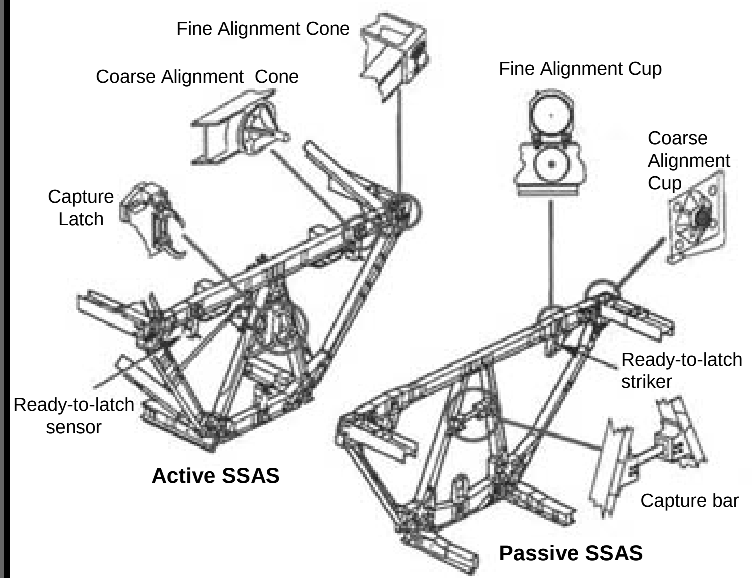
Common Attach System

ISS Truss Payloads / Logistics Interface

SPACECRAFT SYSTEMS DESIGN & OPERATIONS

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.

Segment to Segment Attach System (SSAS)

ISS Truss Segment Interface

Mechanisms:	Functions:
Common Berthing Mechanism (CBM)	Connects US modules together
Lab Cradle Assembly (LCA)	Connects integrated truss (SO) to the Lab
Segment-to-Segment Attach System (SSAS)	Connects integrated truss segments together
Rocketdyne Truss Attach System (RTAS)	Connects integrated truss segments together
Common Attach System (CAS)	Connects exposed payloads and logistics carriers to the truss
Androgynous Peripheral Attach System (APAS)	Mates FGB and PMA1, and docks the Orbiter to the Station
Probe/ Drogue Docking System	Connects Russian modules together
Hybrid Docking Assembly	Connects Russian modules together

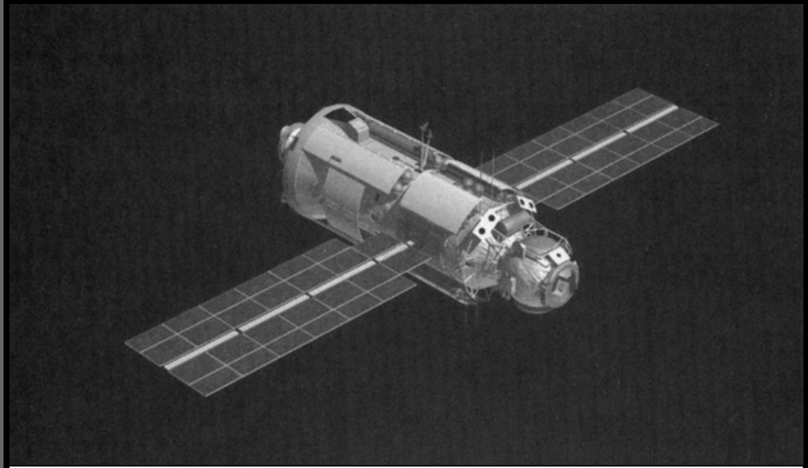
Summary of ISS Attachment Elements and Functions

ISS Interface Systems

NASA

Elements and Functions:

- Zarya provides early propulsion, power, fuel storage, communication and serves as the rendezvous and docking port for the Zvezda Service Module.
- Currently serves as a passageway, stowage facility, docking port and fuel tank.



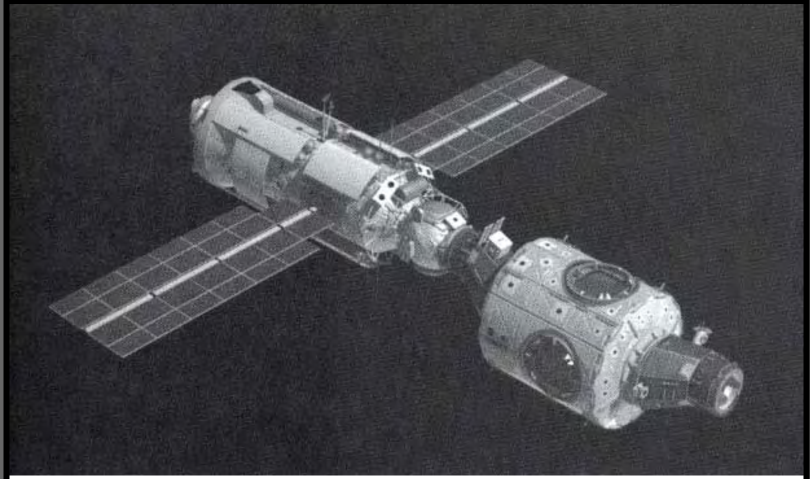
Elements:	Zarya Control Module (Functional Cargo Block - FCB)
Launch Date:	Nov. 20, 1998
Launch Vehicle:	Russian Proton Rocket

FLIGHT 1A/R

NASA

Elements and Functions:

- PMA-1 connects US and Russian elements, while PMA-2 provides a Shuttle docking location.
- Unity's six ports provide connecting points for the Z1 truss exterior framework: US Lab; airlock; cupola; Node 3; MPLM and the Control Module.



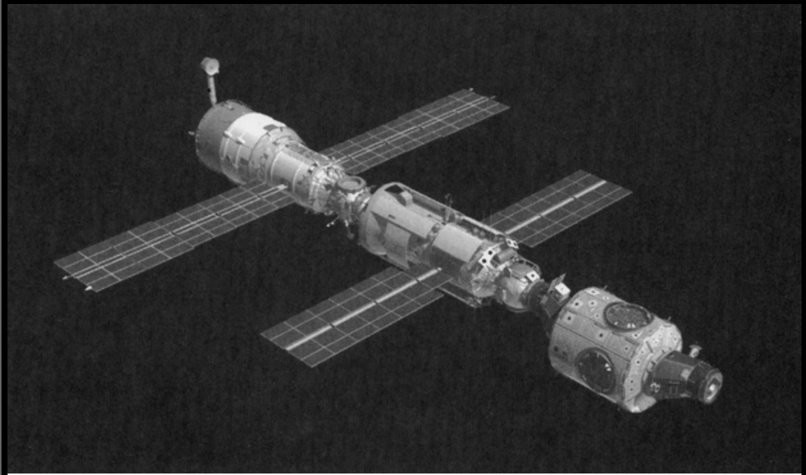
Elements:	Unity Node (one Stowage Rack); two Pressurized Mating Adapters (PMAs)
Launch Date:	Dec. 4, 1998
Launch Vehicle:	Space Shuttle Endeavour/ STS-88

FLIGHT 2A

NASA

Elements and Functions:

- Primary Russian station contribution and early station living quarters.
- Provides life support system functions to all early elements.
- Primary docking port for Progress-type cargo re-supply vehicle and Soyuz vehicle carrying Expedition One crew.
- Provides propulsive attitude control and re-boost capability for early station.



Elements:	Zvezda Service Module
Launch Date:	July 12, 2000
Launch Vehicle:	Russian Proton Rocket

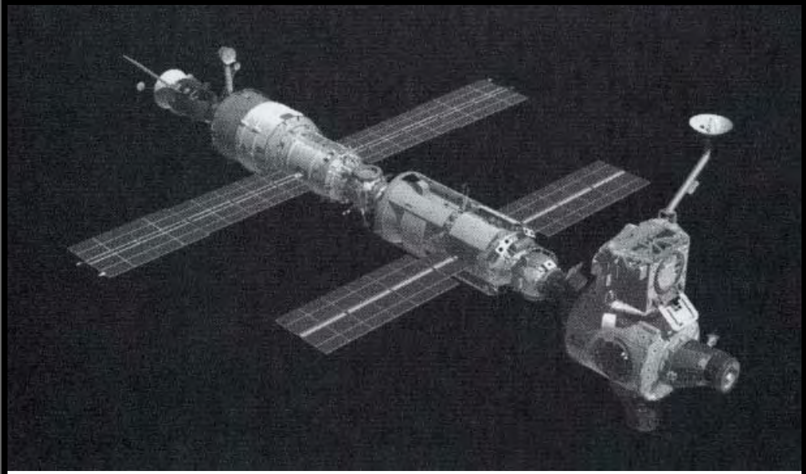
FLIGHT 1R

NASA

Elements and Functions:

- Crew, Commander Bill Shepherd, Soyuz Commander Yuri Gidzenko, and Flight Engineer Sergei Krikalev, established the first permanent human presence in space with three-person crew.
- Crew stayed 136 days and was relieved by Expedition Two crew on March 14, 2001.
- Activities included:

- Performed flight test of the new station.
- Checked out communications systems; activated food warmers; charged batteries for power tools; started water processors; activated the toilet.
- Activated life support systems.
- Began scientific experiments.
- Continued stowage and checkout of the new station.



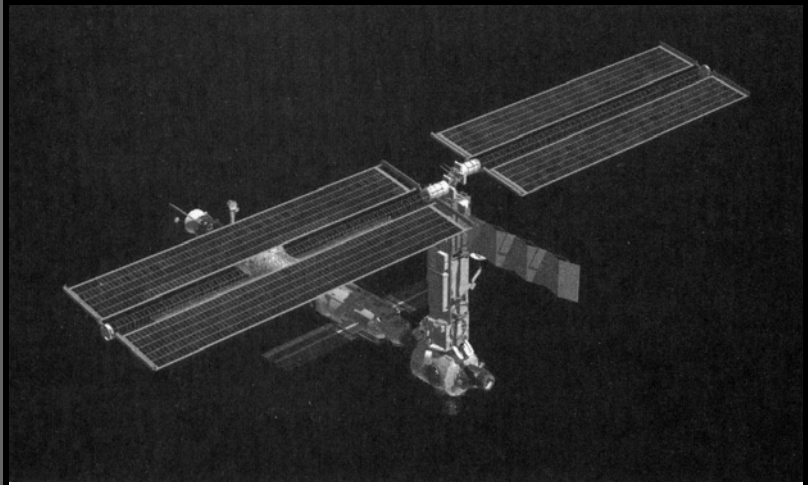
Elements:	Expedition One Crew
Launch Date:	Oct. 31, 2000
Launch Vehicle:	Russian Soyuz

FLIGHT 2R

Elements and Functions:

- Provided the first US solar power with solar arrays and batteries, called Photovoltaic Module (PV).
- First PV module installed temporarily on Z1 truss until after 13A when it is moved to the P5 truss.
- Two radiators provide early cooling, called photovoltaic (PV) Thermal Control System (TCS) radiators. Also, a S-band communications system was activated for voice and telemetry.

NASA



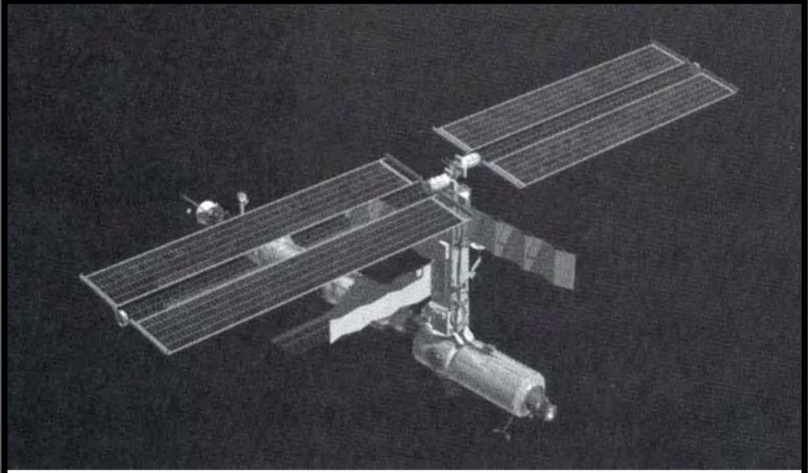
Elements:	Integrated Truss Structure P6, Photovoltaic Module, Radiators
Launch Date:	Nov. 30, 2000
Launch Vehicle:	Space Shuttle Endeavour/ STS-97

FLIGHT 4A

NASA

Elements and Functions:

- Installation of Destiny- centerpiece of ISS where unprecedented science experiments are performed in the near zero gravity of space.
- Destiny arrives with five system racks including computers that provide command and control of the entire ISS.
- Control Moment Gyroscopes are activated with delivery of electronics in lab, providing electrically-powered attitude control.



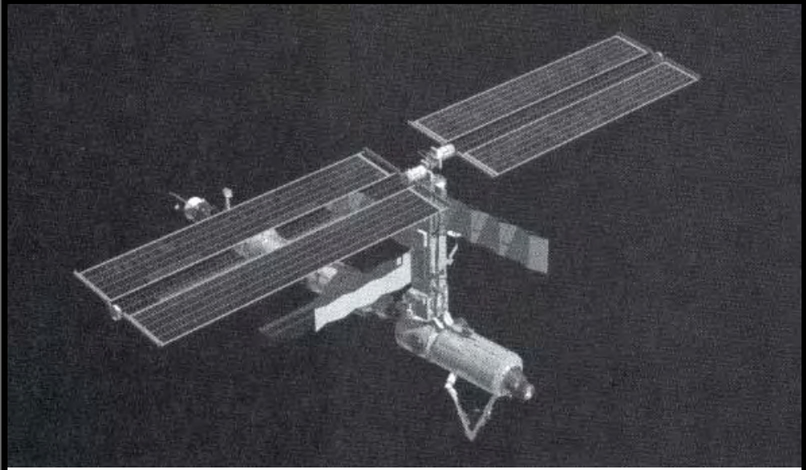
Elements:	US Laboratory module Destiny
Launch Date:	Feb. 7, 2001
Launch Vehicle:	Space Shuttle Atlantis/ STS-98

FLIGHT 5A

NASA

Elements and Functions:

- MPLMs serve as station's "moving vans" – carry new laboratory racks filled with equipment, experiments and supplies and return old racks and experiments to Earth. Italian-built MPLM Raffaello carries six system racks for Destiny and two storage racks for the U.S. Lab.
- UHF antenna provides space-to-space communications capability for U.S.-based space walks.
- Delivers Canadian SSRMS, the station's mechanical arm, which is needed to perform assembly operations on later flights.



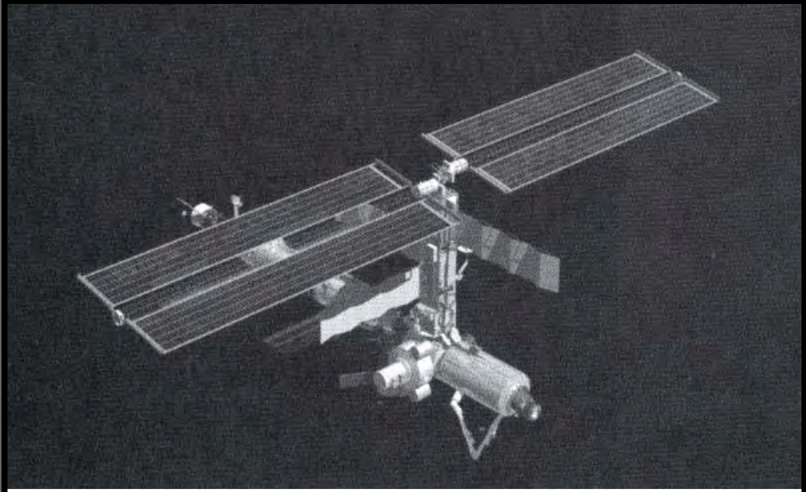
Elements:	Rafaello MPLM (Lab outfitting), Ultra High Frequency (UHF) antenna Space Station Remote Manipulator System (SSRMS)
Launch Date:	April 19, 2001
Launch Vehicle:	Space Shuttle Endeavour/ STS-100

FLIGHT 6A

NASA

Elements and Functions:

- Boeing-built Airlock provides station space walking capability for both US and Russian spacesuits. With this addition, ISS takes on a degree of self-sufficiency and capabilities for full-fledged research in the attached laboratory module.
- A high-pressure gas assembly supports space walk operations and augments the Service Module gas re-supply system.



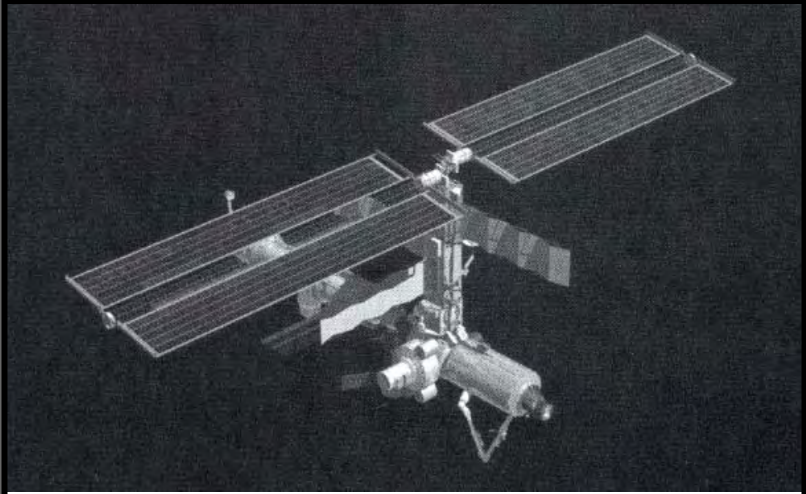
Elements:	Joint Airlock and High Pressure Gas Assembly
Launch Date:	July 12, 2001
Launch Vehicle:	Space Shuttle Atlantis/ STS-104

FLIGHT 7A

NASA

Elements and Functions:

- Provides additional egress and ingress location for Russian-based space walks and a Soyuz docking port.



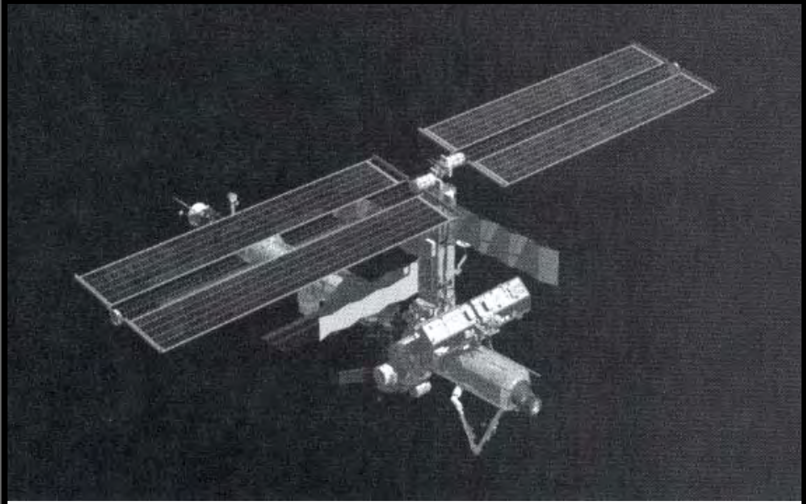
Elements:	Docking Compartment 1 (DC-1) and Strela Boom
Launch Date:	Sept. 14, 2001
Launch Vehicle:	Soyuz Rocket

FLIGHT 4R

NASA

Elements and Functions:

- The Starboard 0 (S0) truss is the next element of the massive integrated truss structure. Power and data cables will wind through the truss to carry energy and information to and from the station's extremities.
- The Mobile Transporter creates a movable base for the station's mechanical arm, Canadarm 2, allowing it to travel along the station truss after the delivery of the Mobile Base System.
- Four spacewalks were planned with the Expedition Four crew to install the S0 truss.



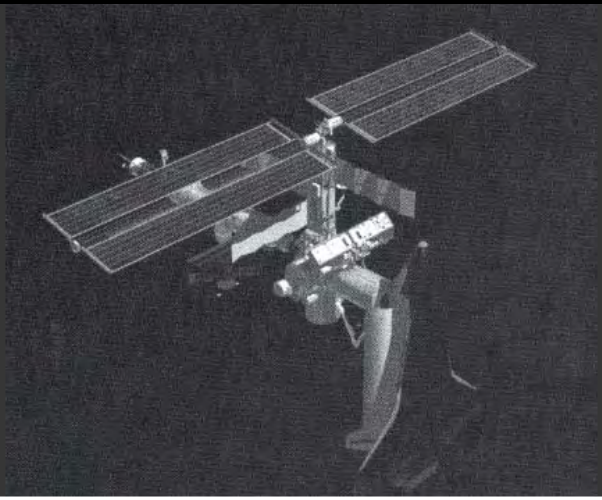
Elements:	Integrated truss structure S0, Mobile Transporter (MT)
Launch Date:	April 8, 2002
Launch Vehicle:	Space Shuttle Atlantis/ STS-110

FLIGHT 8A

NASA

Elements and Functions:

- The crew of Expedition Five- Commander Valeri Corzun and flight engineers Peggy Whitson and Sergei Treschev replace Expedition Four.
- The Leonardo MPLM carries equipment racks and three stowage and re-supply racks to the station.
- The Mobile Base System (MBS) is a work platform that moves along rails covering the length of the ISS that provides lateral mobility for the Canadarm as its traverses the main trusses.



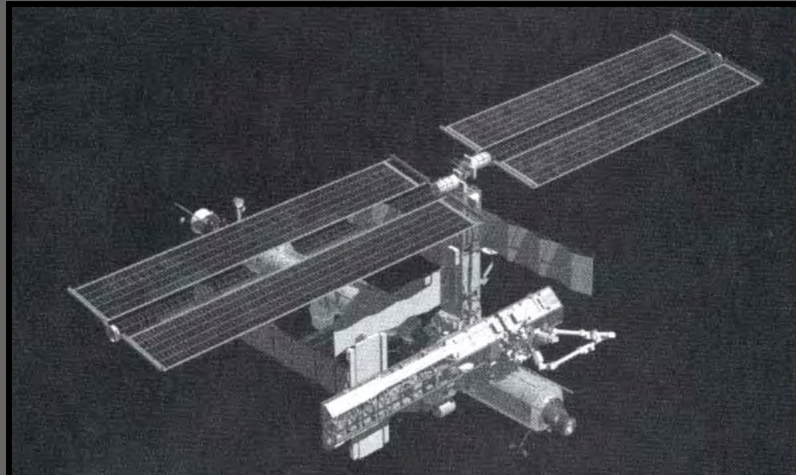
Elements:	Crew exchange, Leonardo multipurpose logistics module (MPLM), Mobile Base System (MBS)
Launch Date:	June 5, 2002
Launch Vehicle:	Space Shuttle Endeavour/ STS-111

FLIGHT UF-2

NASA

Elements and Functions:

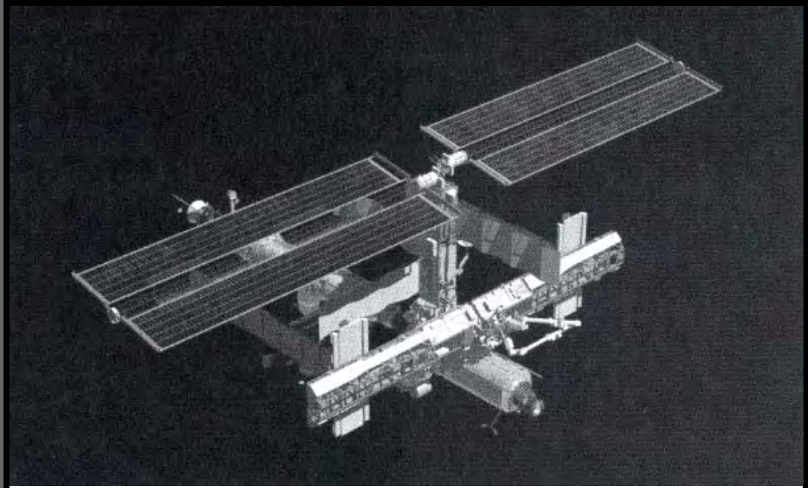
- The first starboard truss is attached to S0 with radiators.
- CETA Cart A is attached to the MT and can be used by spacewalkers to move along the truss with equipment.



Elements:	Starboard 1 (S1) truss with radiators, Crew & Equipment Translation Aid (CETA) Cart
Launch Date:	October 7, 2002
Launch Vehicle:	Atlantis/ STS-112

FLIGHT 9A

NASA



Elements:	Port 1 (P1) truss with radiators, CETA Cart B, UHF antenna
Launch Date:	Nov. 23, 2002
Launch Vehicle:	Endeavour/ STS-113

Elements and Functions:

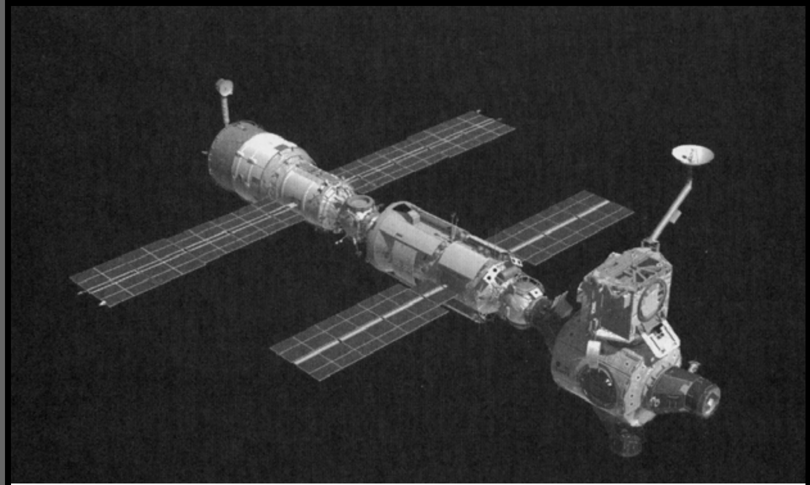
- Three spacewalks attach the P1 truss to S0 with radiators.
- CETA Cart B attached to the MT can be used by spacewalkers to move along the truss with equipment.
- Astronauts can use the CETA Cart B to deploy UHF antenna to improve communications.

FLIGHT 11A

NASA

Elements and Functions:

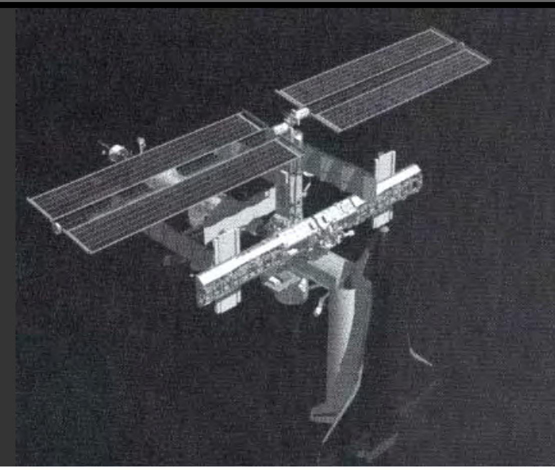
- ITS Z1 is the early exterior framework to allow first US solar arrays on flight 4A to be temporarily installed on Unity for early power.
- Ku-band communication system supports early science capability and US television on 6A.
- CMGs provide non-propulsive (electrically-powered) attitude control when activated on 5A.
- PMA-3 provides Shuttle docking port of solar array installation on 4A, Lab installation on 5A.



Elements:	Integrated Truss Structure (ITS) Z1, Ku-band Communications System, CMG, PMA-3
Launch Date:	Oct. 11, 2000
Launch Vehicle:	Space Shuttle Discovery/ STS-92

FLIGHT 3A

NASA



Elements:	Utilization and Logistics Flight
Launch Date:	Under Review
Launch Vehicle:	US Space Shuttle Discovery/ STS-121

Elements and Functions:

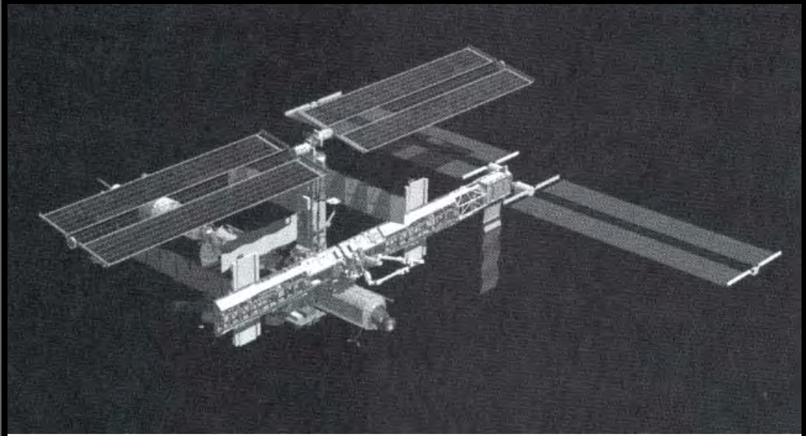
- Return to Flight test mission.
- Crew rotation.

FLIGHT ULF1

NASA

Elements and Functions:

- Delivers the second port truss segment, the P3/P4 Truss, to attach to the first port truss segment, the P1 Truss.
- Deploys solar array set 2A and 4A. Deploys P4 Truss radiators.
- Activates and checks out Solar Alpha Rotary Joint (SARJ).



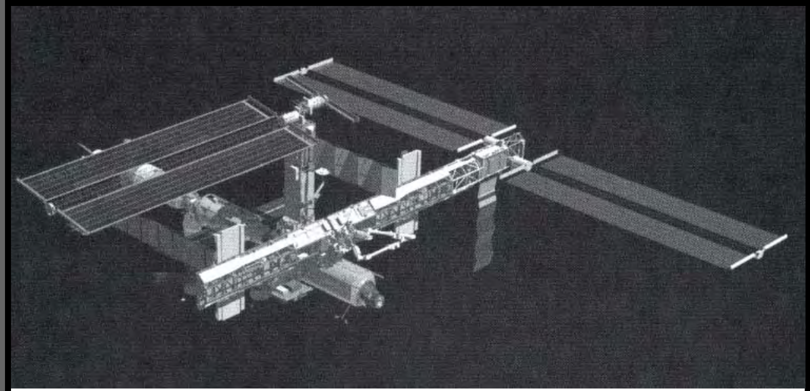
Elements:	Second left-side truss segment (ITS P3/P4); Solar array and batteries.
Launch Date:	Under review
Launch Vehicle:	US Space Shuttle Endeavour/ STS-115

FLIGHT 12A

NASA

Elements and Functions:

- Delivers third port truss segment, the P5 Truss, to attach to second port truss segment, the P3/P4 Truss.
- Deactivates and retracts P6 Truss Channel 4B (port-side) solar array.
- Reconfigures station power from 2A and 4A solar arrays.



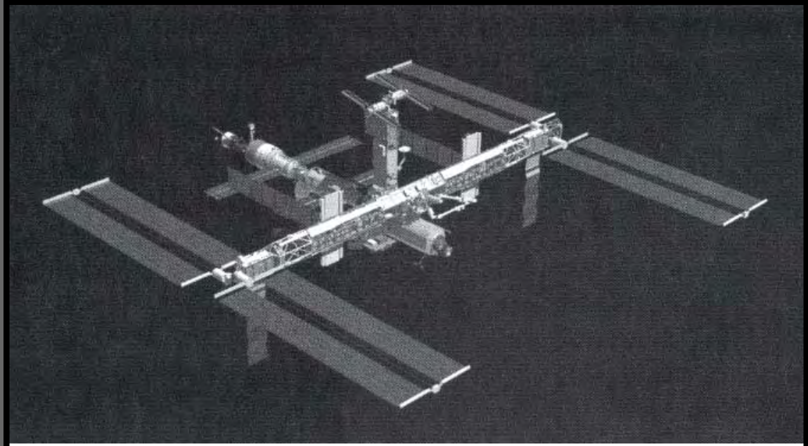
Elements:	Third left-side truss segment (ITS P5), logistics and supplies, SPACEHAB single cargo module
Launch Date:	Under review
Launch Vehicle:	US Orbiter/ STS-116

FLIGHT 12A1

NASA

Elements and Functions:

- The second starboard truss segment, the S3/S4 Truss, is attached to the first starboard truss, the S1, along with a third set of solar arrays.
- Four external attachment sites for truss-mounted exterior experiments and research are delivered.
- Activates and checks out S4 Truss Solar Alpha Rotary Joint (SARJ).
- Channel 1A and 3A solar arrays are deployed and station power supply reconfigured.
- P6 Truss Channel 2B (starboard) solar array is retracted.



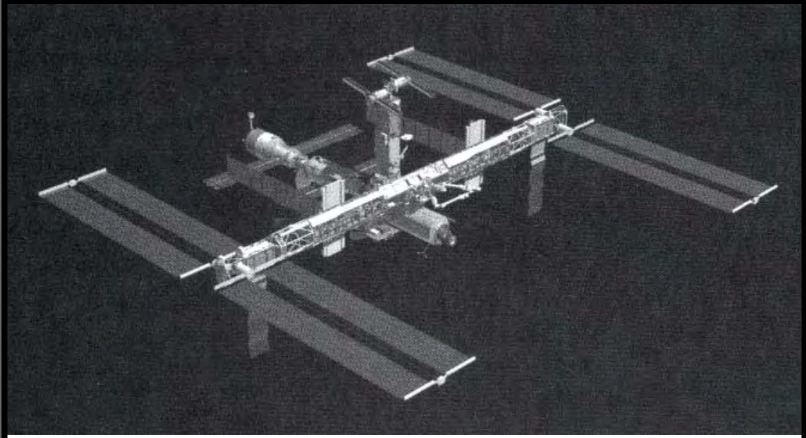
Elements:	Second right-side truss segment (ITS S3/S4); Solar array set and batteries (Photovoltaic Module)
Launch Date:	Under review
Launch Vehicle:	US Orbiter/ STS-117

FLIGHT 13A

NASA

Elements and Functions:

- The third starboard truss segment, the ITS S5 Truss, is attached to the station.
- A SPACEHAB Single Cargo Module delivers supplies and equipment.



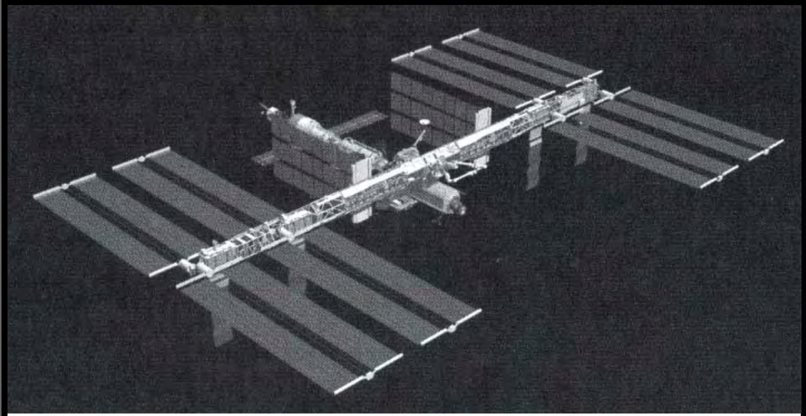
Elements:	SPACEHAB Single Cargo Module; Third starboard truss segment (ITS S5)
Launch Date:	Under review
Launch Vehicle:	US Orbiter/ STS-118

FLIGHT 13A1

NASA

Elements and Functions

- The fourth and final set of US solar arrays is delivered along with fourth starboard truss segment, the S6 Truss.
- Relocates the P6 Truss from atop the Z1 Truss to final assembly location attached to the P5 Truss (becomes final port-side truss segment).
- Redeploys and activates the P6 Truss Channel 2B and 4B solar arrays.



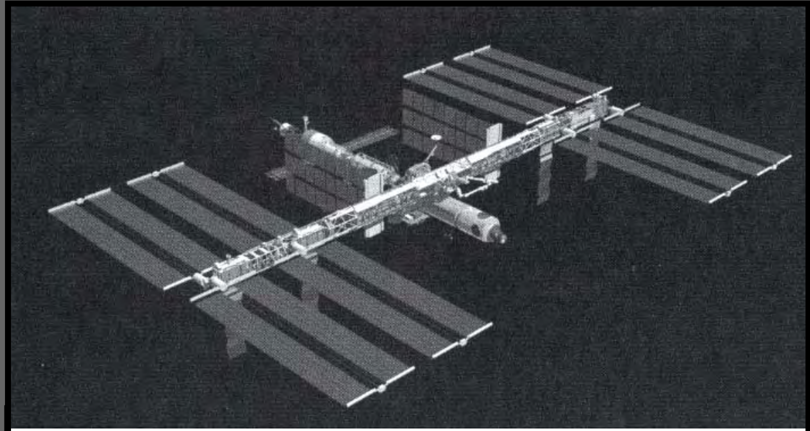
Elements:	Solar Arrays and Batteries (Photovoltaic Module S6)
Launch Date:	Under review
Launch Vehicle:	US Orbiter/ STS-119

FLIGHT 15A

NASA

Elements and Functions

- The second of three station connecting modules, Node 2, attaches to end of US Lab and provides attach locations for the Japanese laboratory, European laboratory, the Centrifuge Accommodation Module and later Multipurpose Logistics Modules.
- Primary docking location for the Shuttle is the Pressurized Mating Adapter attached to Node 2.
- ISS US Core complete.



Elements:	US Node 2
Launch Date:	Under review
Launch Vehicle:	US Orbiter/ STS-120

FLIGHT 10A

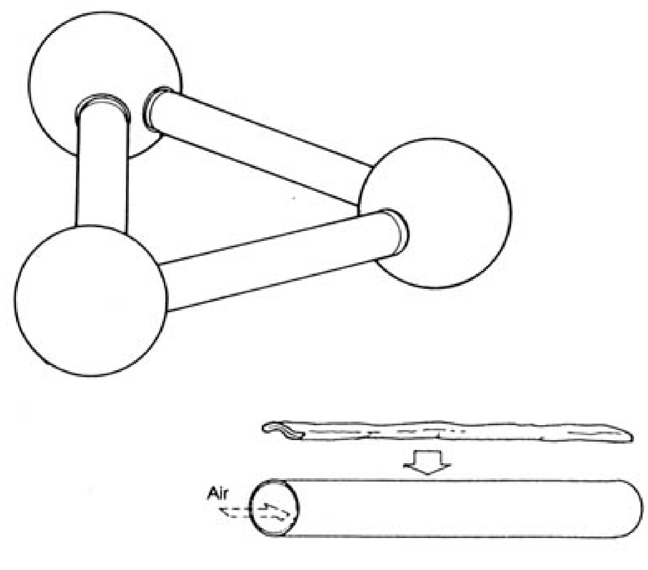
Characteristics of Variously Used Metals and Composites.

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

Comparison of Conventional Space Construction Materials

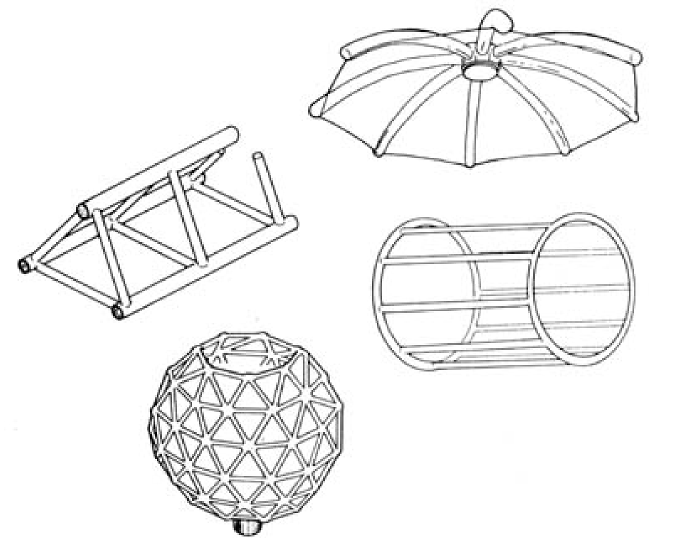
Inflatable and inflation-deployed structures offer potential advantages and applications for future space structure development:

- 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.

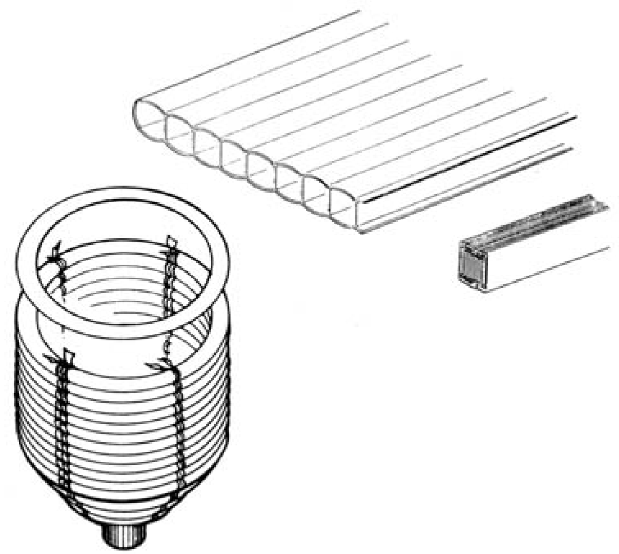


Simple Tubes/Bladders

Possible Forms

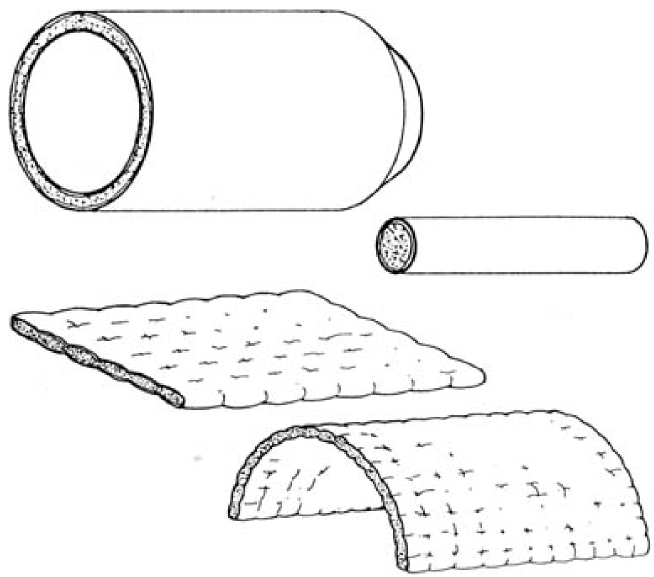


Tubular Frame Structures

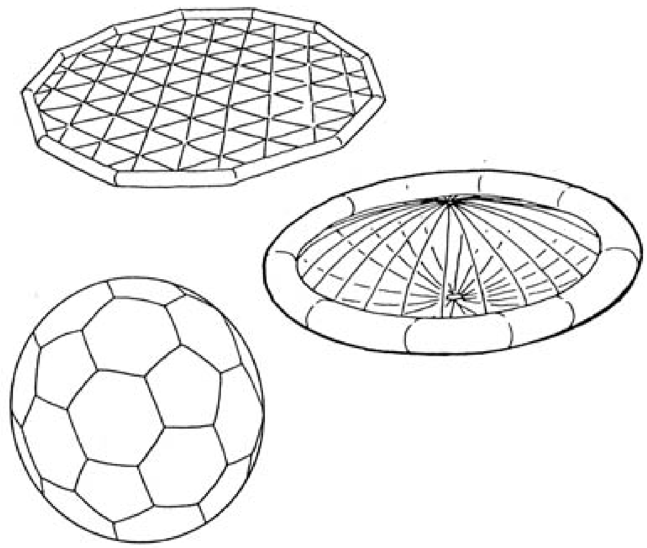


Cocoon/Ribbed Structures

Possible Forms

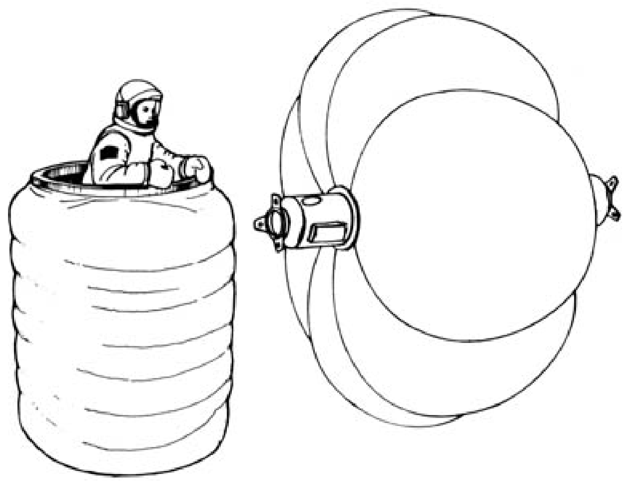


Foam-Rigidized Tubes/Bladders

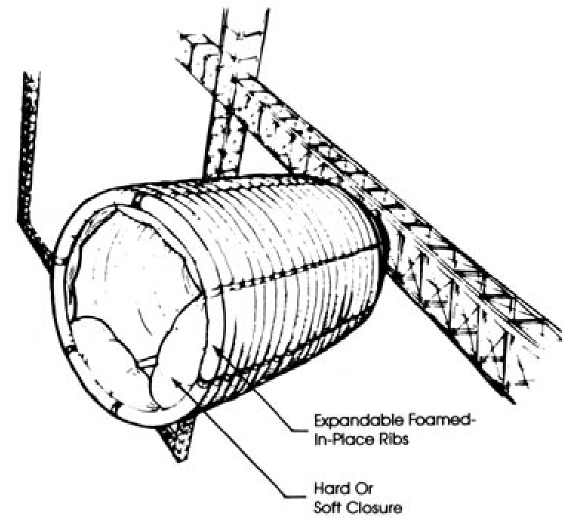


Mechanically-Rigidized Structures

Possible Forms



Airlocks and Space Habitats

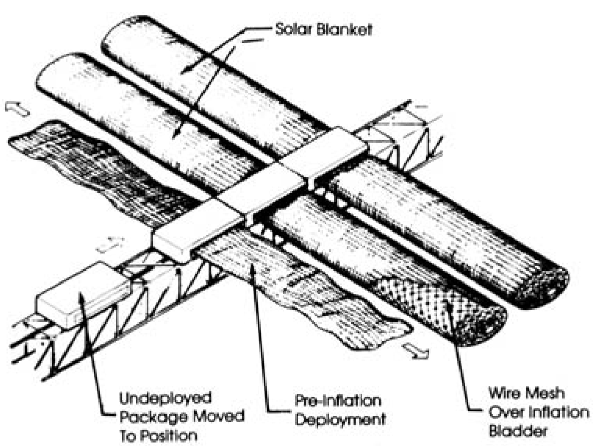


Orbital Transfer Vehicle Hangars

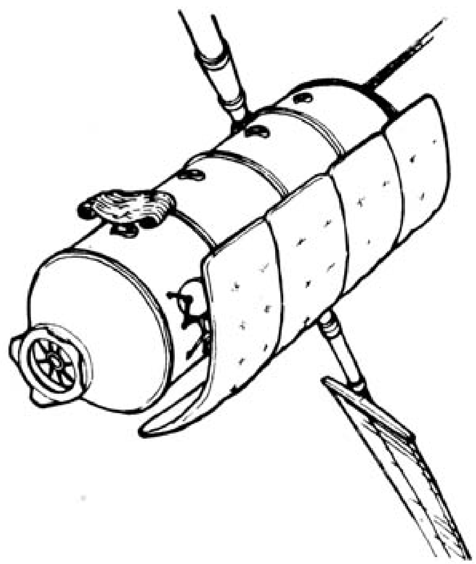
Possible Applications

CONSTRUCTION AND MATERIALS

INFLATABLE SYSTEMS



Tubular Frame Structures



Cocoon/Ribbed Structures

Possible Applications

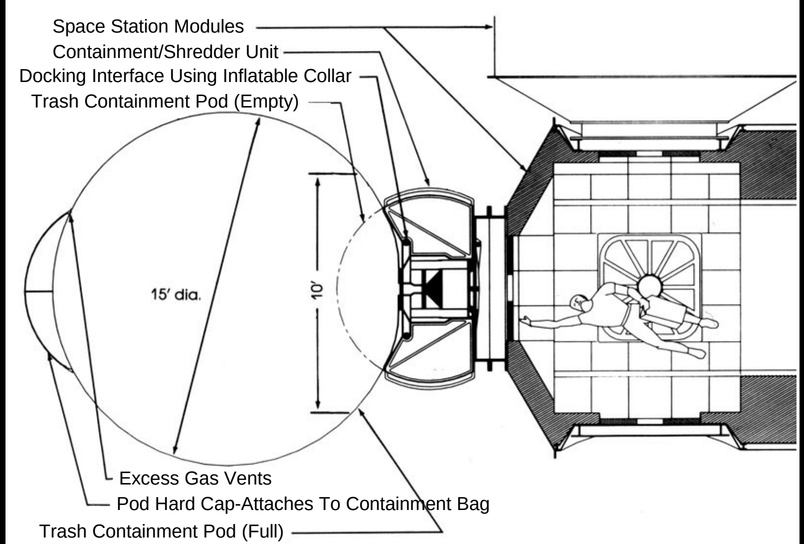
CONSTRUCTION AND MATERIALS

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:

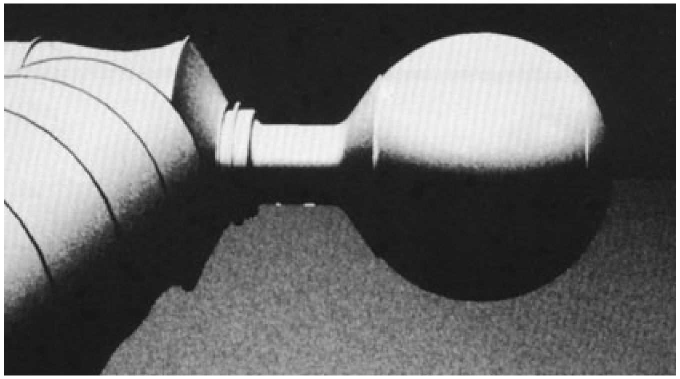
- Trash is inserted into a 4 cubic ft. airlock and automatically forced through shredding blades into the container.
- The deployed 15 ft. diameter spherical container provides 1,767 cubic ft. of holding volume.



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

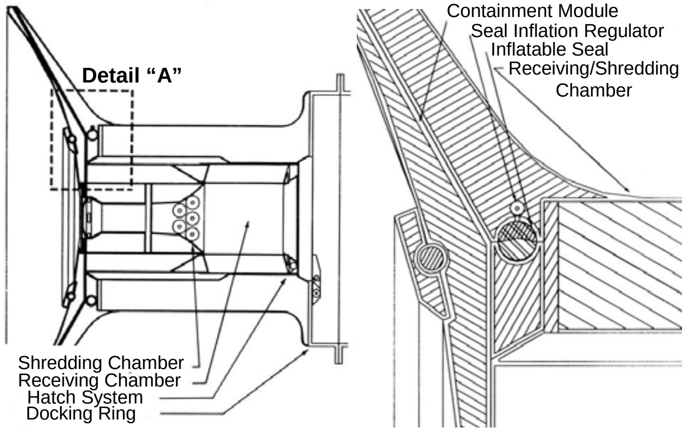
Shredder Unit and Containment Rod

SICSA Trash Management Concept



Containment pods attached to spacecraft berthing ports hold and isolate contaminates and bacteria from internal spaces.

Externally Mounted Containment Pod



Section Through Receiving Chamber

Detail "A" Showing Bag Attachment Seal

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

Future settlements on the Moon or planetary bodies may utilize in-situ materials for a variety of applications:

- Volatiles such as oxygen obtained from the lunar “soil” (regolith) might be used to replenish atmosphere supplies and as a component of cryogenic rocket fuel.
- Silicates, metals, glass and basalt obtained from regolith might be used in the construction of space structures.

The Moon as a Material Source

Samples obtained from 9 Apollo landing sites and information revealed by remote sensing observations indicate that the Moon contains abundant materials that might possibly be used for construction:

- Dark maria 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.
- Oxygen is also plentiful in lunar regolith, affording many beneficial uses.

	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

Alton, J. H., et al. 1985. “Guide to Using Lunar Soil and Simulants for Experimentation.”*

Lunar Resources

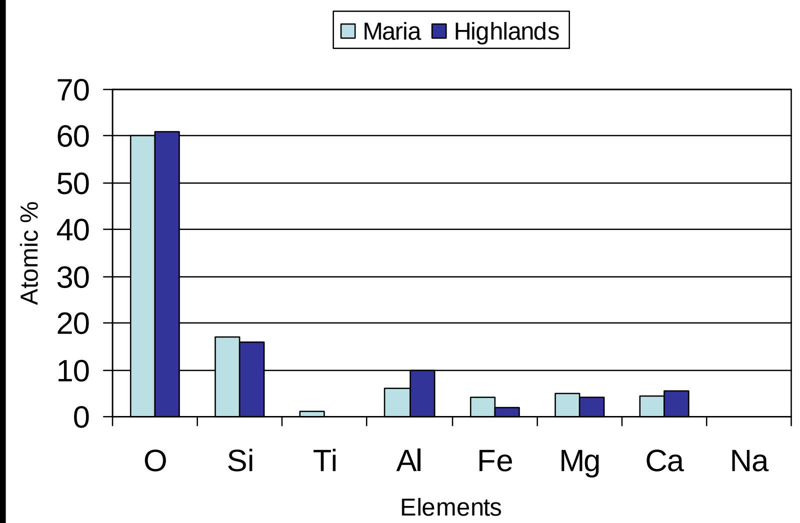
Lunar maria and highland regolith contains significant amounts of potentially valuable resources:

- Lunar Regolith (2 Primary Groups):

- Fe, Mg, Ti-Maria basalts
- Al, Ca-Anorthositic highland rocks

- Elements (7 Primary Groups):

- Oxygen
- Silicon
- Magnesium
- Iron
- Calcium
- Aluminum
- Titanium



Average Elemental Compositions of Lunar Surface Regolith

Source: Leonard, R.S., and Johnson, S.W.(1988)

Lunar Resources

Bulk lunar regolith and its major mineral fractions might be heated, separated, molded and sometimes combined to form a variety of structural elements:

- Calcium oxides obtained from anthrosite materials might provide cement for concrete that is created from lunar aggregates. Oxygen combined with hydrogen from Earth can provide necessary water (or lunar water can be used if it exists).
- Melting and slow cooling of regolith can cause crystallization of cast basalt, and rapid cooling under anhydrous lunar conditions might create ultra-strong glass.

Lunar Concrete:

- Conventional type (using water)
- Sulfur concrete (without water)

Lunar Basalt:

- Sintered (direct melting of surface soil)
- Cast (products formed using metal molds)

Lunar Glass:

- Spun fibers (cables and fiberglass cloth)
- Formed (structural and product applications)

Lunar Metals:

- Iron
- Titanium
- Aluminum
- Nickel

Material Types

Lunar Construction Materials

Concrete made of cement and aggregate from regolith has been proposed by many scientists and engineers:

- Lunar concrete might contain approximately the same ratios of cement and aggregate as concrete on Earth, but use epoxy or other binders to conserve precious water.
- Hydrogen for water might be transported to the Moon in a liquid form (cooled below its boiling point of -252°C).
- Hydrogen might also be delivered in the form of methane (CH_4) or ammonia (NH_3).

Conventional Type:

- For large pressurized / unpressurized structures
- Requires imported water or hydrogen
  - 75% aggregate, 10% cement and 15% water (89% oxygen, 11% hydrogen by weight)
  - Hydrogen might be brought in cooled liquid form (-252ºC), as methane (CH_4) or as ammonia (NH_3)
  - Requires sealed containment to reclaim water
- Other materials available on Moon:
  - Portland cement; 65% calcium oxide (CaO), 4% alumina
  - (Al_2O_3) -8% by weight.
  - Anorthositic rock is a good calcium source.
- Requires relatively long curing time:
  - Large curing containment facilities.

Sulfur Concrete:

- Used for housing in Middle East.
- Produced without water – sulfur added to heated aggregate.
- Develops early strength.
- May deteriorate at high lunar surface temperatures.

Lunar Concrete

Lunar Construction Materials

Basalt is a black or greenish gray ceramic material associated with volcanic magma on Earth and lunar mare and highland regions:

- It can potentially be cast into construction products such as slabs, bricks, columns, beams and hollow pipes.
- Casting entails melting raw material, discharging it into a homogenizing drum, pouring the melt into metal molds, and slow controlled cooling to prevent cracking during annealing.
- "Paving" of lunar surfaces might be accomplished by sintering a basalt crust through the application of heat and pressure.

Cast Basalt:
- Used in Czechoslovakia and other Eastern European countries for utility pipes and other products:
- Derived from volcanic magma
- Highly abrasive-resistant
- Can be produced by melting/ slowly cooling regolith at 1320-1350°C.
- Controlled cooling to prevent cracking and other imperfections during solidification and crystallization.
- Cooling requires about 24 hours on Earth.
- By-products can include oxygen, titanium (from titanium oxide (TiO_2) and hydrogen (50-100 grams/ metric ton of soil).
- Requires metal molds for forming.

Sintered Basalt:
- Can involve direct melting of surface regolith:
- Slabs for road beds/ launch pads/ foundations.
- Interior, pressure tight tunnels/ cavities for habitats and liquid/ gas storage.
- Might use microwave heaters for melting.

Lunar Basalt

Lunar Construction Materials

Lunar metals might be applied for beneficial construction uses provided that they can be mined, processed and formed in a practical manner:

- Highland soils are believed to contain significant amounts of aluminum, and mare soils contain some aluminum, much iron and small amounts of titanium.
- Purity levels of lunar regolith minerals are low compared with Earth soils, but iron-rich meteoroid fragments might be harvested by drawing a magnet along the surface.

Background:

- Lunar soils contain several metals:
  - Highlands contain aluminum (approximately 27% Al_2O_3).
  - Mare soils contain less aluminum, more iron (approximately 16% FeO) and titanium (2.7-9% TiO_2).
  - Iron-rich soils often contain nickel and cobalt.

Processing:

- Purity of minerals in regolith is much lower than soils on Earth:
  - Extraction/ processing may only be practical as by-products of other processes (e.g. ilmenite reduction to obtain oxygen).
  - Iron may be most practical due to higher yields with less power for melting.
- Product control may be difficult on the Moon:
  - Reducing agents (carbon and hydrogen) for iron extraction must be imported).
  - Equipment for forming will be large/ complex.

Lunar Metals

Anhydrous glass created under vacuum conditions on the Moon may be one of the strongest known materials with applications that include filaments for cables and reinforcement fabrics, foam glass for beams, and thermal insulation:

- Glass can be made entirely from lunar regolith which contains abundant silicon (particularly in highland regions).
- Processing requirements are similar to basalt except for more controls to prevent crystallization and optimize tempering during cooling.

Background:
- Glass has been used since the beginning of recorded history:
- Natural state, broken, cut or shaped obsidian.
- Intrinsically one of strongest known materials:
- In lunar vacuum (without moisture) might attain tensile strength of 2 million psi.
- Strength due to atomic network of silicon and oxygen bonds which is weakened by polar water.

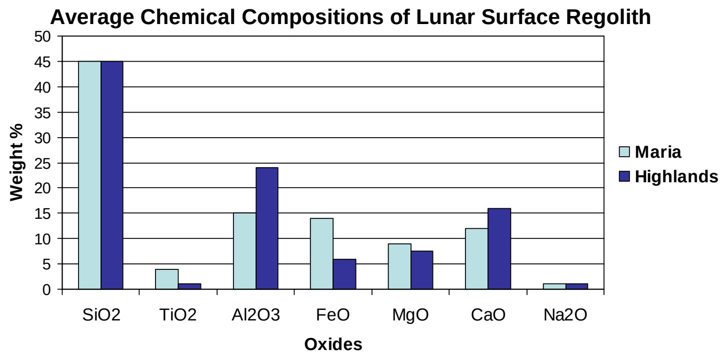
Processing:
- Can provide rigid elements or spun fibers.
- Can be made entirely from regolith (which is typically 22% silicon).
- Requirements are similar to basalt processing except:
- More stringently controlled cooling is necessary.
- More equipment/ control is necessary for finishing.

Lunar Glass

Lunar Construction Materials

Availability:

- Basalt and glass can be produced from regolith common to all lunar sites.
- Aluminum, iron, titanium and other metals are present at many sites, but in small proportions.
- Conventional concrete will require substantial quantities of imported water/ hydrogen.

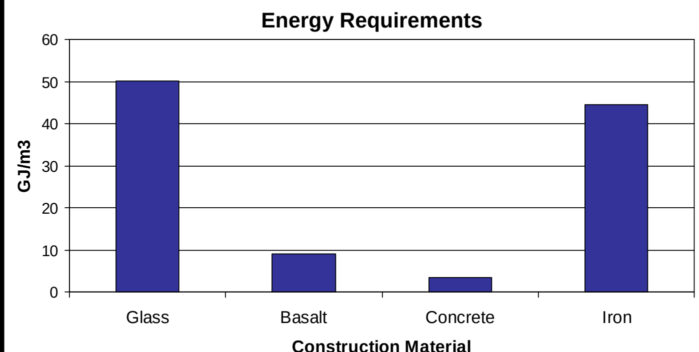


*Adapted from Lunar Science:A Post-Apollo View by Stuart Ross Taylor

Material Comparisons

Energy Requirements:

- Energy requirements for glass and metals are substantially higher than for other processes.
- Energy requirements for concrete will be impacted by environmental containment/ controls during curing.

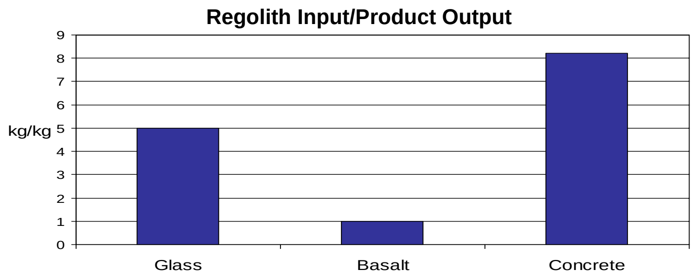


Material Comparisons

Lunar Construction Materials

Material Yields:

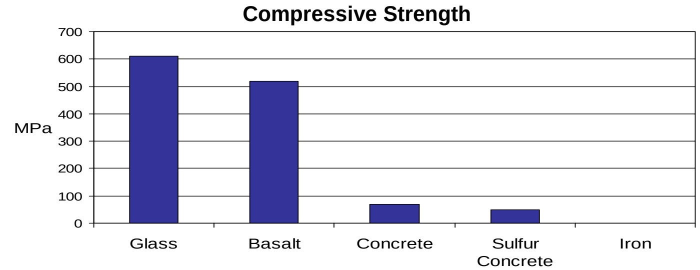
- Basalt products will have a very high (nearly 100%) yield efficiency.
- Glass will have a relatively high input/ output yield but will require extra power/ complex systems for forming, curing and finishing.
- Concrete will have a relatively low yield due to element extraction/ grading requirements.
- Metals will have very low yields- might be linked as by-products of ilimenite reduction for oxygen.

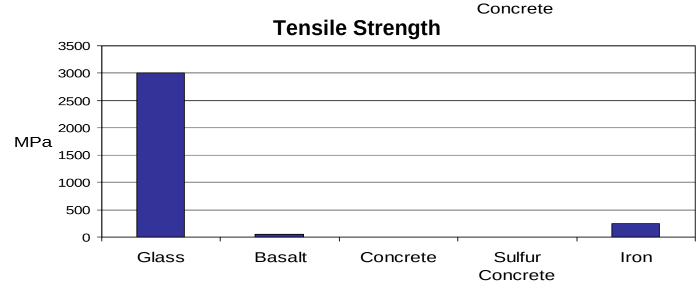


Material Comparisons

Strength:

- Glass, basalt and metals have high compressive strength.
- Anhydrous glass has by far the greatest tensile strength.
- Basalt and concrete might be used for relatively thick-walled pressurized structures.





Material Comparisons

Lunar Construction Materials

Various materials offer relative advantages and disadvantages associated with prospective properties, process requirements and construction applications.

	Glass	Basalt	Concrete	Sulfur Con.	Iron
Compressive Strength (MPa)	620	540	76	55	--
Tensile Strength (Map)	3000	35	--	7.1	270
Modulus of Elasticity (GPa)	870	110	21	--	196
Density (g/cm^3)	2.7	2.9	2.4	2.4	7.8
Melting Point (^oC)	1500	1300	600	115	1537
Cooling Point (^oC)	760	800	--	--	--
Thermal Expansion (cm/cm^{o}C)	4.2x10-6	7.8x10-7	1.19x10-5	1.44x10-5	1.2x10-5

Physical Properties

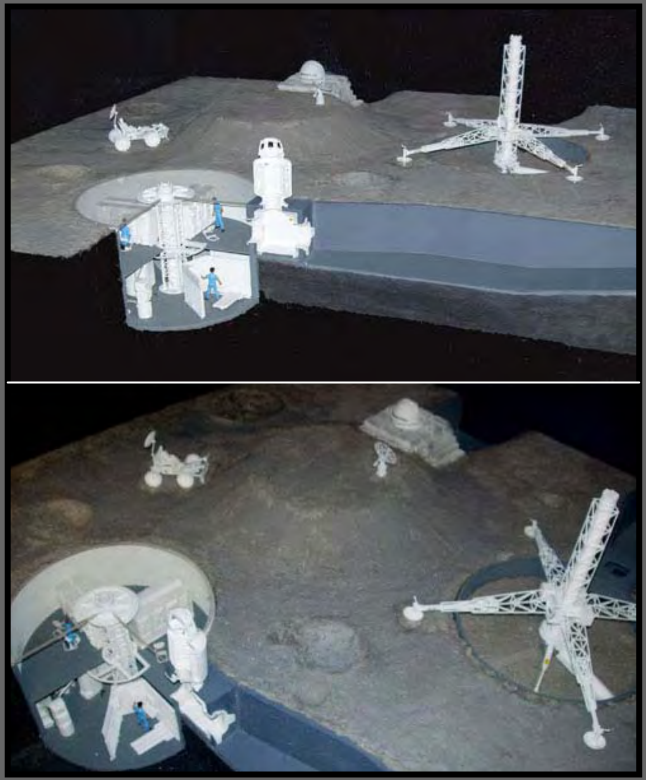
	Advantages	Disadvantages
Concrete	•Low Energy •Gradual Failure •Easily Cast •Abundant Resources •High Abrasion Resistance •Simple Production	•Must Import Hydrogen •Low Tensile Strength •Pressurized Processing Area Required •Long Curing Time
Sulfur Concrete	•Abundant Resources •No Water Needed •High Early Strength •High Resistance to Corrosion	•Deteriorates at Lunar Daytime Temperatures •Sulfur Must be Extracted •Sulfur is Flamable •Requires Surface Protection
Basalt	•High Compressive Strength •Simple Processing •High Abrasion & Chemical Resistance •High Resource Yields •Easily Cast In-Place •Abundant Resources	•Low Tensile Strength •Brittle •Must Use Metal Molds for Precision Casting
Glass	•High Compressive and Tensile Strength •Abundant Resources •Many Applications of Products •High Abrasion Resistance	•High Energy Requirement •Brittle •Organic Bonding Agents are Required for Fiberglass
Metal	•High Tensile Strength •High Density	•Low Yields •Complicated Process •High Energy Requirement

Summary Features

Lunar Construction Materials

SICSA's proposed in-situ construction approach lands an auger system to excavate a cylindrical habitat core into the lunar surface:

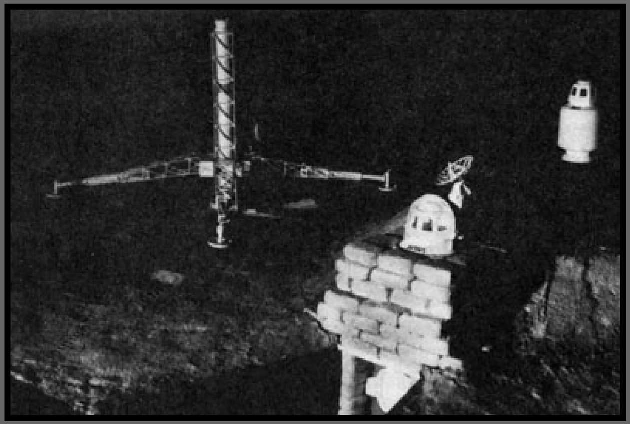
- A microwave element at the end of the auger sinters the regolith to create a gas pressure liner.
- Cast basalt interior structures are produced from the regolith for partitioning, floor and roof systems.
- Prefabricated pressure hatches and airlocks are delivered and incorporated.
- Excavated regolith is placed on top for solar radiation shielding.

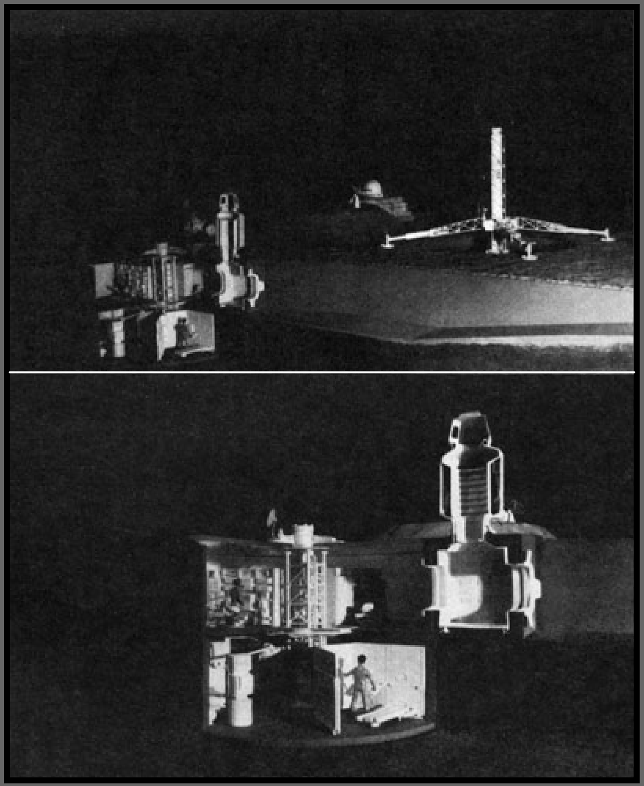


SICSA In-Situ Construction Approach

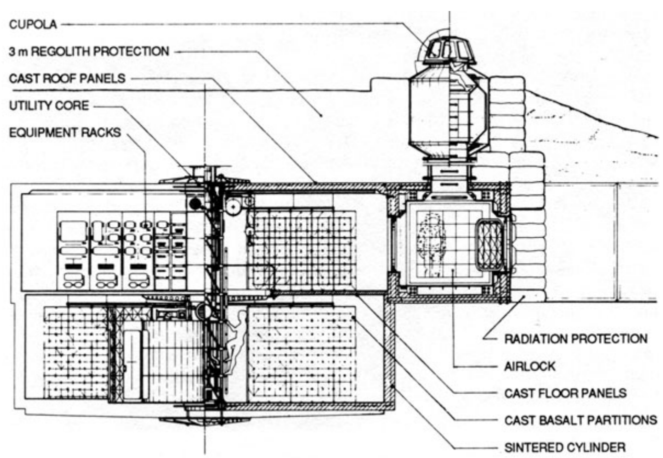
Proposed facility components:

- Sintered/ cast roadways and landing pads.
- Excavated/ sintered pressurized habitat with cast slab airlocks.
- Cast block and slab exterior/ interior structures (floors/ walls/ roof).

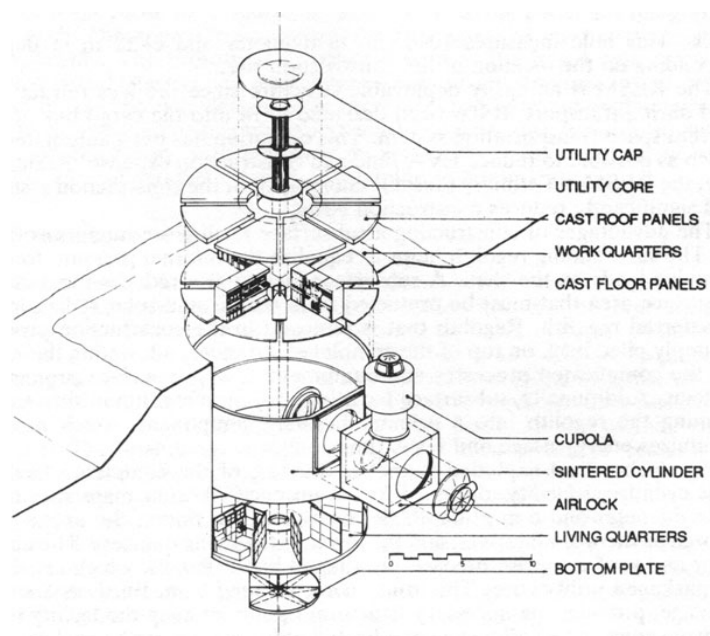




SICSA In-Situ-Constructed Facility



Section – Elevation of Facility

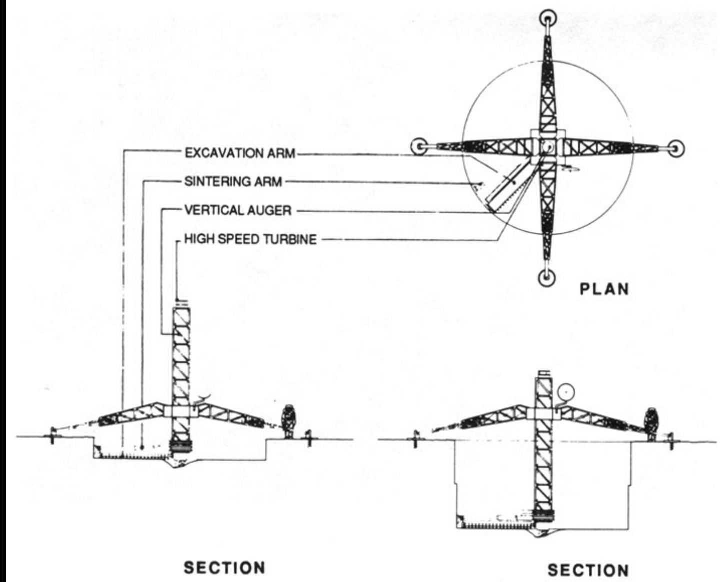


Facility Elements

SICSA In-Situ-Constructed Facility

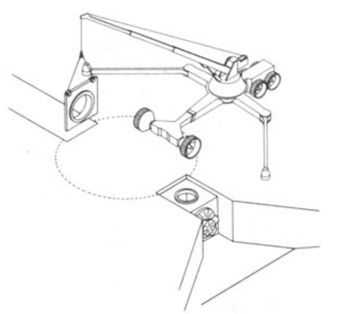
Proposed construction stages:

- Stage 1: An excavation auger with an excavation arm, microwave sintering element, and helical regolith removal screw is dispatched to the lunar surface.
- Stage 2: The excavation arm pivots around the helical screw shaft and excavates a core habitat volume. As this process occurs, the interior wall surface is sintered by the microwave device at the end of the sintering arm. Regolith that is excavated is transported by the screw and cast outside the cored area.
- Stage 3: Airlocks enclosures are cast of basalt along with habitat walls, floors, partitions and roof structures. Airlocks can be sealed by internal pressure membranes.
- Stage 4: Prefabricated elements are delivered to the site and incorporated into the structures, including cupolas, pressure hatches, utility systems and other equipment.

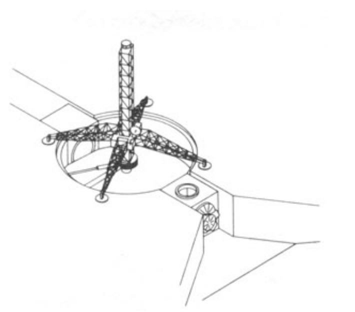


Augering Process

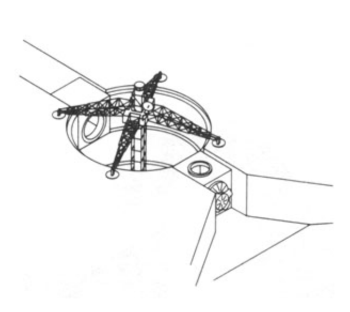
SICSA In-Situ-Constructed System



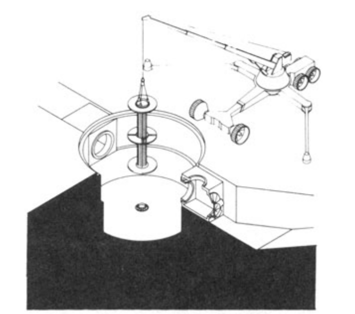
1. Excavate trenches and installation of airlocks



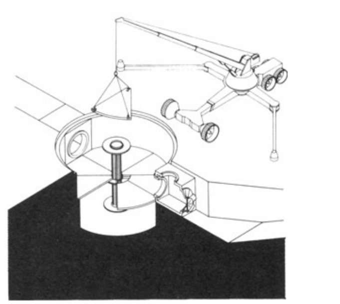
2. Land coring machine and begin operations



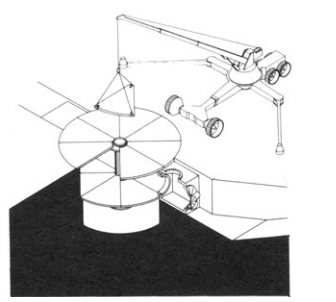
3. Complete coring/ Sintering: install plate



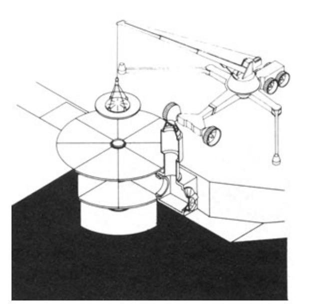
4. Place/Secure central utility system



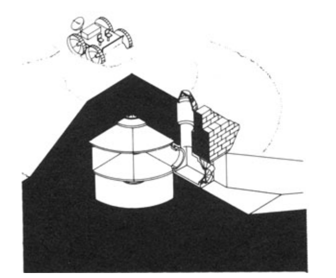
5. Cast/install basalt floor panels



6. Cast/install/seal basalt roof panels



7. Install cupola: cap & pressurize facility



8. Cover with regolith for radiation protection

SICSA In-Situ-Constructed Events

Additional information relevant to this section can be found in Part II (all sections) of this SICSA Space Architecture Seminar Lecture Series titled Human Adaptation and Safety in Space, along with other publications listed below:

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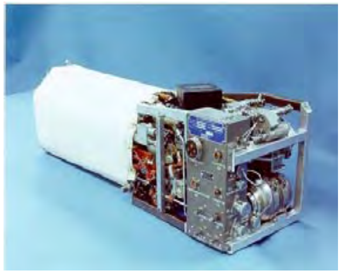
OF CONTENTS

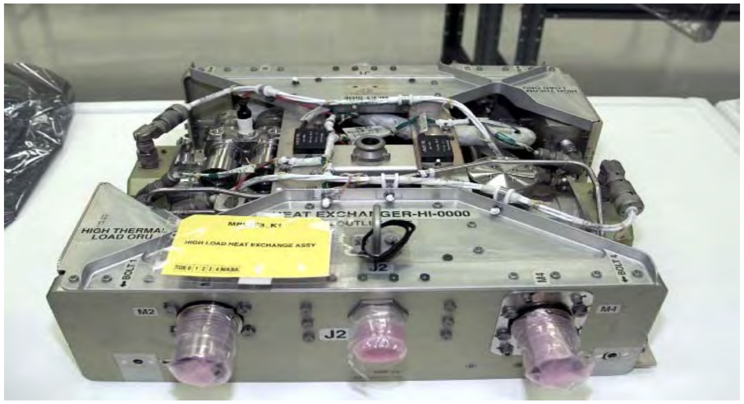
SECTION C : HABITAT SUPPORT SYSTEMS

SPACECRAFT SYSTEMS
DESIGN & OPERATIONS

Space architecture entails the planning and integration of a variety of support systems that are required to maintain effective equipment performance, operational safety and human comfort:

- Electrical power generation and conditioning systems.
- Active and passive thermal control devices.
- Environmental control and life EVA airlocks.
- Communications, command and data handling systems.





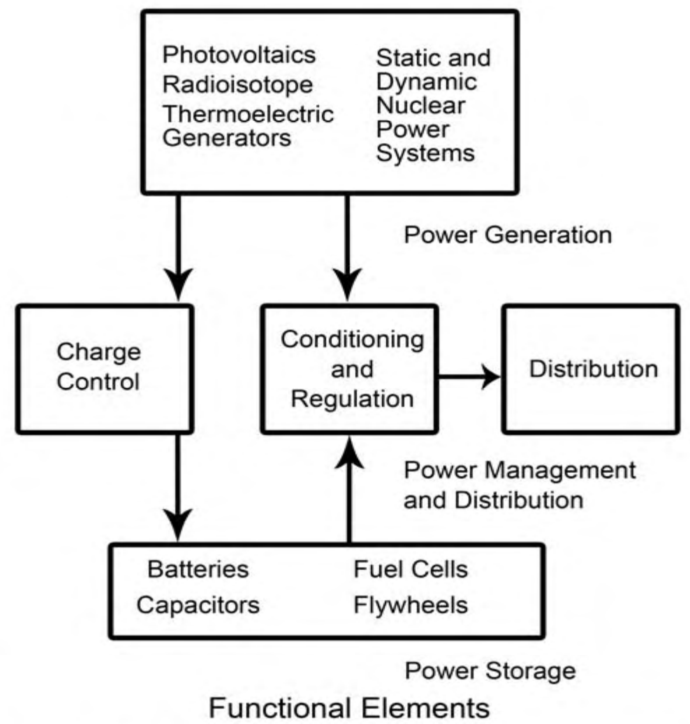
SPACECRAFT SYSTEMS DESIGN & OPERATIONS

Electrical power systems convert an energy source into electricity at the desired voltages. Functional elements include:

- Power generation:
  Primary sources are photovoltaics (PV), fuel cells, and radioisotope thermoelectric generators.

- Power management and distribution:
  Provides interfaces between power sources and loads, and isolates system faults to avoid single-point failures.

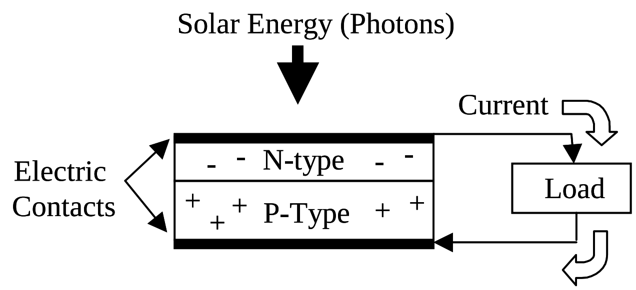
- Power Storage:
  Is needed during solar eclipses, for backup/ emergency power, and for short-duration primary power.



Power Generation, Management and Storage

Photovoltaics convert sunlight directly into electricity:

- A demonstrated energy conversion of about 29% may be slightly improved.
- Assemblies called PV panels or solar arrays have small PV cells cemented to a substrate.
- Arrays must be gimbaled/articulated for sun pointing.
- Continuous solar exposure and space radiation degrade efficiency about 1-2%/year.
- Performance also decreases with distance from the sun (i.e., past Mars).
- Concentrator arrays use lenses or mirrors to focus sunlight.
- Thin film arrays improve the power-to-weight ratios.



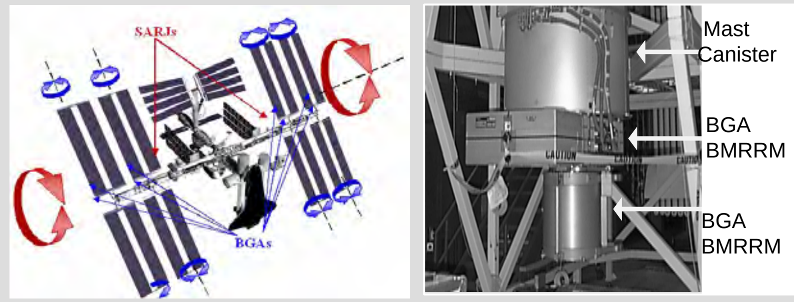
Solar Cell Type	Efficiency	Voltage at Pmax	Best Lab Efficiency
Production:			
Silicon	14.8	0.5	20.8%
GaAs	18.5	0.85	21.8%
Concentrator	20.5	2.2	27.0%
Developmental:			
GaInP Dual Junction	22.0	2.1	25.7%
InP	18.0	0.75	19.9%
Thin Film Si	5.0	1.0	10.0%
Thin Film CIS	7.0	0.5	13%
Triple Junction	25.0	2.3	23.3%

Solar Cell Efficiency

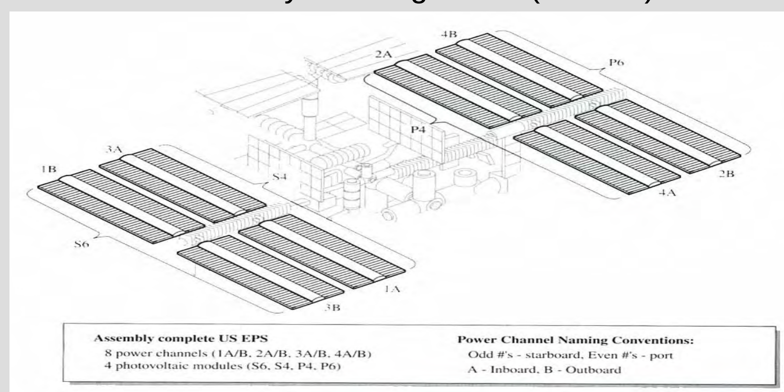
Photovoltaic Power Systems

An ISS "Solar Array Wing" (SAW) is comprised of PV blankets and containment boxes with masts:

- Each PV blanket is a collection of solar cells wired in series (2 blankets per PV array).
- Blanket boxes are attached to canisters that house and provide SAW extension/retraction masts.
- Beta Gimbal Assemblies (BGAs) and Solar Array Rotating Joints (SARJs) rotate to maximize solar array planar sun orientation.
- SARJs provide power/data paths while sun tracking, but can't provide fluid connections requiring independent thermal control.



Beta Gimbal Assemblies (BGS's) and
Solar Array Rotating Joints (SARJ's)

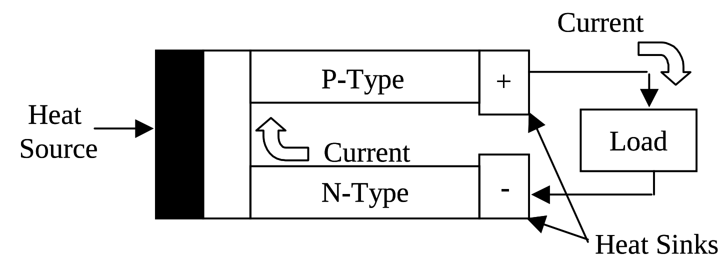


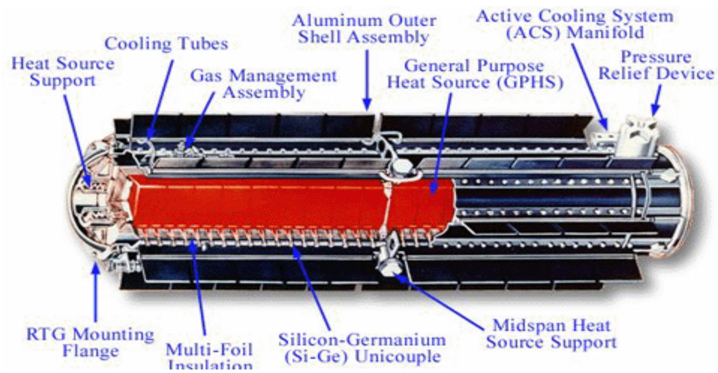
ISS PV Solar Array Wings

International Space Station (ISS)

Radioisotope Thermoelectric Generators (RTGs) can be used when spacecraft are at significant distances from the sun or where sunlight isn't available for PVs:

- Consists of a radioisotope core surrounded by silicon-germanium thermocouples for power generation.
- Natural isotope decay produces heat (no fission or fusion used).
- Voltages are produced by effects of temperature differences between hot and colder side thermocouples.
- The higher the temperature difference, the greater the power produced (limited by strength of materials).



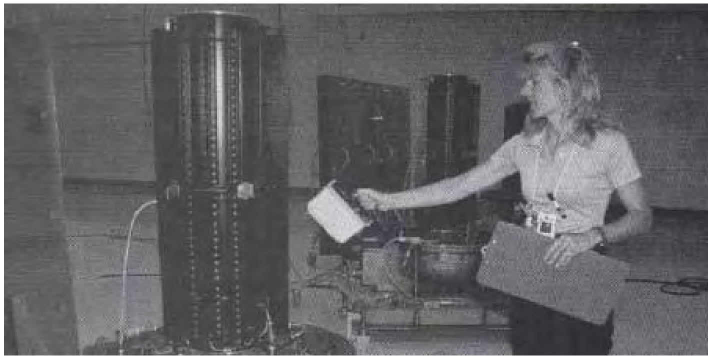


Cutaway View of Cassini RTG

Radioisotope Thermoelectric Generators

RTG's have no moving parts:

- Present state-of-art using silicon-germanium offers 9-10% efficiency (1,300 K hot side/ 500-600° K cold side).
- Performance degrades about 1-2%/year (comparable to PVs).
- Waste heat is radiated into space by heat sinks or metal fins.
- Space RTGs must contain several kilograms of a radioactive isotope (such as Plutonium 238) in an oxide pellet form.
- Radiation health hazards require US Presidential approval for launch.



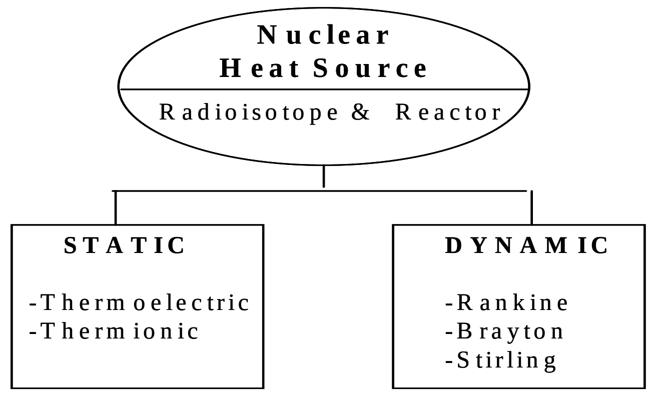
Isotope	Fuel	Decay	Power Density (W/g)	$T_{1/2}$ (yr)
Polonium 210	GdPo	α	82.00	0.38
Plutonium 238	PuO_2	α	0.41	86.4
Curium 242	Cm_2O_3	α	98.00	0.4
Curium 244	Cm_2O_3	α	2.6	18.0
Promethium 147	Pm_2O_3	α	0.28	2.6
Strontium 90	SrO	β	0.24	28.0

RTG Performance Comparisons

Radioisotope Thermoelectric Generators

Nuclear systems are essential for human exploration outside Low Earth Orbit (LEO):

- They offer long endurance/high power densities for electrical power and propulsion.
- Are useful for long voyages where sunlight is too weak for PVs.
- Power densities can be higher than RTGs are able to provide.
- Static systems convert heat from reactors to electricity by thermoelectric or thermionic solid-state devices.
- Dynamic systems covert heat to electricity through a thermodynamic cycle using turbines or generators.
- The US and former USSR have developed nuclear RTG and reactor systems for space applications.



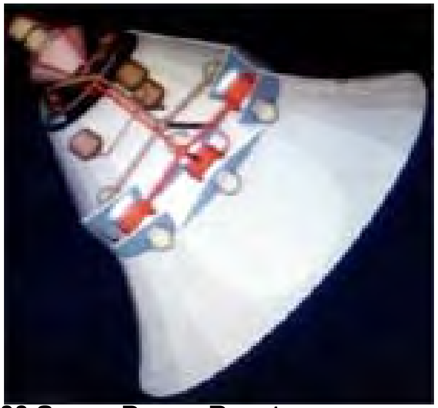
	US	USSR
RTG's	-20 in Interplanetary Space -11 in Orbit -6 on the Moon -5 on Mars -3 Failed in Orbit -1 Re-entered	-2 in Orbit -2 on the Moon -2 Failed on Orbit
Reactors	-1 in Orbit	-33 in Orbit -2 on the Moon -2 Failed on Orbit

US and USSR Nuclear Space Applications

The use of nuclear systems in space, presents special risks and controversies:

- US restrictions require placement in a 700 km minimum orbit and a 300 year orbital lifetime to avoid radiation hazards on Earth.
- The USSR hasn't applied such requirements and has taken the lead in spacecraft reactor systems.
- NASA, DoD and DoE are developing a small wastebasket-sized SP-100 system that is scalable from 0.1-1 MW (electric) with a specific mass of 50-100 kg/kW.
- Smaller (2.5-6 MWe) nuclear/dynamic isotope systems are also being developed.

Designed to be launched radioactively cold, safely shut down and stored in space for hundreds of years after use.



100 Kwe Sp-100 Space Power Reactor

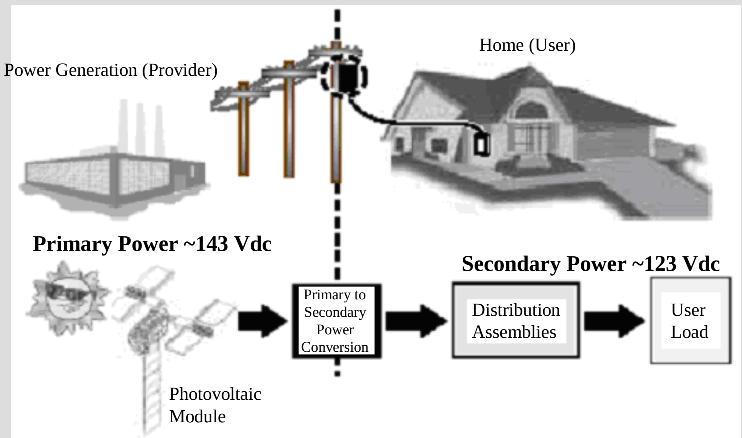
Nuclear Power System

Dynamic Isotope System

Nuclear Power Conversions

The Electrical Power System (EPS) must provide transfer and management for all necessary functions:

- The ISS EPS interfaces with other systems to provide power and to receive data from Guidance/Navigation & Control (GN&C), Command & Data Handling (C&DH) and Thermal Control Systems (TCSs).
- The EPS must ensure uninterrupted ability to generate, store, convert and distribute power, and protect users from electrical hazards.
- ISS Russian and US segments provide power sources for their own modules and for sharing with international partners.



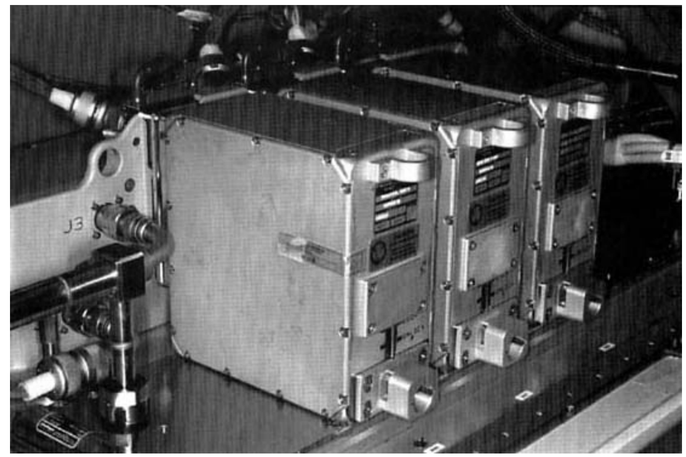
The US ISS segment distributes power to various modules in a similar manner to municipal utilities:

- High voltage primary power (~160V dc) is used for transmission over significant distances.
- Primary is converted to secondary power (~124V dc) to local uses.

Municipal/ ISS Power Analogy

ISS EPS control and distribution can be grouped into three principal functions:

- Primary power regulation/transfer is a function of the Direct Current Switching Unit (DCSU) which connects PV arrays (during solar exposure) and batteries (for charging and power during eclipses) to the ISS Main Bus.
- Secondary power regulation/transfer is also supported by the DCSU which routes electricity to DC-DC Conversion Units (DDCUs) on PV modules.
- Support subsystems include thermal control, Electrical hazard grounding, command and control, and fault detection.



The Remote Power Controller Module (RPCM) is the central element of the ISS secondary power distribution system:

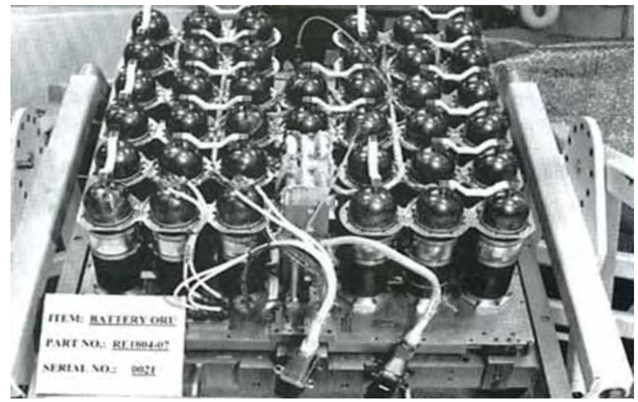
▪A multi-channel, high-power circuit breaker that regulates distribution of downstream loads.

▪Protects the EPS against faults from over currents.

Secondary Power Conversion/Distribution

ISS power storage utilizes nickel-hydrogen (Ni-Hz) battery assemblies and Battery Charge/Discharge Units (BCDUs) to control the state of discharge.

- Battery assemblies are charged by PV arrays and discharged for power during orbital eclipse periods.
- Stored power can supplement PVs to satisfy temporary high-power loads or failures.
- Batteries can supply power for one complete orbit following an eclipse period.
- Storage system is designed for a 35% depth of discharge to supply nominal power needs during orbital eclipses.
- Power discharge occurs before conversion to secondary power to minimize weight.



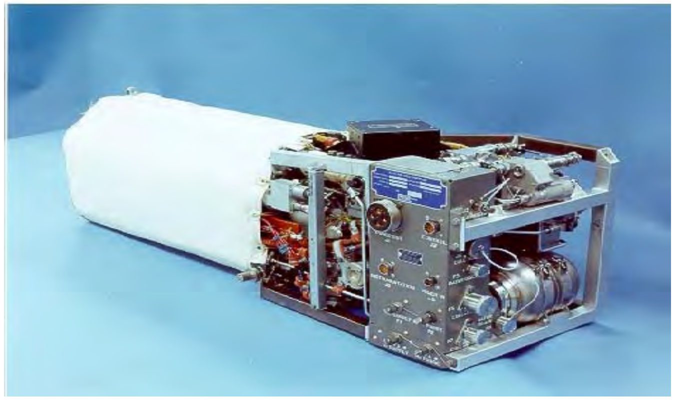
Nickel-Hydrogen Batteries Wired in Series

Type	Specific Energy (W-hr/kg)
Ni-Cd	39
$Ni\text{-}H_2$	52
Ag-Zn	60
Ni-MH	60
Li-Ion	80
$Li\text{-}TiS_2$	125
Na-S	150

Typical Battery Performance

Fuel cells can be used to store energy in the form of hydrogen and oxygen to produce electrical power when needed:

- Fuel cell power plants have a power section where chemical reaction occurs, and an accessory section that controls/monitors performance.
- Power generation cells contain an electrolyte (potassium hydroxide and water).
- Cells generate heat and water as electrical generation by-products.
- Excess heat goes to heat exchangers and is rejected by coolant loops.
- Fuel cells are reusable, but must by periodically purged of wastes.



Space Shuttle Fuel Cell

The Space Shuttle has 3 fuel cell plants (96 cells each) located under the forward position of the Orbiter's mid-fuselage:

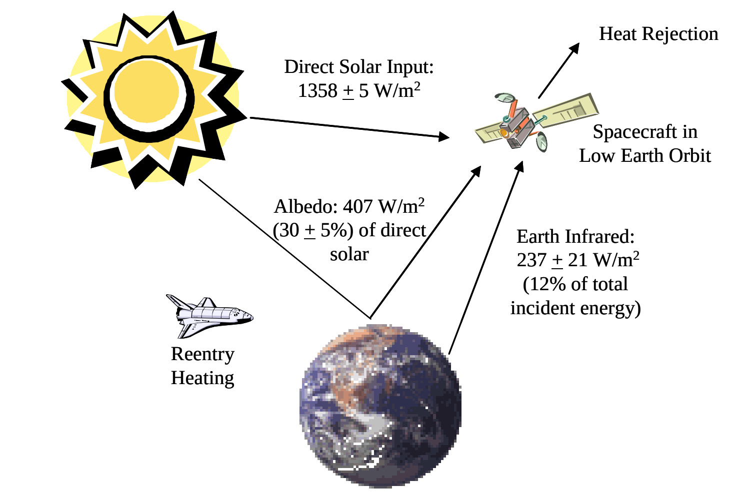
- Plants generate 28 Vdc for the vehicle through all operations.
- Cryogenic hydrogen and oxygen are stored in spherical tanks.

Fuel Cells

Primary purposes of a spacecraft Thermal Control System (TCS) are to maintain proper equipment operating temperatures and support human comfort.

Important TCS design influences include:

- The type and size of the spacecraft power system.
- Temperature range limitations for equipment/processes and crews.
- Spacecraft attitude positioning.
- Volume and mass constraints.
- Redundancy requirements.
- Atmosphere entry conditions.



Spacecrafts absorb and generate heat that must be rejected. Predominant sources in Low Earth Orbit are:

- ▪Direct Solar Input
- ▪Internal Generation
- ▪Reflected Albedo
- ▪Reentry Heating
- ▪Earth Infrared

LEO Heat Sources

Spacecraft absorb and generate heat that must be rejected:

- Radiation and conduction from the exterior environment, spacecraft operating systems and crew metabolism are primary transfer loads.
- Forced convection using fans is used to transfer thermal energy on manned spacecraft with pressurized atmospheres.
- Complex computer modeling techniques are required to determine overall conduction, radiation and convection loads.

Convection: $Q = hA\Delta T$

Conduction: $Q = -kA(\Delta T/\Delta x)$

Radiation: $Q = \sigma\varepsilon AT^4$

Where:
Q = Rate of heat flow
A = Cross sectional area
Δx = Length of the heat transfer path
ε = Emissivity
T = Temperature
h = Heat transfer coefficient
k = Thermal conductivity
σ = Stefan Boltzmann constant

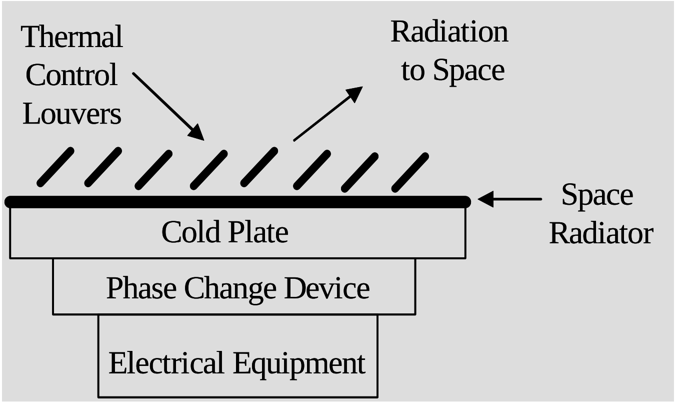
Thermal energy is transferred in three ways:

- Convection - Transfer between a flowing fluid and solid surface.
- Conduction - Transfer through matter in absence of fluid motion.
- Radiation – Transfer of energy through electromagnetic waves.

Thermal Energy Transfer Modes

Passive Thermal Control Systems (PTCSs) reflect and dissipate heat by several control methods:

- Radiator louvers- to radiate heat into space.
- Thermal coatings- includes highly reflective surface colors and materials.
- Insulation-includes multi-layer blankets to reflect infrared energy and thermal shields (ablative or high-efficiency insulators) for protection from spacecraft reentry heat.
- Heaters- include resistive electric thermostatically or remotely controlled.
- Heat pipes- using latent heat of fluid vaporization to absorb heat at one end and reject on the other.



Louvers help to minimize electrical power used for heaters to maintain specified temperatures:

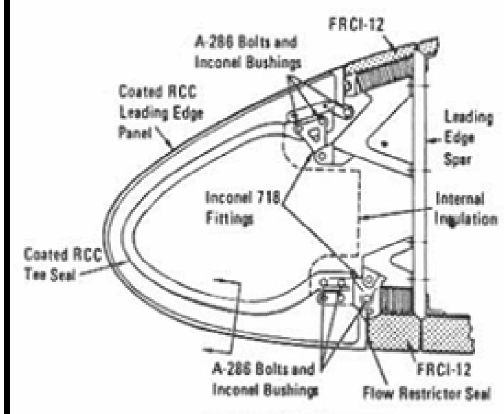
- Thermal control is accomplished by varying blade angles to change effective surface emission.
- Bi-metallic strips force louvers to open under high temperatures to radiate more heat into space.

Passive Louver Control Device

Surface coatings can have large influences upon heat emissivity and absorbtivity, accounting for nearly 80% of thermal control for unmanned vehicles:

- Emissivity is the ability of an object to emit radiant energy (all matter continuously emits electromagnetic radiation).
- Absorbtivity is the ability of an object to absorb radiant energy (the opposite of reflectivity).
- Emissivity and absorbtivity values are defined in relation to a theoretical "black body" that can absorb all radiant energy incident upon it.

Shuttle Orbiter leading edge tiles have black, high-emissivity surface coatings for entry heat rejection.



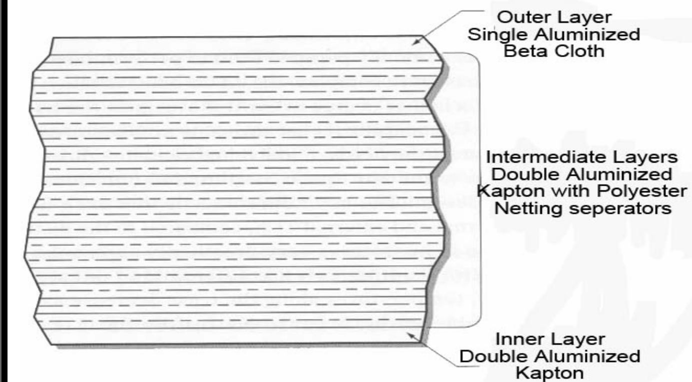
Color doesn't always indicate overall capacity to reflect radiant energy outside the visible spectrum:

- Snow is highly reflective of visible radiation, but strongly absorbs infrared.
- Black absorbs most visible light, but can reflect other wavelengths.

Thermal Coatings

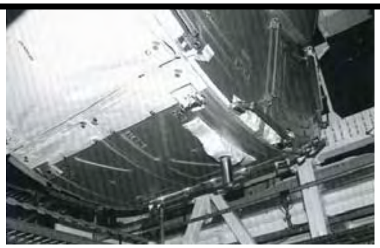
Multi-Layer Insulation (MLI) is used to control heat transfer rates and minimize temperature gradients. Some types also provide outer layers to protect spacecraft from atomic oxygen, meteorites and debris:

- MLI is used outside modules, on truss segments and on external Orbital Replacement Units (ORUs).
- Blankets also serve as a safety device to prevent EVA crew contact with extreme temperatures.
- White aluminized or gold outer layers are often used to reflect solar infrared energy.
- Under some conditions, MLI is used to help retain internal spacecraft heat.



Multi-Layer Blanket

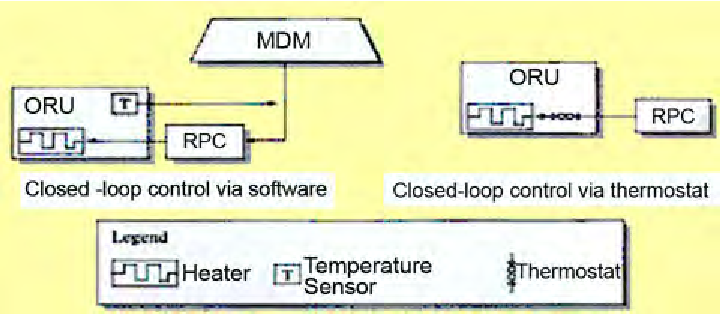
Multi-layer insulation blanket installed on an International Space Station (ISS) module



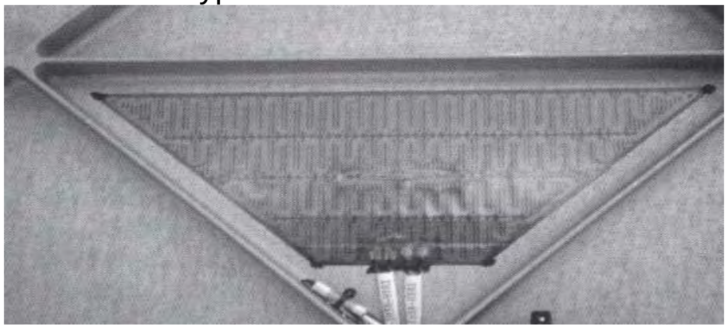
Insulation Materials

Resistive wire electrical heaters are used in external and internal locations where special high and low temperature requirements must be satisfied:

- Operational heaters are used to maintain components at or above minimum performance temperatures.
- Survival heaters prevent components from being damaged by low temperatures when not powered.
- Shell heaters prevent condensation from forming on pressurized module walls by maintaining temperatures above dew-point levels.



Typical Heater Controllers

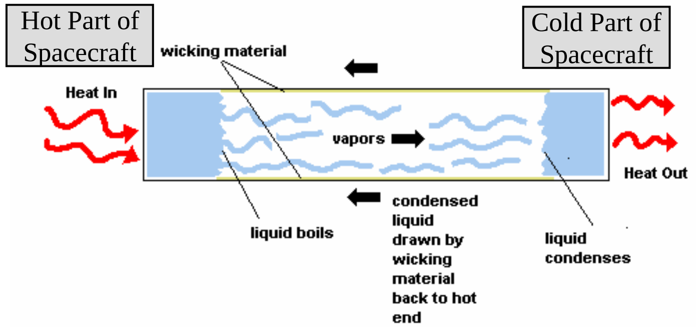


Shell Heater on ISS US Lab

Localized Electric Heaters

Heat pipes have no moving parts and provide a near isothermal method to transfer and reject heat over short distances:

- They are used on US ISS elements to provide heat rejection for certain equipment, including:
  - Direct Current-to-Direct Current Converter Units (DDCUs).
  - Remote Power Distribution Assemblies (PRDAs).
  - A Baseband Signal Processor (BSP).
- Russian element passive TCS uses heat pipes that acquire/transfer/reject internal heat to prevent interior condensation.



Basic Operation

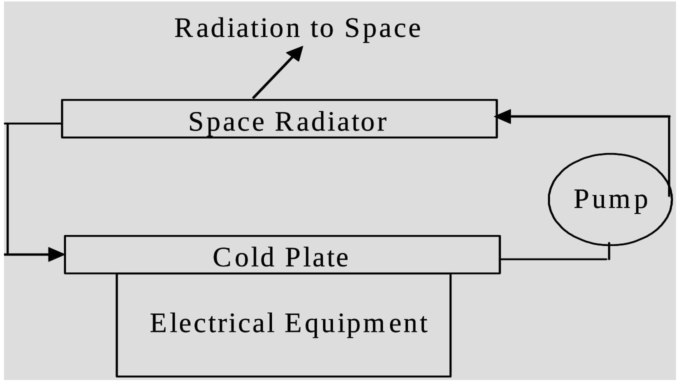
Heat pipes use a fluid (typically ammonia) to absorb heat at one end and reject it into space on the other:

- Working fluid which is evaporated at the warm end travels as vapor to the cold end.
- As heat is rejected, the fluid gives up its latent heat.

Heat Pipes

Active Thermal Control Systems (ATCSs) use cold plates, heat exchangers, fluid pumps and lines, and radiators to maintain internal and external temperatures at desired levels:

- Internal Thermal Control Systems (ITCSs) are provided on all pressurized ISS modules and include low and moderate temperature loops.
- External Thermal Control Systems (ETCSs) are designed to handle heat loads for the entire ISS US segment.



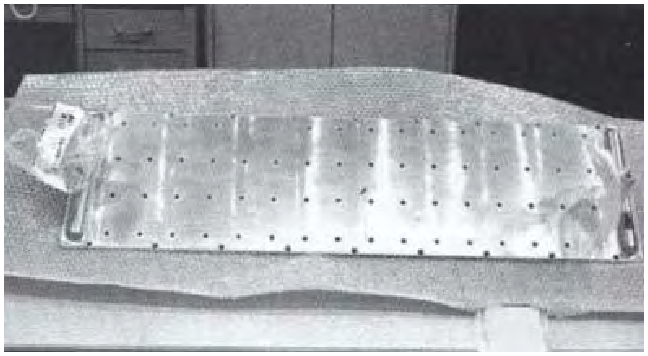
An Active Thermal Control System is required when overall or local heat loads exceed passive capabilities :

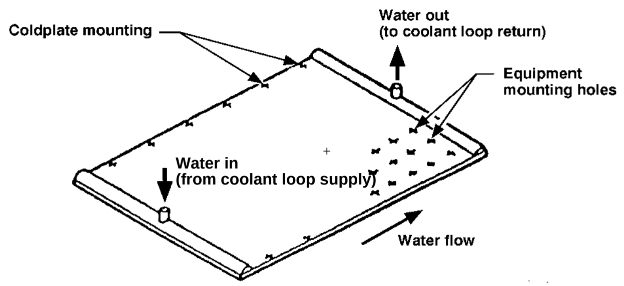
- Uses mechanically pumped fluids (water or ammonia) in closed-loop circuits.
- Can provide heat collection, transport and rejection into space.

Simplified Active Thermal Control System

Internal Thermal Control System (ITCS) waste collection devices principally involve coldplates and heat exchanges located in ISS module racks and endcones:

- Coldplates acquire heat from heat-generating equipment that is transferred by conduction to their surfaces where it is transported by convection by internally flowing water.
- Heat exchangers are similar in function to coldplates but provide fluid-to-fluid heat transfer between alternating layers of finned passages.





Coldplate Examples

ITCS Heat Collection Devices

ISS heat transportation components include pumps, fluid lines, Quick Disconnects (QDs) and valves:

- They transfer the flow of water around loops to transport heat to the ETCS for rejection.
- Some ISS elements provide two separate thermal loops:
  - -Low Temperature loops (40°F)
  - -Moderate temperature loops (63°F)
- ITCS loops can operate independently or can be cross-connected for redundancy to prevent failure loss of critical system cooling.

ISS ITCS Fluid Pump

ISS Interface Heat Exchanger

ITCS Heat Transportation Devices

NASA

External Thermal Control Systems (ETCSs) on the ISS collect, transport and reject heat using ammonia coolant loops:

- The US segment ETCS uses a distributed single-phase loop architecture that serves all US elements.
- The Russian ETCS uses a localized architecture that regulates coolant flow rates through module valves to control temperatures at a set point of 59-95°F.
- Warm ammonia from path loops flow through radiators where it is cooled by radiation into space.

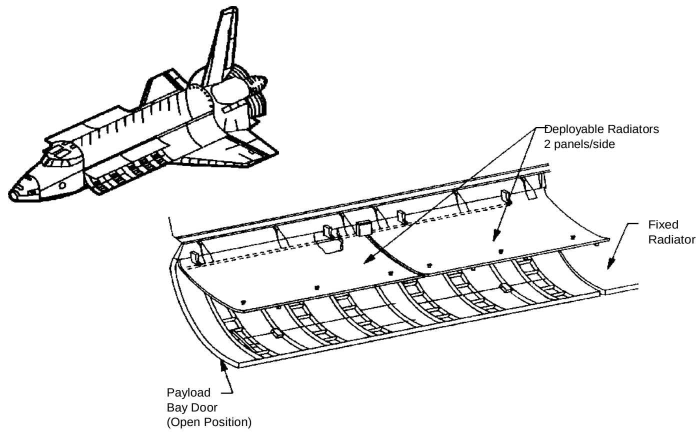
ISS heat rejection is accomplished by two radiators containing 7 aluminum panels with stainless steel flow tubes:

- Panels are hinged together with manifolds and flexible hoses to connect ammonia fluid paths.
- Radiators can be deployed by command or by EVA.

ISS External Thermal Control Systems

The Space Shuttle Orbiter ACTS removes heat from the atmosphere revitalization Freon-21 coolant loop and the fuel cell heat exchangers:

- Heat loads exceeding radiator capacities are rejected by a flash evaporator at reentry altitudes down to 100,000 ft where water can't provide adequate Freon-21 coolant temperatures.
- Boilers use boiling ammonia to cool Freon-21 loops below 100,000 ft during reentry.
- A Water Coolant Loop (WCL) provides cabin air-to-water heat exchange for Crew comfort.



Space Shuttle Orbiter radiators are attached to payload bay doors:

- Deployable radiators are attached to forward doors on each side which can be operated together or separately.
- Aft radiator panels are fixed and operate only from the upper surface.

Orbiter External Thermal Control Systems

Artificial life support systems can be defined as a set of man-made and/or mechanically supported biological mechanisms that work in concert to provide life-sustaining environments in harsh and difficult settings:

- Submarine life support systems generate water and oxygen; remove carbon dioxide and other toxic gases; maintain internal pressure, temperature and humidity; and discharge wastes.
- Spacecraft systems are less capable of replenishing food, oxygen, water and atmospheric gases due to greater isolation and resupply difficulties.

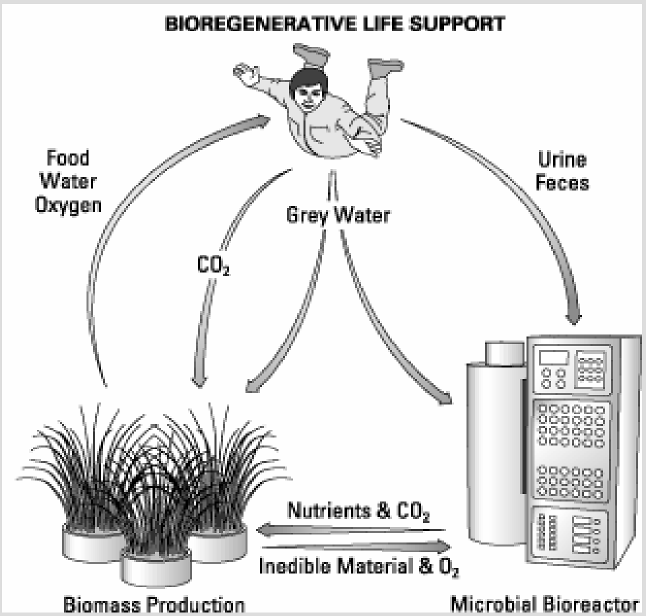
Spacecraft and EVA Suits

Nuclear Submarines

Artificial Life Support Applications

Four basic space life support requirements are atmosphere, water, food and waste management:

- Traditionally these requirements have been addressed by non-regenerable physio-chemical systems.
- As the requirements are increasingly fulfilled by regenerative processes, the system becomes more “closed”.
- Regenerative processes can be physio-chemical, biological or a hybrid.
- If biological processes are involved, it becomes a Controlled Ecological Life Support System (CELSS).

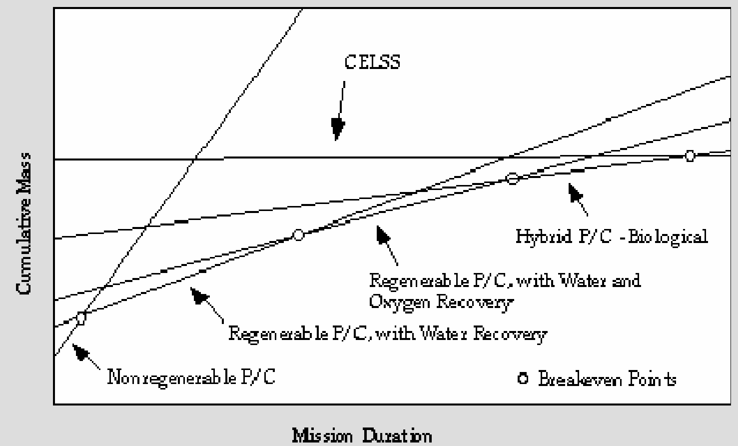


This illustration is closed with respect to mass, but is still open in regard to energy output.

Partially Closed Life Support

Long-duration missions will require biogenerative capabilities that provide life support functions by bioreactors:

- Nutrients can be recovered from crop or food residues for hydroponics.
- Microorganisms can convert plant biomass, human wastes and other materials into food, carbon dioxide, water, and useful inorganic materials.
- Anaerobic digesters can transform fatty acids into edible yeasts, soluble organics into carbon dioxide, and oxidized ammonium into nitrate fertilizer.



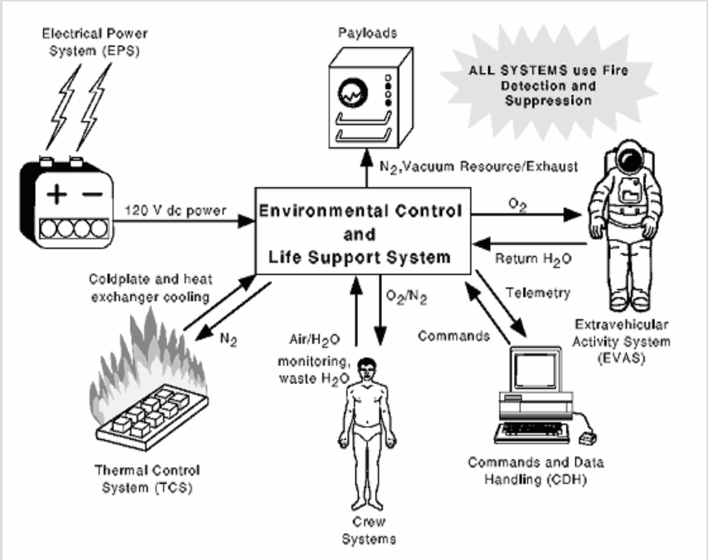
"Breakeven" points that correlate mass-loop economies with mission duration are compared for 5 available technologies:

- The approaches range from an open mass loop to closed water, oxygen food loops.
- At intersection points, comparative mass conservation benefits are lost.

Mission Duration Influences on CELSS

The Environmental Control and Life Support System (ECLSS) incorporates 5 major subsystems:

- Atmosphere Control and Supply (ACS) that produces oxygen and nitrogen at correct pressures and compositions.
- Atmosphere Revitalization (AR) which ensures that air is safe to breathe.
- Temperature and Humidity Control (THC) to circulate air, remove moisture and particulates and maintain proper temperature.
- Fire Detection and Suppression (FDS) includes smoke sensors, fire extinguishers, portable breathing equipment and alarms.
- Water Recovery and Management (WRM) that collects, stores and distributes water.

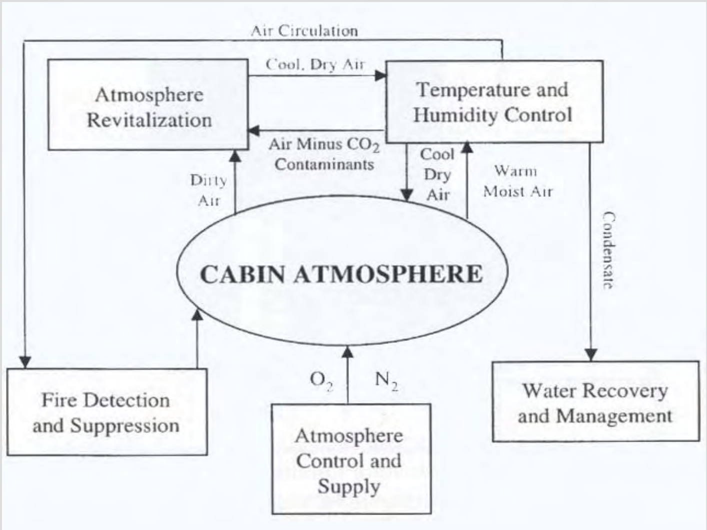


The ECLSS and its subsystems must support and interface with several other spacecraft functions to ensure that all human and equipment operations are optimized.

Relationships with Other Functions

The Atmosphere Control and Supply (ACS) subsystem must provide oxygen at proper pressure, temperature and humidity with safe levels of carbon dioxide and trace contaminants:

- Oxygen pressures at or below 13.75 kP produce altitude sickness effects, including shortness of breath, headaches, insomnia, impaired concentration and nausea.
- Excessive carbon dioxide levels can cause increased respiration rates, heart rates and brain blood flow; hearing losses; depression; headaches; dizziness and nausea; and unconsciousness.

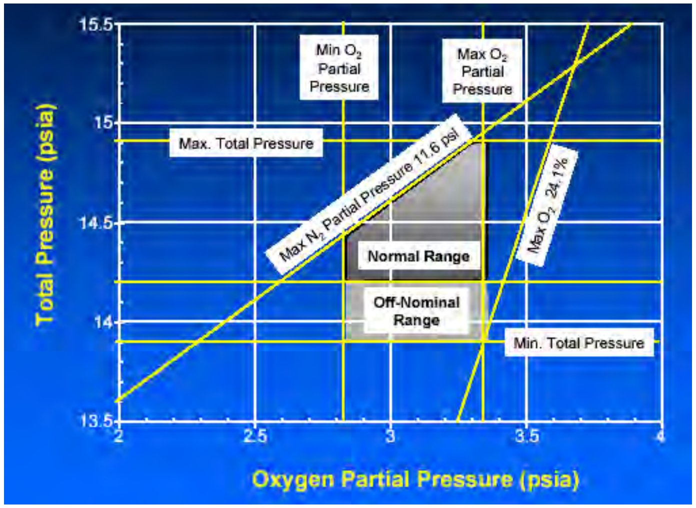


Oxygen, nitrogen and carbon dioxide (the product of breathing) are the 3 predominant atmospheric gases. Nitrogen must be added to reduce fire hazards, but since it isn't consumed, only small amounts must be replenished to compensate for leakages

Atmosphere Gas Subsystems

Humans rapidly perish without oxygen, and even sooner when exposed to high levels of carbon dioxide:

- Green plants can be used to remove carbon dioxide from human respiration, and also produce oxygen and food.
- Carbon dioxide can be collected and converted into water and methane with hydrogen:
  - The water produced can be electrolyzed into separate hydrogen and oxygen components;
  - The hydrogen can then be combined with respirated carbon dioxide to repeat the cycle.



Oxygen Partial Pressure Limits/Operational Ranges

Gas	Partial pressure
Oxygen	Lower limit 2.35 psi (hypoxia)
Oxygen	Upper limit 15.00 psi (hyperoxia, fire hazard)
Nitrogen	Upper limit 50.00 psi (nitrogen narcosis)
Carbon dioxide	Upper limit 0.44 psi (toxic)

Oxygen, Nitrogen and Carbon Dioxide Limits

Carbon dioxide removal processes include:

- Bioregeration: photosynthesis by plant chlorophyll converts carbon dioxide and water into a simple sugar (glucose), water and oxygen.
- Lithium hydroxide absorption: uses replaceable canisters or filters which become saturated to remove carbon dioxide.
- Molecular sieves: apply crystalline materials (zeolites) composed of silicon or aluminum to absorb and separate carbon dioxide.
- Sabatier process: uses combustion with hydrogen to convert carbon dioxide to methane and oxygen.

O_2 GENERATION

- *Static Feed Water Electrolysis*
- Solid Polymer Electrolysis
- CO_2 Electrolysis
- Water Vapor Electrolysis
- Bioregeneration

Italics = International Space Station

CO_2 REDUCTION

- *Sabatier Reactor*
- Bosch Reactor
- Advanced Carbon Reactor
- CO_2 Electrolysis
- Bioregeneration

CO_2 REMOVAL

- *Four Bed Molecular Sieve*
- Solid Amine Water Desorbed
- Electrochemical Depolarized Concentrator
- Two-Bed Molecular Sieve
- Lithium Hydroxide (LiOH)
- Bioregeneration

Water + Carbon Dioxide ⇨ Glucose + Water + Oxygen

Simplified Photosynthesis Equation

$$12H_2O + 6CO_2 \Rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

Photosynthesis Equation

$$CO_2 \Rightarrow CO(g) + O_2$$

Decomposition of CO_2

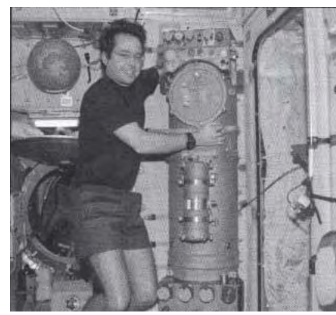
$$2H_2O \Rightarrow O_2 + 2H_2$$

Electrolysis of Water

Oxygen Generation and Carbon Dioxide Removal

Oxygen and nitrogen gases for the US ISS elements are supplied by the Atmosphere Control and Supply (ACS) subsystem:

- 4 high-pressure gas tanks (2 oxygen and 2 nitrogen) are stored on the EVA airlock exterior.
- Gases are distributed to different users by tubing throughout all US elements.
- Another high-pressure plumbing system allows tanks to be recharged by the Shuttle (tanks can also be replaced).
- Oxygen compressors in the airlock enable tanks to be fully recharged (the Orbiter doesn't store oxygen at high enough pressure).



Elektron Oxygen Generator

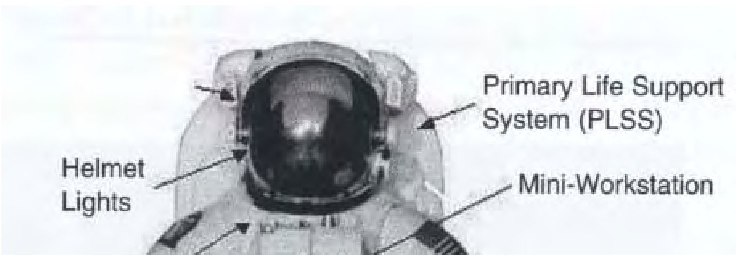
Solid Fuel Oxygen Generator

US Airlock High-Pressure Tanks

ISS Atmosphere Supply

Lithium hydroxide canisters are currently used to remove carbon dioxide in the EVA Mobility Suit Primary Life Support System (PLSS) and were used on the Space Shuttle Orbiter:

- Chemical absorption occurs in a 2-stage process:
  - Lithium hydroxide is first produced through an exothermic reaction;
  - Lithium carbonate is then formed in an endothermic reaction.
- The lithium hydroxide process has been replaced on the Shuttle by a vaccum-regenerable solid armine-based system which binds carbon dioxide to a resin and is vented to space.



EVA Mobility Suit and Primary Life Support System

Shuttle Lithium Hydroxide Canister Replacement

Lithium Hydroxide CO_2 Removal

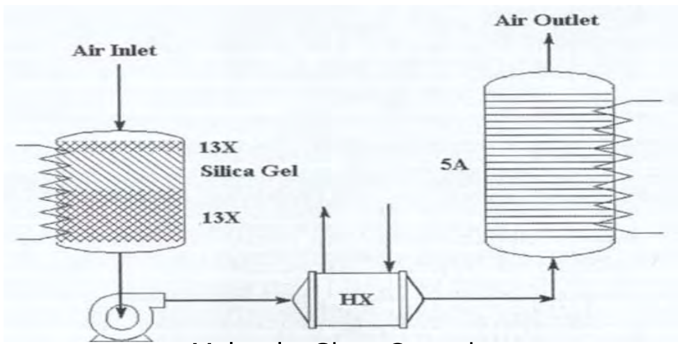
The ISS Air Revitalization System (ARS) uses a 4-Bed Molecular Sieve (4BMS) to remove carbon dioxide from the atmosphere:

- The central component is the Carbon Dioxide Removal Assembly (CDRA):

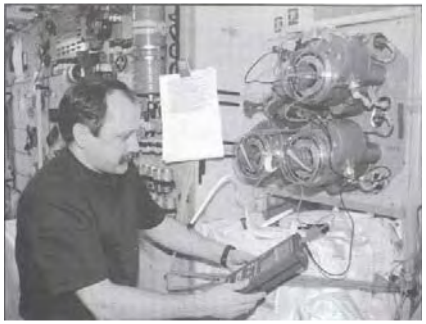
  -It requires cold, dry air received from the Temperature and Humidity Control subsystem which interfaces with the Internal Thermal Control System (ITCS) low temperature loop;

  -A silica gel absorbs, selectively removes and concentrates carbon dioxide for further processing or venting to space.

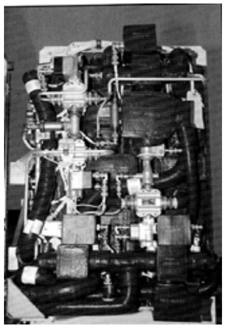
- The Russian Vozdukh system uses the same process.



Molecular Sieve Operation



Russian Vozdukh System

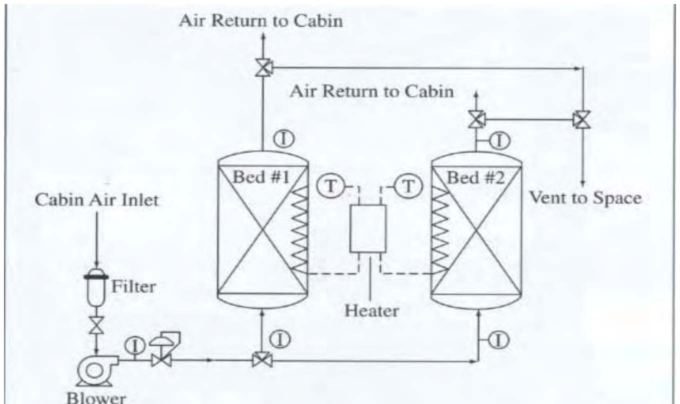


US CDRA

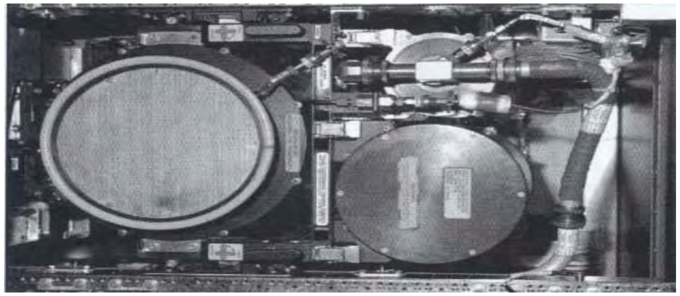
Molecular Sieve Carbon Dioxide Removal

In addition to carbon dioxide, a variety of other hazardous trace contaminants must be removed from the cabin atmosphere to protect crew health:

- The Russian Mir Space Station used thermally-regenerable activated carbon beds to remove airborne organic contaminants.
- The ISS US segment Trace Contaminant Control System (TCCS) uses activated carbon impregnated with phosphoric acids to facilitate ammonia gas removal.
- A TCCS sub-assembly filters and catalyzes numerous gaseous contaminants and odors caused by material off-gassing, leaks, spills and other events.
- Micropurification Unit filters provide backup contaminant control.



Thermally Regenerable Trace Contaminate Control



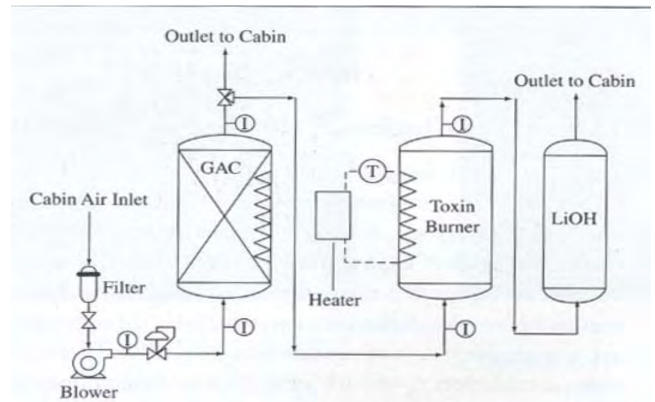
US Trace Contaminant Control System

Trace Contaminant Control

A portion of the TCCS effluent is routed through a catalytic toxic burner to remove any contaminants that may bleed off the activated carbon bed or break through early:

- A gas-phase catalytic oxidation reactor operating at 450°C uses a 0.5 percent palladium on alumina catalyst to oxidize methane, the highest-concentration organic contaminant.

- Acid gases resulting from decomposition of halogen, nitrogen and sulfur-containing organics are removed by sorption using an expendable lithium hydroxide bed.



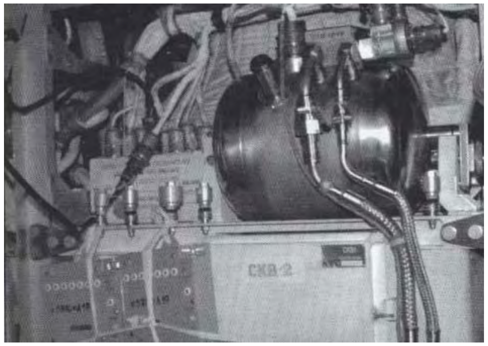
Atmosphere Revitalization	Monitor Atmospheric Partial Pressures and Remove Gaseous Contaminants
Gas Analyzer	Monitor O_2, CO_2, H_2O
Gas Analyzer	Monitor O_2, CO_2, H_2O, H_2
Carbon Monixide Analyzer	Monitor CO
Major Constituent Analyer	Monitor O_2, N_2, CO_2, H_2, CH_4
Vozdukh	Remove CO_2 from air
Carbon Dioxide Removal Assembly	Remove CO_2 from air
Lithium Hydroxide based canisters	Remove CO_2 from air
Sabateir	Reduce CO_2 and make H_2O
Trace Contaminant Control Unit	Remove trace contaminants from air
Harmful Impurities Filter	Remove trace contaminants from air
Trace Contaminant Control Subassembly	Remove trace contaminants from air

ISS Atmosphere Revitalization Summary

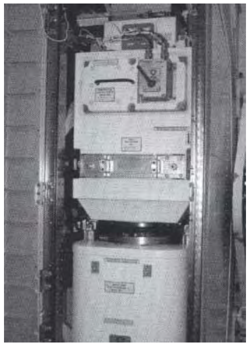
Trace Contaminant Control

Ventilation, temperature and humidity control subsystems help maintain a safe and comfortable environment:

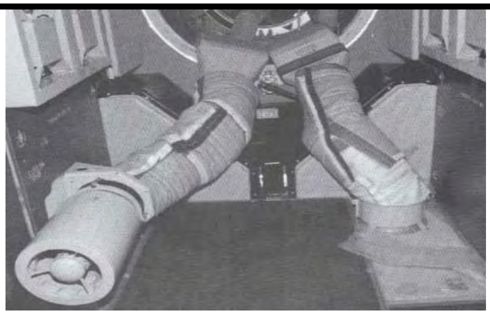
- Forced circulation of conditioned air minimizes temperature variations, ensures homogenous atmospheric composition, and provides means for smoke detection.
- Intramodule ventilation provides circulation and supports cooling and humidity removal within a single module.
- Rack ventilation cools and circulates air within individual racks.
- Intermodal ventilation ensures a homogeneous station atmosphere.



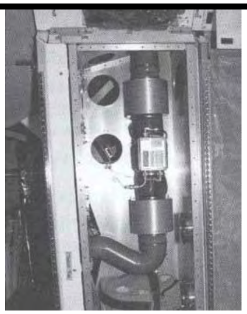
Russian AC Unit



Cabin Air Ass.



Drag-Through Ducting



Intermodule Fan

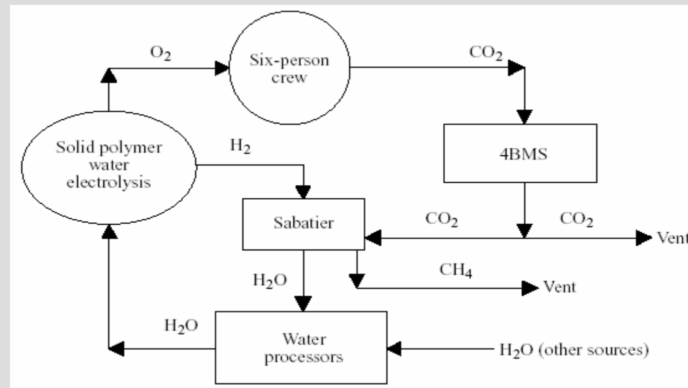
Ventilation, Temperature and Humidity Control

A planned upgrade to the ISS life support architecture is a Sabatier Reactor:

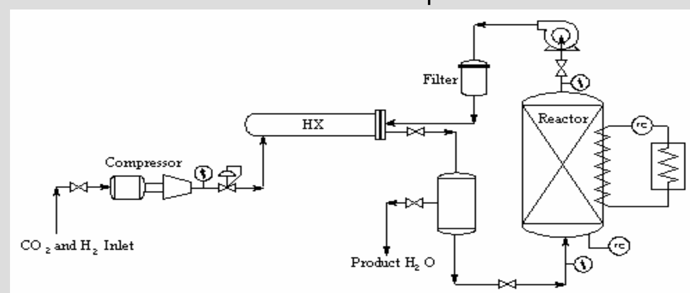
- Carbon dioxide recovered from the atmosphere is reduced by combustion with hydrogen to produce methane and oxygen.
- The methane is vented into space, resulting in half of the hydrogen being lost.
- Half of the hydrogen remaining is combined with oxygen to create water.

A Bosch reaction process is similar but produces only water and carbon:

- All of the hydrogen used can be recovered by electrolysis.



Sabatier Water Production/Atmosphere Control for ISS

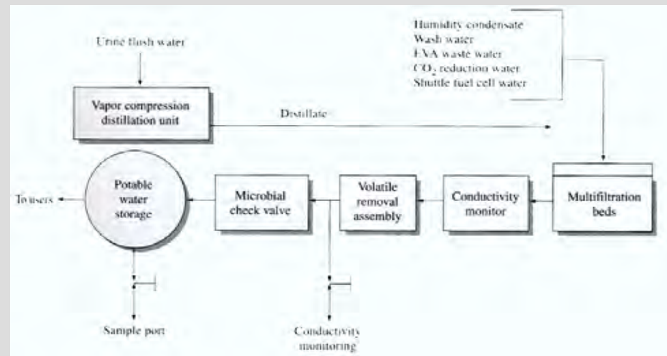


Bosch Reactor Water Production Process

Advanced Water Production Systems

The ISS Water Recovery and Management (WRM) system collects, stores and distributes the station's water resources:

- Water collected includes condensate from the Temperature and Humidity Control subsystem and return water from EVAs.
- The Russian segment is responsible for WRM functions during station assembly stages (collecting condensate from heat exchangers and receiving water from the US segment).
- A Total Organic Carbon Analyzer (TOCA) is used to monitor water quality.
- Water is re-purified to remove minerals if used to produce oxygen in the Elektron.



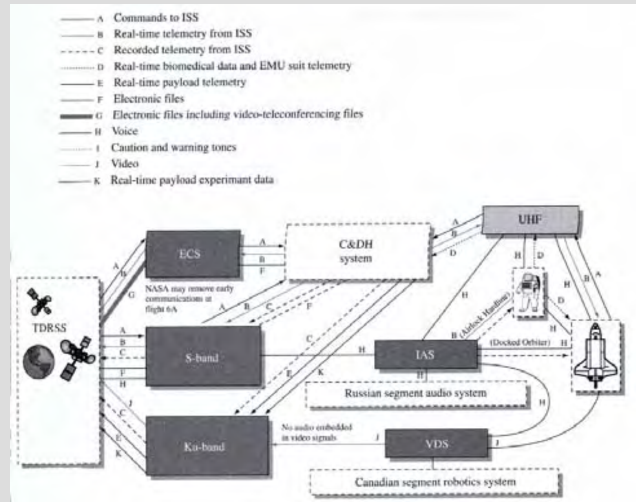
ISS Water Recovery / Management System

Total organic Carbon Analyzer

Condensate Tank

Water Recovery and Management

Communication & Tracking (C&T) systems have close interactions with Command & Data Handling (C&DH) systems that are essential to maintain most space mission functions. For purposes of this overview, an emphasis on communications is combined with C&DH since a discussion of tracking systems falls outside the primary scope of this presentation segment.

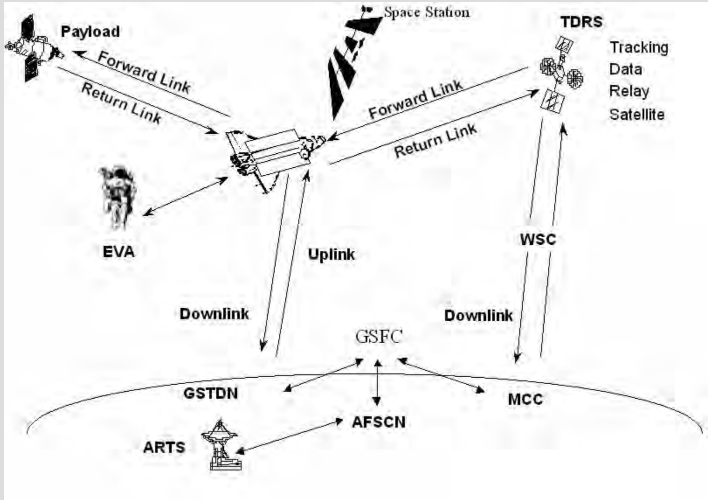


Command and Control subsystems depend upon communication services that support onboard, orbital and ground-linked mission operations.

Communications/C&T System Overview

The spacecraft communications system transfers telemetry information about vehicle operating conditions as well as commands to various systems, including:

- Two-way audio and video communications among crew members (including EVA).
- Two-way audio, video and file transfer communications with flight control teams in the Mission Control Center-Houston (MCC-H) and payloads scientists on the ground.
- One-way communication of experiment data to the Payload Operations Integration Center (POIC).
- Control of the ISS by flight controllers through MCC-H, POIC and the Shuttle Orbiter.



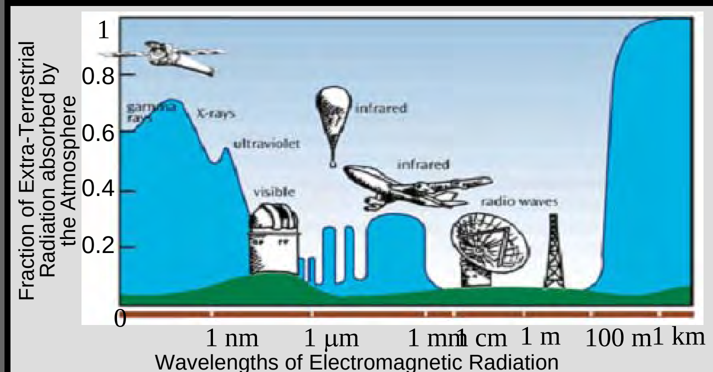
Ground communication is essential to maintain safe and reliable spacecraft operation as well as mission activity support and monitoring.Information is transferred with direct RF links to the surface through the Tracking & Data Relay Satellite System (TDRSS) and between separate orbital stations/elements.

Integrated ISS / Shuttle Network

Electromagnetic radiation with frequencies between 10 kHz and 100 GHz are referred to as “radio frequencies” (RF):

- Frequencies are divided into groups within certain wavelength ranges called “bands”.
- Bands are divided into small frequency ranges called “channels”.
- Many deep-space vehicles use channels in the S-band and X-band range (2-10 GHz) which are among these called “microwaves”.
- Deep-space systems are being developed for even higher frequency K-band.
- Earth’s atmosphere (pollution, dust rain and snow) can absorb and scatter RF to interfere with reception.

Band	Approx. Range of Wavelengths (cm	Approximate Frequencies
UHF	100 – 10	300 - 3000 MHz
L	30 – 15	1 - 2 GHz
S	15 - 7.5	2 - 4 GHz
C	7.5 - 3.75	4 - 8 GHz
X	3.75 - 2.4	8 - 12 GHz
K	2.4 - 0.75	12 - 40 GHz
Q	0.75 - 0.6	40 - 50 GHz
V	0.6 - 0.4	50 - 80 GHz
W	0.4 - 0.3	80 - 90 GHz

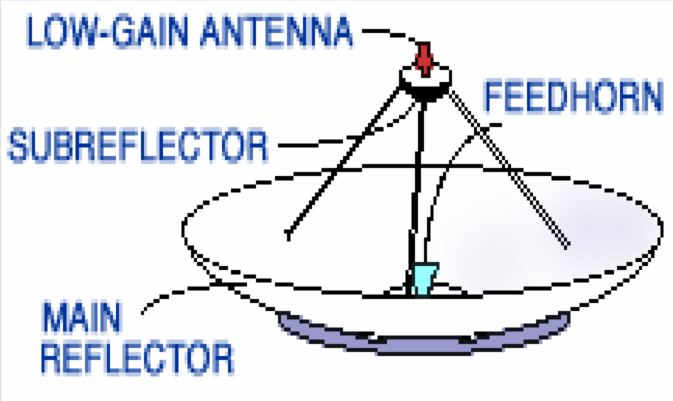


Atmosphere Window for Electromagnetic Radiation

Radio Frequencies and Interference

Telecommunications subsystem components are selected to satisfy planned distances, frequency bands, data rates, on- board power availability and other particular mission and spacecraft characteristics:

- Dish-shaped High-Gain Antennas (HGAs) are mounted on the spacecraft for communications with Earth, and can be of moveable or fixed types.
- Low-Gain Antennas (LGAs) can offer nearly omni-directional coverage (except for areas shadowed by the spacecraft body) for relatively close range, low data rate applications.
- Spacecraft transmitters are lightweight devices that operate at a single frequency (typically S, K and Ka-bands).



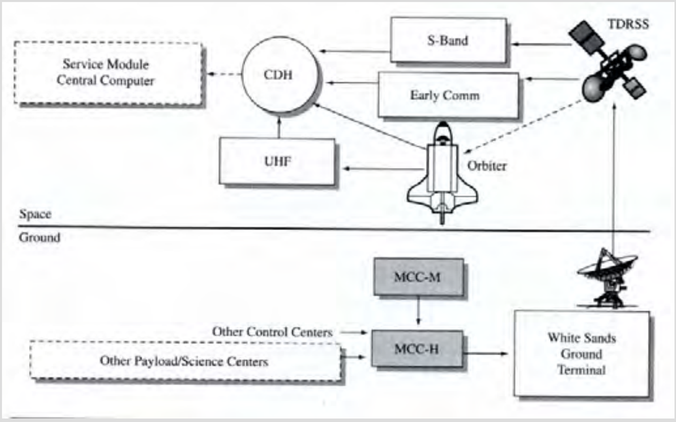
Low Gain Antenna Mounted Atop a High Gain Antenna

LGA's can sometimes be conveniently attached to the sub reflectors of HGA's.(Voyager,Magellan,Cassini and Galileo)

Antennas and Transmitters

ISS operations and control commands are sent through an MCC-H communication link, including commands to all international segments:

- Commands can also reach ISS through docked Orbiter and Russian Communication subsystems routed through MCC-H using S-band and UHF subsystems.
- Operational system and critical payload telemetry from ISS to MCC-H use the same paths in the reverse direction (but do no use UHF).
- Communication availability or coverage is about 50% due to signal blockage by the station itself (compared with about 90% for the Orbiter using two TDRSs).

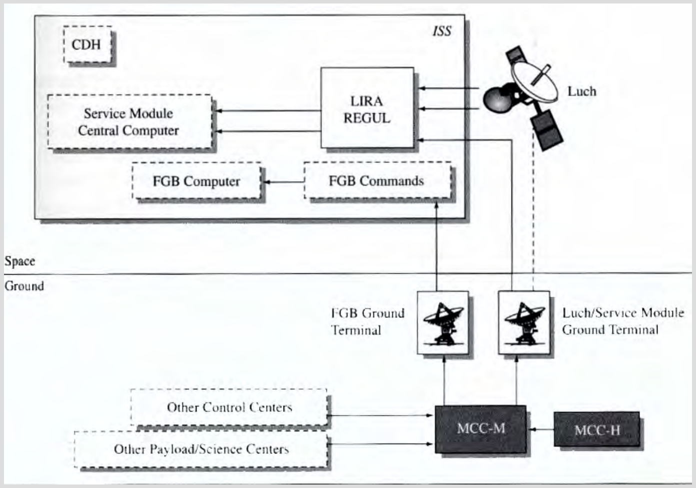


ISS operations and control are vital functions supported by the Communication & Tracking (C&T) system. The Russian segments, along with the European Space Agency (ESA) and the National Space and Development Agency of Japan (NASDA) payload centers, channel their communications through MCC-H.

ISS Command Paths

The Russian command path to Russian ISS segments and between US and Russian segments pass through a C&DH Command & Control Multiplexer/ Demultipexer (C&CMDM):

- Russian subsystems can communicate directly from ground stations through their Regul subsystem, or receive commands from their LUCH satellite through the Lira or Regul system.
- Command functions can be initiated from the Mission Control Center-Moscow (MCC-M) or MCC-H, as well as through other control and payload centers as appropriate.

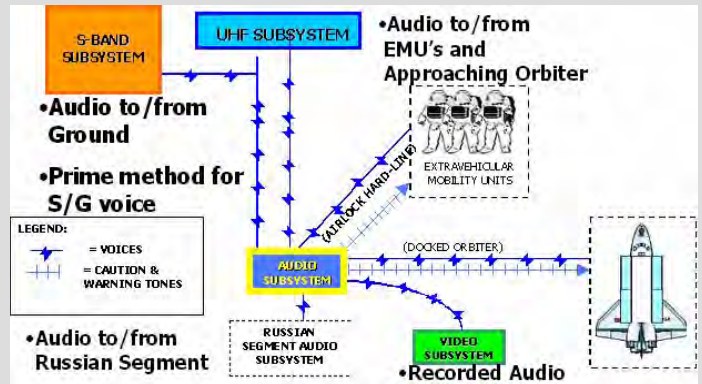


Telemetry from the Russian segments follows the same paths as commands, but in the opposite direction. Russian communication coverage is nearly continuous using Russian ground stations, but is available only for about 45 minutes per orbit.

Russian Segment Command Path

The Internal Audio Subsystem (IAS) distributes voice and Caution-and-Warning (C&W) tones onboard the ISS:

- Signals are passed to S-band, UHF and VDS subsystems for further internal and external distribution to the Orbiter, ground and EVA crews.
- At the ISS "Assembly Complete" stage, the IAS will be the primary means to distribute audio between all modules.
- The Audio Terminal Unit (ATU) serves as the crew's telephone for individual conversations and conferences.
- A Russian Telephone and Telegraph Communication (TTC) subsystem offers hard-wire audio capabilities.

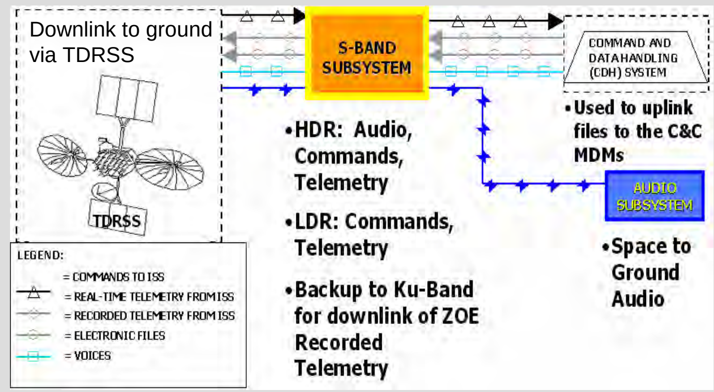


Audio Terminal Unit

Internal Audio Subsystem

The ISS S-band subsystem consists of three main components:

- The Baseband Signal Processor (BSP) receives two channels of digital audio data from the IAS which is compressed, segmented and encoded in High Data Rate (HDR).
- A transponder creates and modulates a radio signal and sends it to the Radio Frequency Group (RFG), or conversely, receives a RFG signal, demodulates it, and transforms it to digital.
- The Radio Frequency Group receives a RF signal from the transponder, amplifies it, and broadcasts it through a high-or low-gain antenna to the TDRSS.



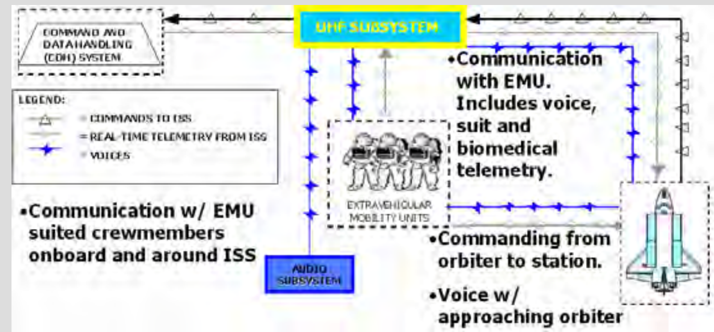
The S-Band subsystem transmits and receives at a HDR of 192kbps return link and 6kbps forward link .

Flight controllers at MCC-H perform primary operating roles and the crew acts as a backup under certain Loss-Of-Signal (LOS) conditions.

S-Band Subsystem

The Ultrahigh Frequency (UHF) subsystem is one of the Space-to-Space Communication Systems (SSCSs), and includes external and internal antennas:

- The UHF external antennas (2 pairs mounted on the US Lab Module and truss) can receive signals up to 7 kilometers away and provide nearly continuous EVA communication.
- The UHF internal antennas located throughout US pressurized modules enable EVA crews to communicate in an airlock (using the airlock antenna) and within unpressurized modules for repair operations.

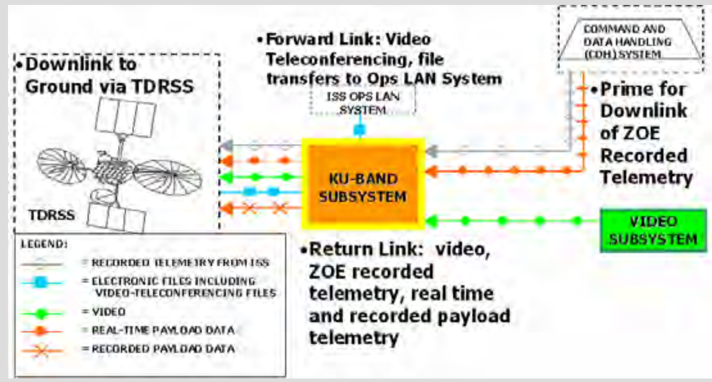


The UHF subsystem provides space-to-space communications between the ISS and the Orbiter for voice,commands and telemetry ; EVA crewmembers for voice,biomedical and EVA Mobility Unit (EMU) data ; and to accommodate future Free Flyer (FF) payloads for commands and telemetry.

Ultrahigh Frequency Subsystem

Major components of the Ku-band subsystems are the Video Baseband Signal Processor (VBSP), High-Rate Frame Multiplexer (HRFM), High-Rate Modem (HRM), and the Antenna Group:

- The VBSP converts a video signal from a fiber-optic to digital format and sends it to the HRFM.
- The HRFM multiplexes and encodes 12 inputs into a one bit stream and sends the signal to the HRM.
- The HRM modulates the signal and converts it to an intermediate frequency to be broadcast to a TDRSS by a Ku-band directional gimbaled antenna.



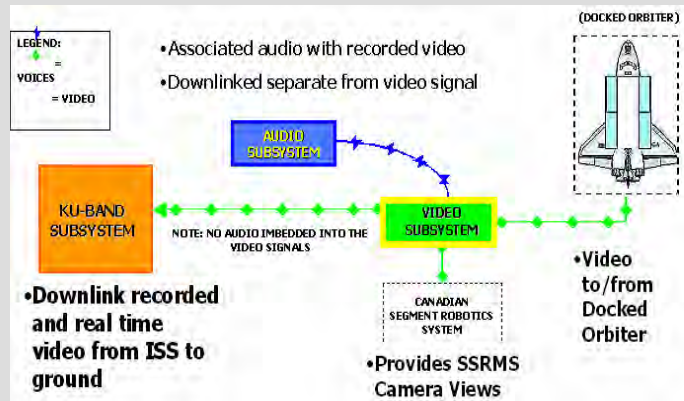
The Ku-band subsystem has a downlink data rate of 150Mbps and a Communications Outage Recorder(COR) for recording payload data.It also offers 2-way transfer of video signals and an interface with internal audio and video distribution subsystems.

Ku-Band Subsystem

The US Video Distribution Subsystem (VDS) interfaces with International Partner (IP) video subsystems and includes external and internal cameras and recording devices:

- The US segment provides 14 outside ports for the External Television Cameras Group (ETVCG) which contains an externally mounted camera, a light source, means for panning/tilting, and video-to-fiber-optic signal conversion.

- Robotic Workstations (RWSs) located in the Lab Module and Cupola are connected via a Power Data Grapple Fixture (PDGF) with means to receive signals from cameras on the Space Station Robotics Manipulator System (SSRMS) elbow and wrist to support operations.



The US segment Video Distribution Subsystems(VDS) provides handheld camera, rack cameras and external cameras along with associated recording devices to monitor and support IVA and EVA activities including ISS robotic arm operations.

Video Distribution Subsystem

The Command & Data Handling(C&DH) system is sometimes referred to as "spacecraft central", a computer or computer group responsible for overall activity management. The system has two primary functions:

1) It receives, checks, interprets and distributes commands to all spacecraft and telemetry for down-linking and onboard use.

2) It collects, processes and formats acquired mission data related to the vehicle's status and operational readiness.

Shuttle Malfunction Electronic Display System

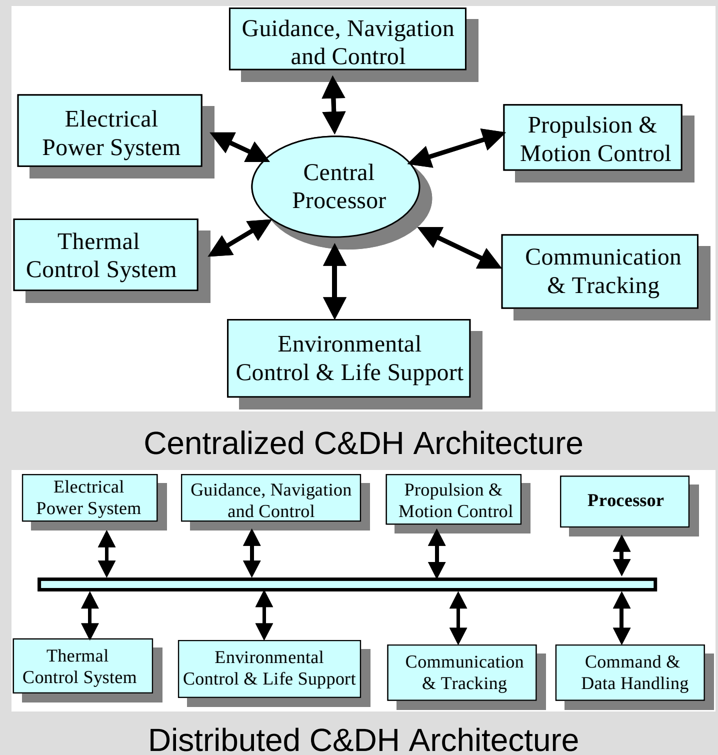
Advancements in computer technology are responsible for major improvements in C&DH subsystem capabilities and reliability.System redundancy requires an ability to complete a mission after a single failure and provide safe return after two failures.

Subsystem Functions and Requirements

Two alternative architecture philosophies can guide the C&DH system design:

- A centralized architecture provides discrete point-to-point connections between a central processor and the various spacecraft subsystems. (This is relatively simple and most appropriate with a limited number of subsystems.)

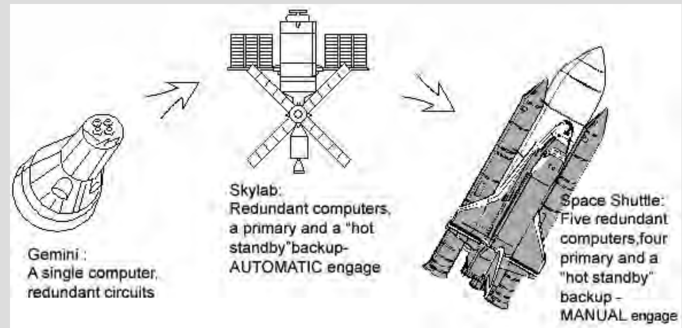
- A distributed architecture utilizes a common data bus for all spacecraft systems as well as a standard protocol and communication scheme. (Adding equipment is easy, but extra command-response protocols add complexity and can increase costs/risks).



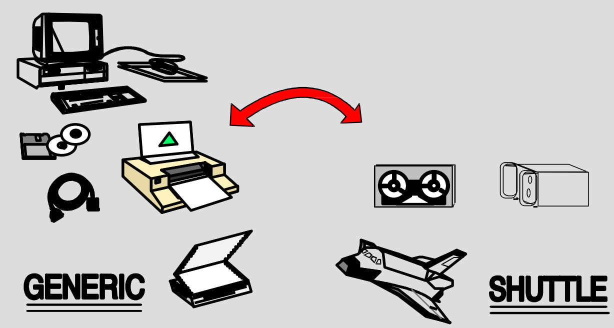
Subsystem Architectures

The Space Shuttle Data Processing System (DPS) controls or assists in controlling most other system functions, including:

- Automatic determination of the vehicle's status and operational readiness.
- Implementation sequencing and control of the Solid Rocket Boosters (SRBs) and External Tank (ET) during launch/ascent.
- System performance monitoring.
- Digital data processing.
- Communications and tracking.
- Payload and system management.
- Guidance, navigation and control.
- Electrical power distribution for the Orbiter and its propulsion systems.



Historical C&DH Developments

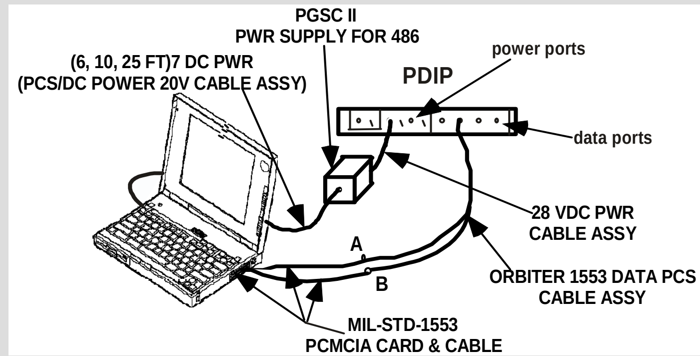


Home Data Processing Compared With Shuttle

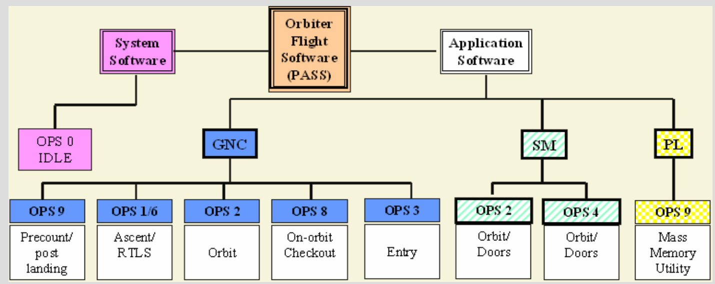
Space Shuttle C&DH Systems

The Shuttle DPS hardware includes 5 General-Purpose Computers (GPCs) and 20 Multiplexes/Demultiplexes (MDMs):

- All GPCs are IBM AP-101 computers, each providing a central processor unit and an input/output processor.
- During non-critical orbital flight periods only one or two GPCs are used for GN&G tasks, along with another for systems management and payload operations.
- The MDMs convert and format serial digital GPC commands into separate parallel discrete digital and analog commands for various vehicle system hardware.



Shuttle Aft Deck Power Data Interface

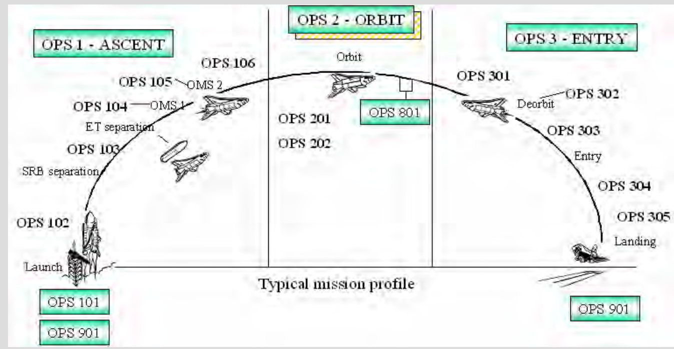


Shuttle Software Memory Configuration

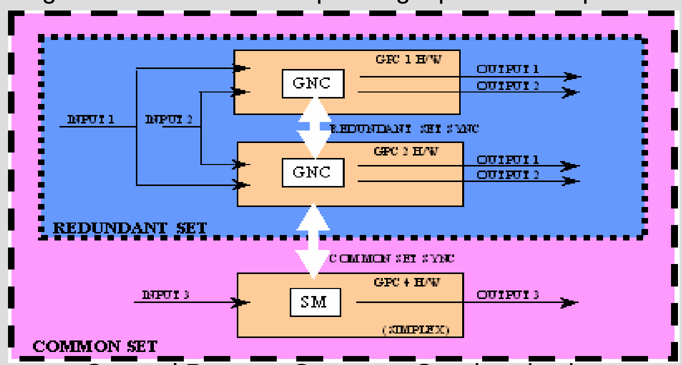
Shuttle DPS Equipment / Interfaces

Shuttle Orbiter GPC software is divided into two major groups: system software and applications software:

- The Primary Avionics Software System (PASS) contains all programs needed to control the vehicle throughout all mission phases and to manage all vehicle and payload functions.
- The applications software performs the actual duties required to fly and operate the vehicle and payload functions.
- Synchronization refers to a software scheme used to ensure proper and reliable inter-computer functioning and backups.



Flight Phases with Corresponding Operation Sequences

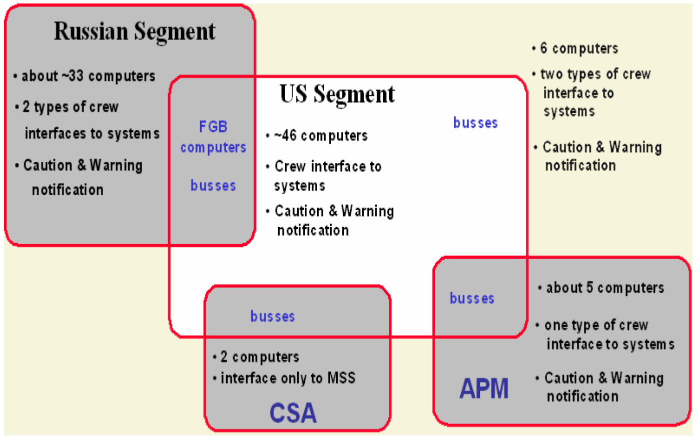


General Purpose Computer Synchronization

Shuttle System and Applications Software

The US ISS segment C&DH system connects with C&DH computers provided by the International Partners (IPs):

- The US C&DH provides "station-level software control" to keep all parts of the overall vehicle operationally integrated.
- Software access is gained through 7 different types of crew interface computers, including a Portable Computer System (PCS), a Station Support Computer (SSC), a Russian laptop Control Post Computer (CPC) and other subsystems.
- Most IPs provide their own computer and software with the exception of the Russian Functional Cargo Block (FGB) and Canadian robotics system.

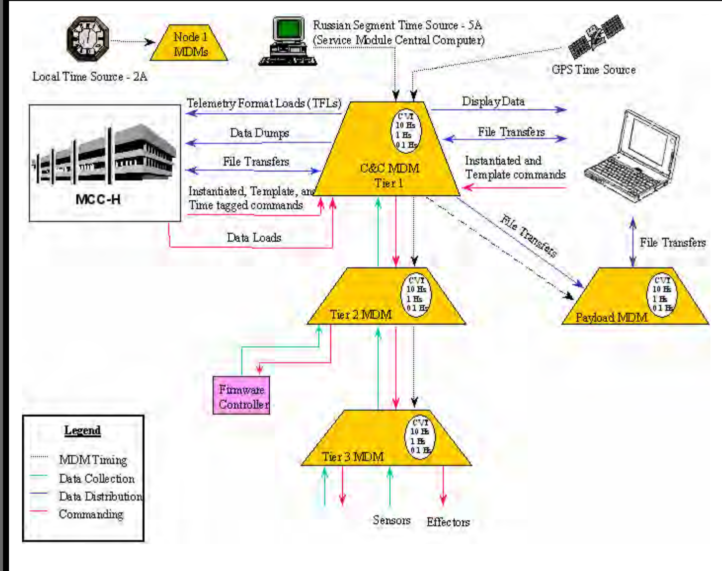


ISS flight computers are primarily used to collect data from onboard systems and payloads, process that data with various types of software and distribute it to the right equipment

ISS C&DH Providers and Equipment

The ISS US segment C&DH subsystem follows a distributed, 3-tier architecture with 25 processing computers interconnected by data busses that collect, process and distribute data and commands:

- Tier 1 provides the only crew-ground interface to the system and is 2-fault tolerant.
- Tier 2 (known as the “local tier”) executes system-specific software and generally has single-fault tolerant Multiplexer/Demultiplexers (MDMs).
- Tier 3, the lowest tier, is the sensor and effector interface point, has the most MDMs, and is least redundant.



The ISS tiered architecture offers 2-fault tolerant redundancy overall which is obtained by a complex allocation of softwares and “warm” (power on) backups

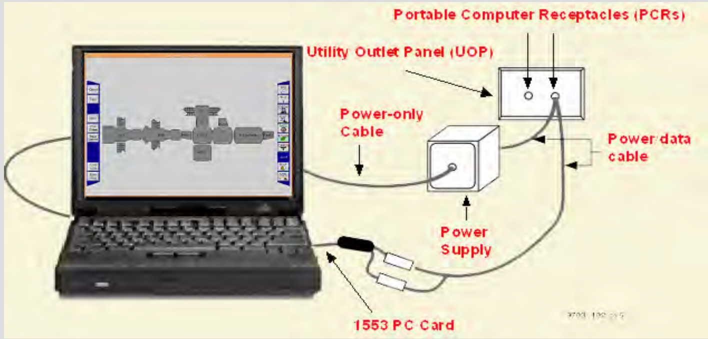
ISS Tiered Architecture Approach

Laptop crew interface computers are used throughout the ISS because of the ease of upgrading them and ability to move them throughout the station:

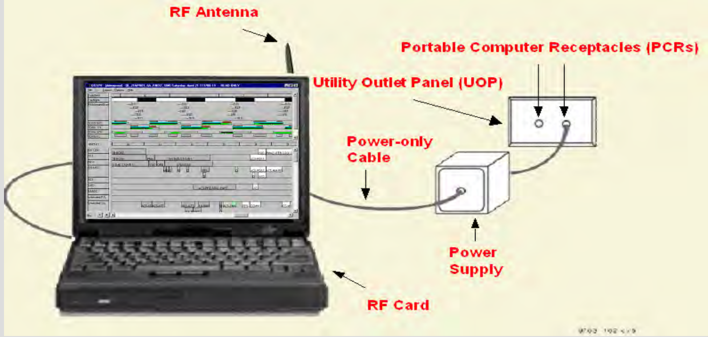
- The IBM Thinkpad 760x D laptop is presently used for the US segment PCS, Station Support Computer (SSC), Crew Health Care System and robotic workstation.
- The same hardware is used in the Japanese JEM and Attached Pressurized Module (APM).

IBM Thinkpad 760 XD	• PCS • SSC	• 166 MHZ • 64MB RAM • 3GB HD
PCS	• CMD & Control • Manage C&W • Station Moding	• UNIX • Data Cable
SSC	• View Procedures • Inventory • Office Tools	• Windows 95 • RF Cards

Characteristics of ISS Laptops



PCS Power and Data Connection

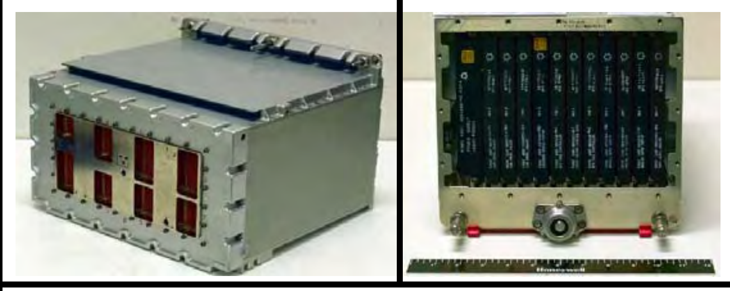


Support Computer Power and Data Interfaces

ISS Crew Interface Computers

ISS Multiplexers/Demultiplexers are significantly different from Space Shuttle Orbiter MDMs because they can run application software and process information in addition to their multiplexing/demultiplexing tasks:

- The Input/Output Controller Unit (IOCU) is the main MDM processing card which is based upon Intel 80386 5x technology.
- While limited in capability by today's standards, the 80386 chip was selected because it sufficiently performs all required processing, fits into the limited space provided, and uses less power (producing less heat) than newer chips.



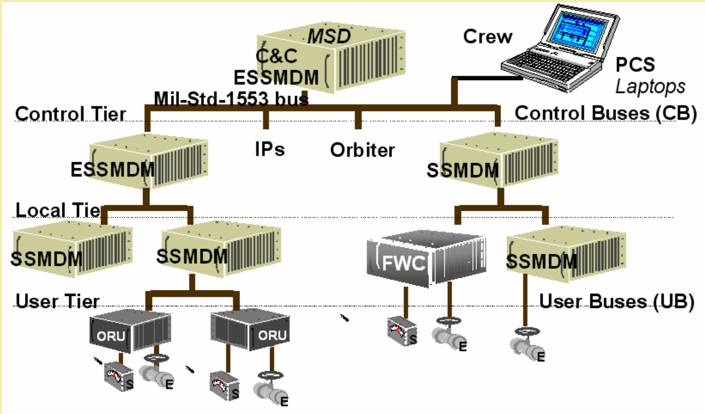
Typical ISS MDM Units

MDMs are modularized components that use computer chips located on processing cards that are designed to slide out horizontally from the frames.They come in 3 sizes based on the number of cards needed, and include external application units designed to withstand the harsh space environment

ISS Multiplexers / Demultiplexers

ISS MDMs utilize 1553B to exchange data and commands among themselves:

- The busses are also used for communication between a C&DH MDM and "smart" components in other non-C&DH systems.
- Each 1553B bus consists of 2 channels for redundancy, each channel comprised of 2 copper wires.
- The 2 channels are usually physically routed separately within a module to enhance redundancy.



Communication on busses occurs in one direction at a time, and must be precisely timed to avoid collisions.

The speed of the 1553 B bus is about 100 times slower than fiber-optic networks.

ISS Data Transfer Busses

Additional information relevant to Environmental Control and Life Support Systems (as they relate to habitability and EVA) can be found in Part II, Section I of this SICSA Space Architecture Seminar Lecture Series titled Human Adaptation and Safety in Space, along with other publications listed below:

•**Power Systems**

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"Space Shuttle Vehicle Familiarization Manual." *SSV FAM 1107*, NASA, Johnson Space Center, Texas, May 26, 1995.

Woodcock, G. *Space Stations and Platforms*. Orbit Books Company, Malabar, Florida, 1986.

• Environmental Control and Life Support

Astore, W., Giffen, R., Larson, W. *Understanding Space: An Introduction to Astronautics*. *2nd Edition*. The McGraw-Hill Companies, Inc., 2000.
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"Space Shuttle Vehicle Familiarization Manual." *SSV FAM 1107*, NASA, Johnson Space Center, Texas, May 26, 1995.
Woodcock, G. *Space Stations and Platforms*. Orbit Books Company, Malabar, Florida, 1986.

• Communications/ Command and Data Handling

Astore, W., Giffen, R., Larson, W. *Understanding Space: An Introduction to Astronautics*. *2nd Edition*. The McGraw-Hill Companies, Inc., 2000.
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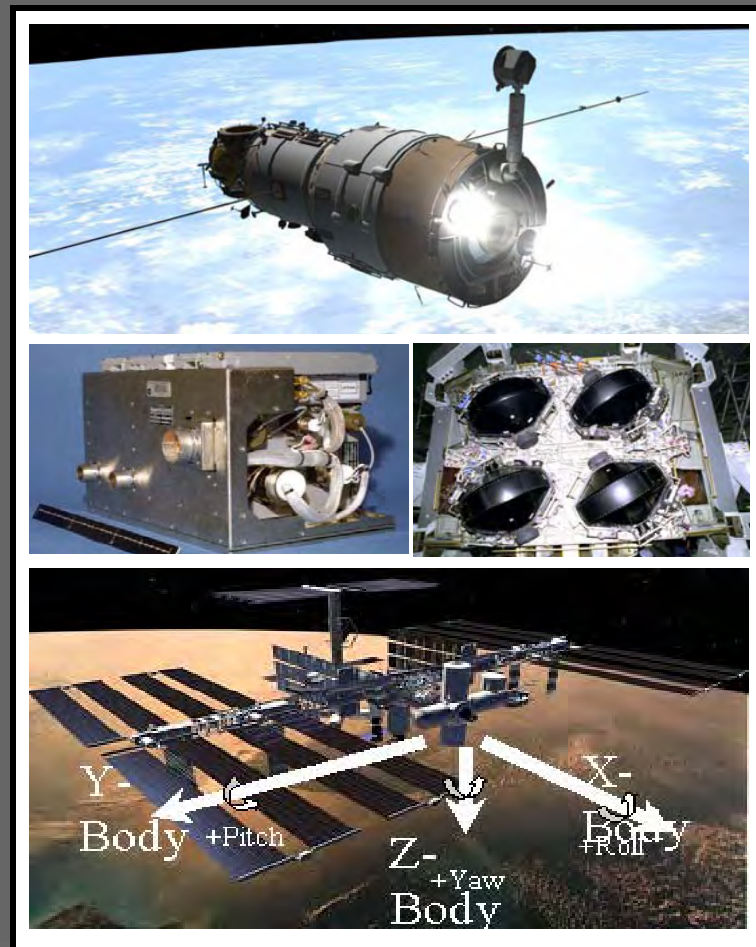
SECTION D: SPACECRAFT FLIGHT SYSTEMS



A variety of past, present and future spacecraft require means to maneuver in orbit for purposes that include rendezvous and docking, maintaining proper orientation, satellite deployments and control, and periodic re-boosts to adjust for altitude decay. Such capabilities depend upon two basic types of systems:

- Guidance, Navigation & Control (GN&C) systems identify the spacecraft's orientation and determine where to point it.

- Propulsion and Motion Control (P&MC) systems execute spacecraft stability and trajectory adjustments.

Space Shuttle Orbiter

Agena Target Docking Vehicle Seen from Gemini 8

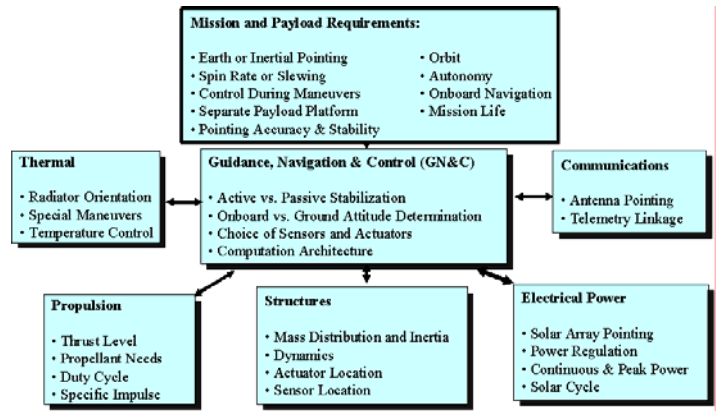
Soyuz TMA-1 Docked to International Space Station

Maneuvering Spacecraft

The Guidance, Navigation and Control (GN&C) system identifies the spacecraft orientation to stabilize it in the presence of disturbance torques and to point onboard systems in the desired directions:

- The GN&C computer receives a commanded attitude and rotation rate, then issues commands to control system actuators.

- Navigation and attitude sensors close the feedback loop by monitoring position and generating error signals when the spacecraft position is incorrect so that control torque adjustments can be properly applied.

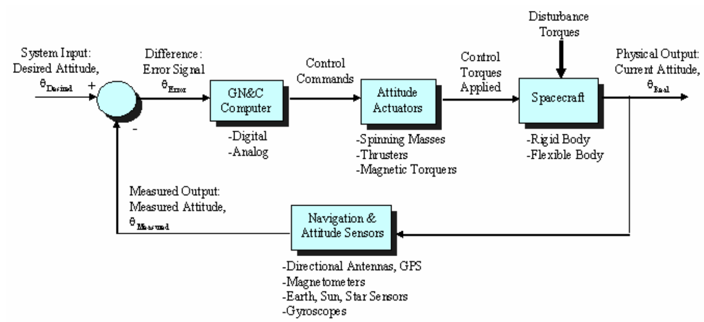


The GN&C system interfaces with a variety of other spacecraft sensors and control devices to ensure that orientation and stability requirements are satisfied for all interdependent systems and functions.

GN&C System Interfaces

The GN&C system must respond to a variety of disturbance torques:

- Gravity gradient torques result from a differential pull of gravity on various parts of a spacecraft causing it to rotate long axis down.
- Solar pressure torques are caused by tiny particles and molecules radiated from the sun that exert small forces.
- Magnetic field torques act on a spacecraft like the needle on a compass.
- Atmospheric drag torques impart a force that slows velocity and can cause rotation.
- Internal disturbances include unbalanced thrusts, flexible body dynamics, sloshing fluids, and onboard mechanisms.



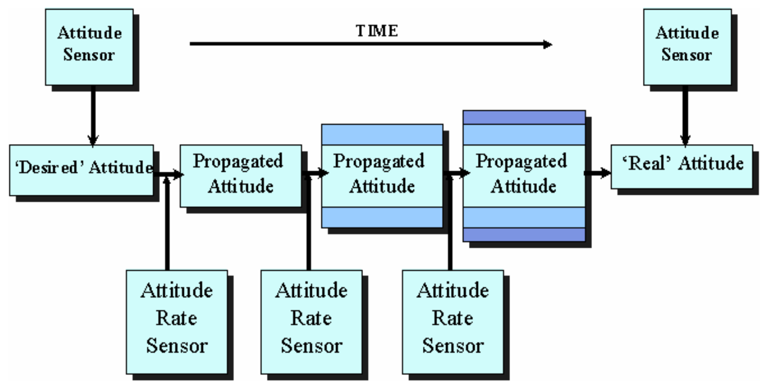
Closed-Loop GN&C System

The GN&C computer maintains an accurate state vector (orbital position and attitude), targets and initiates corrective maneuvers that respond to many constraints: fuel consumption; thermal limits; solar power generation; viewing/remote sensing; communication reception; payload requirements; and rendezvous/proximity operations.

Disturbance Torques and Corrections

The path a spacecraft flies is directly influenced by its attitude (or orientation) in space:

- A vehicle's attitude must be stabilized for accurate pointing of its body vector at intended targets, effective thermal control and power generation, communication, and proper guidance control for short propulsive maneuvers.
- Outside an atmosphere, attitude is changed by articulating the direction of thrust from exhaust nozzles and other control systems.



Attitude performance requirements are driven by a number of operational control modes, such as: orbital insertion, deorbit, rendezvous, sensor acquisition, microgravity, station-keeping, EVA's and many spacecraft and mission contingencies.

Attitude Propagation Factors

Attitude control systems must be designed to satisfy several performance requirements:

- Accuracy refers to how well the vehicle can be controlled with respect to a commanded direction.
- Range is the extent or range of angular motion over which the system must meet requirements.
- Jitter is a specified limit in angle or angular rate on short-term, high frequency motion.
- Drift is a specified limit on a vehicle's slow low-frequency motion.
- Settling time is the specified time to recover from maneuvers or upsets.

$$I_x\dot{\omega}_x + (I_z - I_y)\,\omega_y\omega_z = M_x$$
$$I_y\dot{\omega}_y + (I_x - I_y)\,\omega_x\omega_z = M_y$$
$$I_z\dot{\omega}_z + (I_y - I_x)\,\omega_x\omega_y = M_z$$

where I = moment of Inertia
ω = angular velocities
$\dot{\omega}$ = angular accelerations

Euler's Law of Angular Momentum

According to Euler's Law of Angular Momentum, a perfectly rigid body will continue to spin about its own major axis (largest amount of inertia) or minor axis (smallest amount of inertia) in a stable state. However, flexible body effects for spacecrafts with large solar arrays or long booms can make only the major axis stable.

Spin Axis Stability

Attitude Control Requirements

Passive attitude control strategies include spinning the spacecraft and utilizing gravity and magnetic forces:

- Pure spinners use "gyroscopic stiffness" to maintain the spin vector direction.
- Dual spinners are 2-part satellites with a rotor that maintains stability and a non-spinning platform that provides an ability to point sensors.
- Gravity gradient uses the Earth's gravity to gradually align the major axis with the local vertical.
- Magnetic torquers use magnets mounted to the spacecraft to align it with the Earth's geomagnetic field.

Type	Advantages	Disadvantages
Pure Spin	-Simple approach -Maintains fixed orientation in inertial space	-Lifetime limited to propellant -Difficult to change pointing direction -Re-pointing uses large amount of propellant -Rigid structure required
Dual Spin	-Simple approach -Ability to point sensors from non-spinning platform	-Lifetime limited to propellant -Rigid structure required -Pointing is limited by articulation of de-spun platform
Gravity Gradient	-Maintains stable orientation relative to central body (ie Earth) -Simple design -No propellant	-Oscillatory motion -Limited orientation -Requires long boom or elongated distribution of mass
Passive Magnetic	-Simple design -No propellant	-North/South pointing only -Difficult to model Earth's magnetic lines

Passive attitude control relies upon the dynamics of a spacecraft or the characteristics of the disturbance torques to achieve orientation and stability without mechanical means.

Approaches and Features

Passive Attitude Control Strategies

Active attitude control systems apply attached dynamic devices:

- Momentum-Biased systems use a single wheel that constantly spins at a high speed to provide gyroscopic stiffness in 2 axes perpendicular to spin.
- Momentum Exchange Reaction Wheels use multiple fixed-orientation wheels that can impart a torque by increasing or decreasing their spin rates.
- Momentum Exchange Control Moment Gyros use electronically-powered reaction wheels mounted in 3 orthogonal axes to trade angular momentum back and forth between the spacecraft and wheels.
- Zero Momentum systems use thrusters to rotate/de-spin and translate a vehicle.

Type	Advantages	Disadvantages
Momentum Bias (Single Wheel)	-Simple approach -Gyroscopic stiffness in two axes perpendicular to spin	-Primarily local vertical pointing -Limited spin control -Lifetime limited to sensor and wheel bearings
Momentum Exchange (Reaction Wheel)	-Very accurate pointing -No pointing constraints	-Complex and expensive -Normally need thrusters or magnetic torquers to dump momentum -Lifetime limited to sensor and wheel bearings
Momentum Exchange (Control Moment Gyro)	-Very accurate pointing - No pointing constraints	-Complex and expensive -Normally need thrusters or magnetic torquers to dump momentum -Lifetime limited to sensor and wheel bearings
Zero Momentum (Thrusters only)	-Powerful, fast, flexible -No pointing constraints	-Propellant limited -Limited accuracy -External contamination

Active attitude control relies upon using external torque control capabilities to command the desired orientation and counteract the effects of disturbances.

Approaches and Features

Active Attitude Control Strategies

Attitude determination identifies spacecraft orientation using sensor measurements and estimation algorithms:

- Original Inertial Measurement Unit (IMU) systems use gyros mounted to rotating gimbals and measured gimbal angles.
- Sun sensors allow the sun's rays to shine through slits onto detectors for attitude angles to be determined.
- Star sensors image stars and compare them with digital celestial maps to determine azimuth, elevation and roll.
- Horizon sensors use an IR sensor to detect where the infrared signature drops.
- Magnetometers measure the local magnetic field of the Earth.
- GPS is limited to lower orbits.

Type	Advantages	Disadvantages
Inertial Measurement Unit (IMU)	-Very accurate-short term -No external inputs needed	-Limited long term accuracy -Periodic updates required from other sources
Sun Sensors	-Bright, unambiguous target	-Target not always available due to eclipses
Star Sensors	-High accuracy -Orbit independent	-Heavier and requires more power than other sensors -Need to know general orientation before aiming
Horizon Sensors	-Bright target always available -Direct pitch and roll measurements	-Limited accuracy -Useful only in low Earth orbit
Magnetometer	-Cheap, reliable, light weight	-Limited accuracy -Usable only below 6,000 km -Magnetic field uncertainties
GPS	-Inexpensive, small -No moving parts -Reliable, multiple signals	-Multiple antennas required -Limited to lower orbits

Attitude Measurement Equipment Features

Attitude Determination

SPACECRAFT SYSTEMS DESIGN & OPERATIONS

Real-time orbital determination is the best way to maintain the state vector:

- Celestial reference devices determine attitude by observing celestial bodies using star trackers, star scanners, and planetary sensors and trackers.
- Initial reference devices can be used where celestial references aren't available or appropriate, typically using mechanical and non-mechanical gyroscopes.
- A Conventional Terrestrial Reference System (TRS) uses various Earth satellite systems such as GPS.

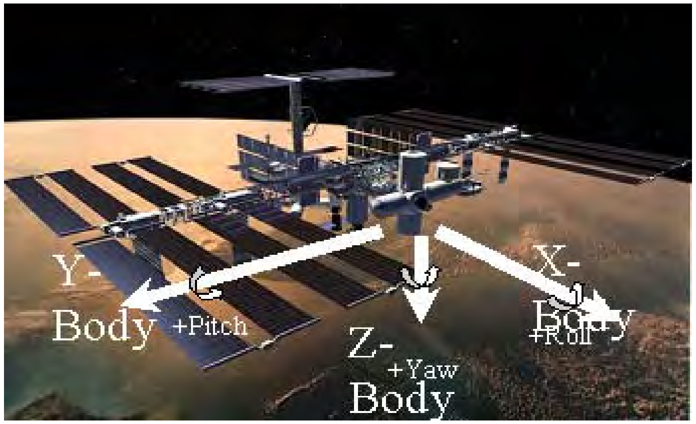
System	Advantages	Disadvantages
Ground Tracking	-Traditional approach -Well established infrastructure	-Accuracy depends on ground station coverage -Manpower intensive
Tracking and Data Relay Satellite (TDRS)	-Standard method for NASA spacecraft -High accuracy -Same hardware for tracking and data links	-Limited autonomy -Reserve mostly for NASA missions -Requires TDRS tracking antenna
Global Positioning System (GPS)	-High availability -High accuracy -Inexpensive	-Semi-autonomous -Long-term maintenance of GPS system
Earth and Star Sensing	-High target availability -Very accurate	-Cost and complexity of star sensors -Potential difficulty identifying stars
Space Sextant	-Could be fully autonomous	-Flight tested prototype only -Relatively heavy and high power
Stellar Refraction	-Could be fully autonomous -Integrates with attitude sensing hardware	-Still in concept and test stage
Landmark Tracking	-Can use payload sensor data	-Still in concept stage -Landmark identification can be difficult -May have geometrical singularities
Satellite Crosslink	-Can use spacecraft crosslink hardware for other purposes	-Unique to each satellite constellation -Position referencing can be difficult -Potential problems with system deployment

Navigation Methods

Navigation Reference Frames

A standard Euler angle sequence is used for yaw, then pitch, then roll (YPR) from a 0,0,0 Local Vertical/Local Horizontal (LVLH) or a 0,0,0 X-Axis Perpendicular to Orbit Plane (X POP) attitude coordinate system:

- The LVLH reference frame maintains the ISS with its positive 2-axis points (nadir) pointing toward the center of the Earth and the positive X-axis pointed in the velocity vector.
- The X POP reference frame is quazi-inertial reference that is used to maximize power generation, a 90° yaw of the LVLH frame at orbital noon.

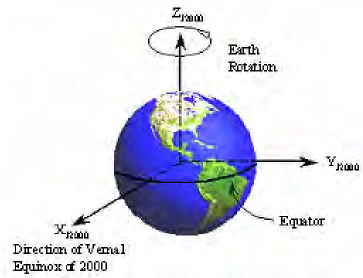


Several different ISS frames are being utilized to coordinate such activities as robotic operations, payload operations, and GN&C software processing. Russian and American software use different reference frames, but a common standard for crew displays and communications.

ISS Reference Frames

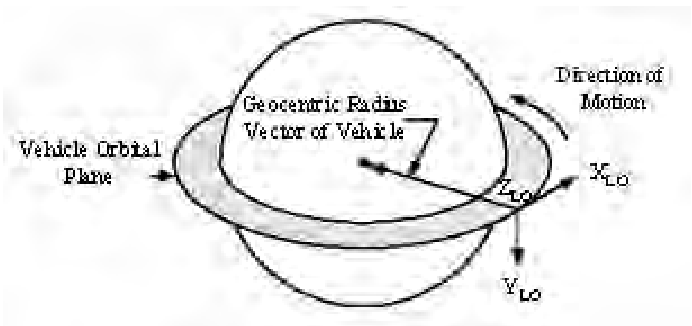
The ISS maintains proper orbital positioning using three basic reference frames:

- The J2000 reference frame is an inertial Cartesian coordinate system where the X-axis is directed towards the mean vernal equinox at noon on January 1, 2000.
- The LVLH reference frame maintains the 2-axis pointing nadir and the 4-axis perpendicular to the orbit plane as the Station makes a complete Earth orbit.
- The X POP reference plane is a quazi-inertial frame that points the X-axis out of plane with the Y and X axes in the orbital plane.



The J2000 is similar to the inertial system used for the Shuttle updated for processed star positions.

The J2000 Frame

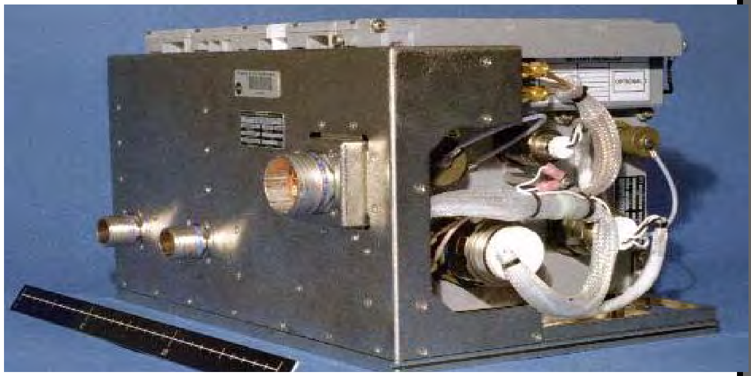


Local Vertical/Local Horizontal Reference

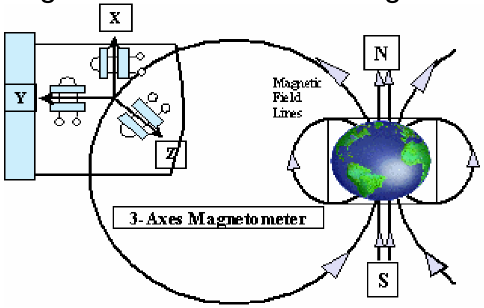
ISS Reference Frames

ISS navigation includes state determination, attitude determination, and pointing and support equipment:

- For state determination, the US segment primary uses GPS, while the Russian segment uses their Global Navigational Satellite System (GLONASS) which is similar along with ground stations.
- A variety of attitude determination equipment systems include: US-provided GPS and Rate Gyro Assemblies (RGAs); and Russian star, sun and horizon sensors; magnetometers and rate gyros.
- Pointing and Support (P&S) subsystems pass state vector, attitude and altitude rate data to other Station systems.



Space Integrated GPS/Inertial Navigation System



Russian 3-Axis Magnetometer

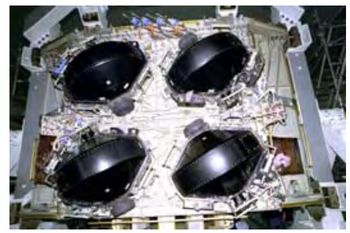
ISS Navigation System

ISS control consists of translational and attitude (rotational) devices:

- Translational maneuvers are necessary to enable the ISS to maintain its altitude by performing re-boosts approximately every 3 months to offset orbital decay from aerodynamic drag. This is accomplished using the Russian Progress main engine, docking thrusters, or the Service Module (SM) thrusters.

- Attitude control is provided by Russian propulsion systems and a non-propulsive US Attitude Control Subsystem (ACS) which includes 4 massive (300 kg) CMGs.

CMG saturation with all angular momentum vectors shown parallel are not able to apply counter-torques.



CMG's Located on the ISS Z-1 Truss

Attitude Control	**Translational Control**
4 CMG's (2 Necessary) Progress Thrusters Service Module Thrusters 6 Russian Gyrodynes	Progress Thrusters Service Module Thrusters

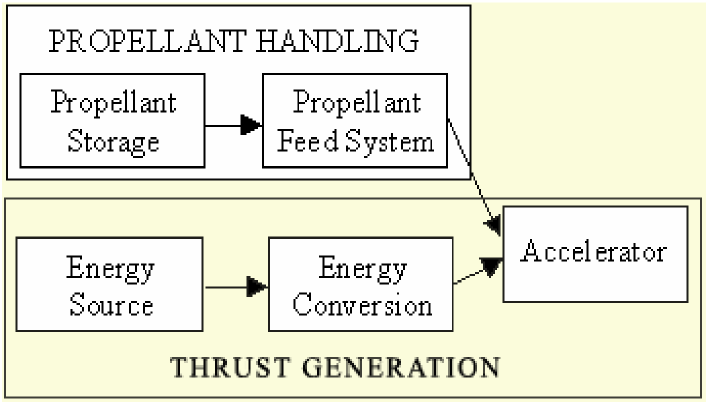
ISS Attitude and Translational Control

ISS Control Devices

Orbital spacecraft typically use sets of small propulsive devices to maintain attitude control, provide three-axis stability, execute maneuvers, and make minor trajectory adjustments:

- Some propulsive systems use hypergolic propellants (two compounds stored separately that ignite spontaneously when mixed in engines or thrusters).

- Other propulsion devices use fuels such as hydrazine which decomposes explosively when brought into contact with an electrically heated metallic catalyst.



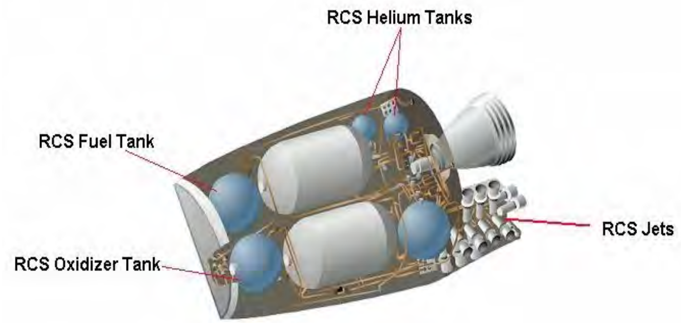
The main system used for space propulsion is a rocket, a device that stores and transports its own propellant mass and expels this mass from a thrust generation nozzle to provide a force.

Basic Propulsion System Elements

Propulsion System Types

The Space Shuttle OMSs are housed in two independent pods located on each side of the Orbiter's aft fuselage:

- The pods also house the aft Reaction Control System (RCS), and can supply up to 1,000 pounds of propellant to the RCS.
- Propellant is pressure-fed to the OMS engines through tank isolation valves and a distribution system.
- Gaseous nitrogen is used to control propellant flow into the OMS engines and to purge residual fuel after they are shut down.



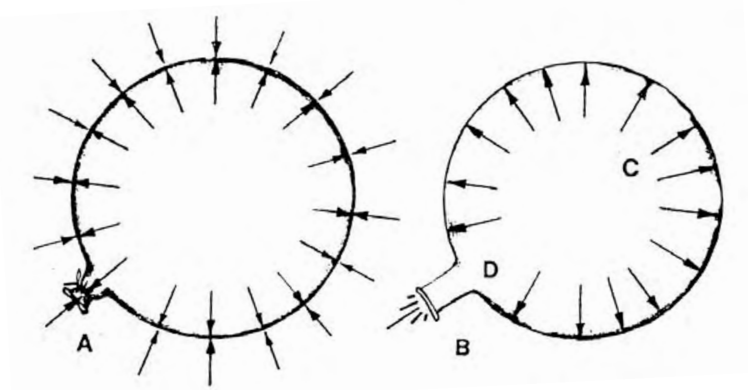
The Shuttle Orbital Maneuvering System (OMS) provides thrust for orbit insertion, orbit transfer rendezvous, deorbit, abort to orbit, and abort once around. The OMS pods use helium to pressurize the monomethyl hydrazine fuel and nitrogen tetroxide oxidizer that powers the thruster.

OMS and RCS System

Shuttle Orbital Maneuvering System

Orbiter RCS units are located in the forward nose area along with those in the OMS/RCS pods:

- The forward RCS has 14 primary and 2 vernier engines, and the aft has 12 primary and 2 vernier engines in each pod.
- Each of the primary RCS engines provide 870 pounds of vacuum thrust, and each of the verniers provide 24.
- Each jet is fixed to fire in a specific direction, controlled by digital autopilot or manual hand controllers.
- Two helium tanks pressurize the fuel (monomethyl hydrazine) and the oxidizer (nitrogen tetroxide).



A balloon is an example of the simple reaction engine principle. The inside air which is contained under pressure escapes at high speed when released through a small nozzle and exerts a reaction force that drives the system forward.

Reaction Engines

Shuttle Reaction Control System

The Russian Service Module's propulsion system provides single-fault tolerance control for yaw, pitch, roll and small x-axis translation maneuvers:

- The system incorporates 32 RCS thrusters arranged in 2 manifolds with 16 thrusters each.
- Service Module main engines can be fired separately or together to perform re-boost operations.
- Nitrogen propellant can be supplied to the main engines from the Service Module or Progress supply vehicle tanks, and attitude control thrusters can additionally be supplied from First Cargo Block (FGB) tanks.

The Russian Service Module propulsion system consists of an integrated orbital maneuvering system and RCS with a common nitrogen propellant supply. Attitude control thrusters provide means for small orbital adjustments and 2 main engines enable periodic re-boost capabilities for the entire ISS.

Russian Propulsion System

The proposed Propulsion Module is comprised of elements which are similar to the Shuttle OMS/RCS:

- It will attach to ISS at PMA 2 (the Shuttle docking location) and provide an interface with the Orbiter.
- Engines are mounted facing the ram direction, requiring the ISS to perform a 180° yaw maneuver prior to re-boost.
- The PM uses 4 liquid bipropellant (nitrogen tetroxide/ monomethyl hydrazine) rocket engines for re-boost (2 of these for redundancy).
- 12 liquid bipropellant RCS units arranged in 6 pairs provide attitude control.

A US Propulsion Module (PM) is proposed to provide additional ISS propulsive capability independent of Russian services. It is being designed for return to Earth by the Orbiter at the end of service life.

US Propulsion Module

Additional information relevant to Propulsion and Motion Control can be found in Part III, Section C of this Space Architecture Seminar Lecture Series titled Space Mission Architecture & Facilities Planning, along with other publications listed below:

• **Guidance Navigation and Control**

"Air Data Subsystem Manual." *ADS2102*, NASA, Johnson Space Center, Texas, May 26, 1995.

"Ascent Guidance and Control Manual." *ASC/ G&C 2102*, NASA, Johnson Space Center, Texas, January, 1995.

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• **Propulsion and Motion Control**

Astore, W., Giffen, R., Larson, W. *Understanding Space: An Introduction to Astronautics*. *2nd Edition*. The McGraw-Hill Companies, Inc., 2000.

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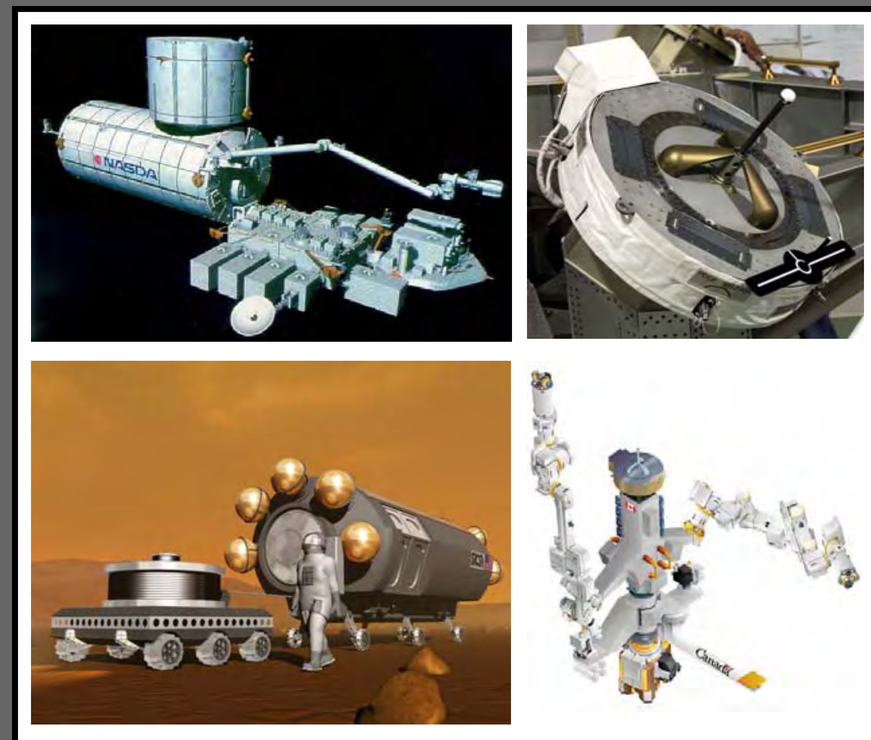
SECTION E : ROBOTIC & MOBILITY SYSTEMS



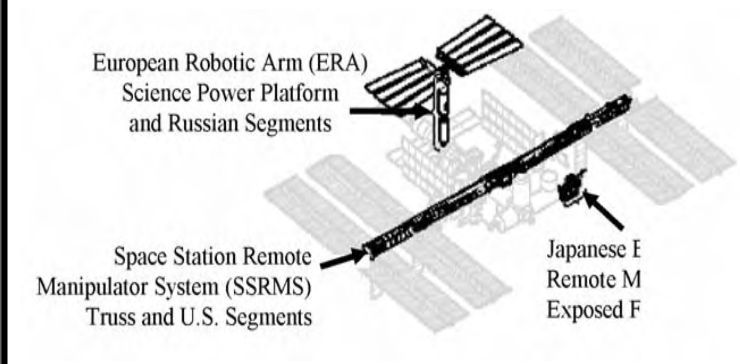
The Orbiter payload deployment and retrieval system includes an electromechanical Remote Manipulator System (RMS):

- The 50ft- 3in long, 15in diameter arm weight 905 pounds, and can manipulate 65,000 pounds payloads under weightless conditions.
- Six degrees of freedom in 6 joints enable pitch, roll and yaw movement.
- The RMS is controlled from the Orbiter's aft deck crew station by a crew member with television camera-assisted viewing.

Space Shuttle Remote Manipulator System

Five international agencies are involved in ISS robotic system development:

- NASA and the Canadian Space Agency (CSA) collaborated in MSS development:
  - -CSA is providing the Space Station Remote Manipulator System (SSRMS), Mobile Remote Service Base System (MBS), and Special Purpose Dexterous Manipulator (SPDM).
  - -NASA is providing the Mobile Transporter (MT) and Robotic Workstations (RWSs).
- The ERA is jointly developed by the European Space Agency (ESA) and Russian Space Agency (RSA).
- The JEMRMS is the sole responsibility of Japan's National Space Development Agency (NASDA).



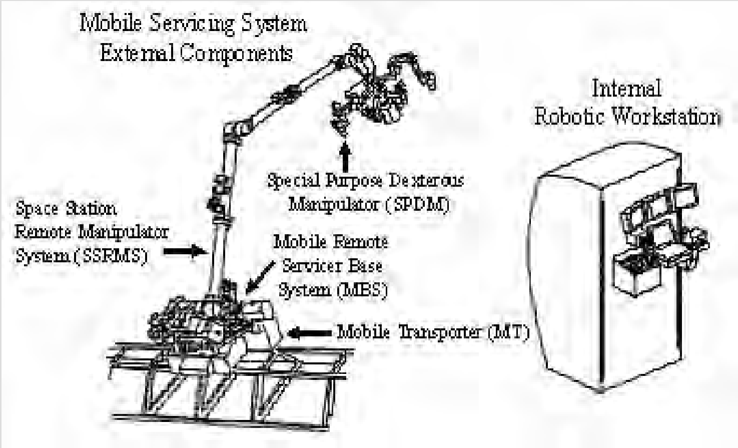
Three different robotic systems used on the ISS include the Mobile Servicing System (MSS), European Robotic Arm (ERA) and the Japanese Experiment Module Remote Manipulator System (JEMRMS).

ISS Robotic Systems and Locations
International Contributions

The Mobile Servicing System offers capabilities to accomplish robotic functions at various ISS locations using a single Space Station Remote Manipulator System (SSRMS) that can be relocated as needed:

- A Mobile Transporter (MT) accomplishes mechanical movement along a truss, and carries the Mobile Remote Service Base (MBS) and SSRMS.

- MSS control is provided via two Robotic Workstations (RWSs) in the US Lab and Cupola which also supports synthetic viewing using TV camera monitors.

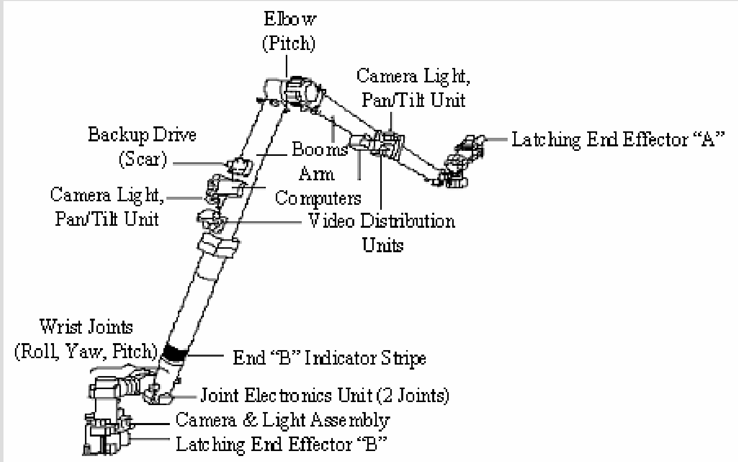


Primary functions of the MSS include ISS assembly, large payload handling, maintenance, EVA support and onboard transportation.

Mobile Servicing System
NASA/ Canadian Space Agency Development

The SSRMS is a 56ft long manipulator that supports electronic boxes and video cameras and is comprised of several main components:

- Latching End Effectors (LEEs) at each end of the boom section create a "walking" capability between attach points called Power and Data Grapple Fixtures (PDGFs).
- Camera light pan/tilt units in each of the 2 boom sections along with computers and video distribution units support synthetic viewing.
- A wrist joint accommodates roll, yaw and pitch, and an elbow joint accommodates pitch only.



The Space Station Remote Manipulator System is used to handle large payload and equipment tasks including berthing/ unberthing, maneuvering and hand-offs with other robotics systems.

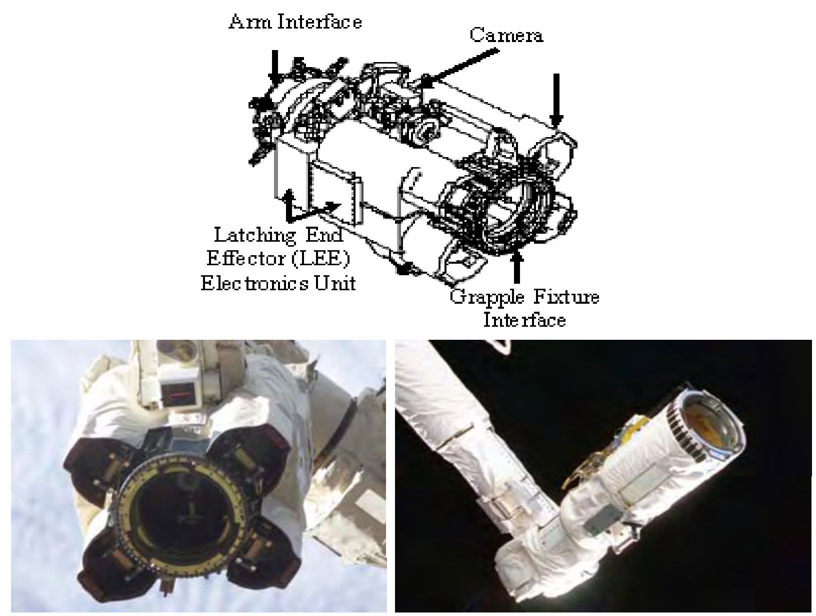
Space Station Remote Manipulator System

Canadian Space Agency Development

The Latching End Effectors (LEEs) incorporate a variety of special devices:

- An Arm Interface enables the system to rotate about its long axis for versatility in radially clocking the Camera and Light Assembly and Grapple Fixtures.

- A Latch/ Umbilical Mechanism Assembly (UMA) provides the capability to transfer power at utility ports for stationary operation of the MBS, SSRMS, or a Special Purpose Dexterous Manipulator (SPDM).



SSRMS Latching End Effectors

Canadian Space Agency Development

The SSRMS uses two different types of grapple fixtures:

- The Power and Data Grapple Fixture (PDGF) is the most versatile of the two, and is the only interface from which the arm can operate. These fixtures are distributed throughout the ISS, and also provide interfaces to other elements and payloads.

- The Flight-Releasable Grapple Fixture (FRGF) is primarily used for handling payloads and moving equipment along the truss and on ISS elements, and does not provide power, data or video connections.

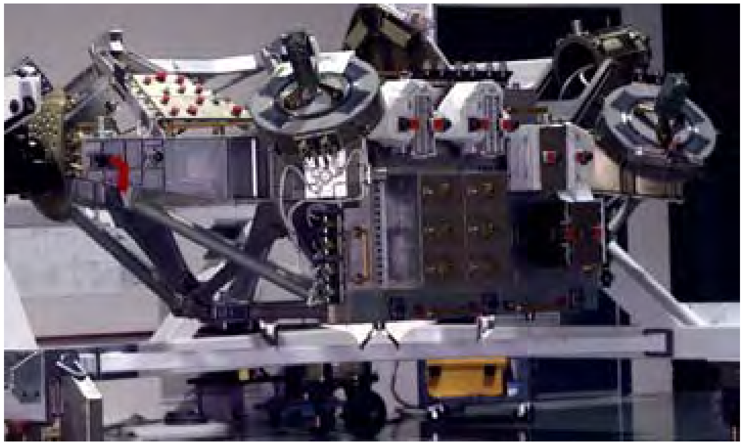
The Power and Data Grapple Fixture (PDGF) provides power, data and video communications to the SSRMS arm.

Power and Data Grapple Fixture

Canadian Space Agency Development

The MBS functions both as a power, data and video link between the ISS and MT, and as a work platform and base for the robotic arm:

- Capture latches attach the MBS onto the MT, and 4 Power and Data Grapple Fixtures (PDGFs) support attachment of the SSRMSs and SPDM.
- The MBS common attachment system also provides for temporary stowage of payloads such as structural, power and data interfaces through the UMA.
- Attachment points are also offered for EVA operations.



The Mobile Remote Servicer Base System (MBS) is the primary interface between the SSRMS, SPDM, payloads, EVA crew and the MT.

Mobile Remote Servicer Base System

Canadian Space Agency Development

The Special Purpose Dexterous Manipulator (SPDM) is designed to perform dexterous operations including maintenance and payload servicing:

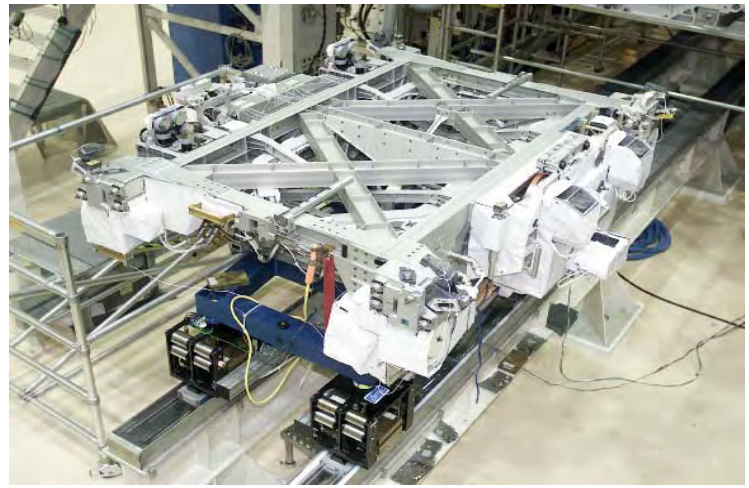
- The SPDM can remove and replace Orbital Replacement Units (ORUs) and ORU subcarriers, inspect and monitor equipment, and provide lighting and closed-circuit television monitoring of EVA and IVA work areas.
- Control is provided through a Robotic Work Station (RWS). Only one SPDM arm can be used at a time while the other stabilizes the work site.

Special Purpose Dexterous Manipulator
Canadian Space Agency Development

The Mobile Transporter moves along ISS truss rails to provide SSRMS mobility between 10 connected MT work sites:

- A linear drive unit translates the MT from one end of the truss to the other in 50 minutes at maximum velocity (1 inch/sec) to minimize impacts on GN&C.

- Power, communication and video connections between the MT and truss are provided by a trailing Umbilical Mechanism Assembly (UMA) that connects to power utility ports for stationary operations.



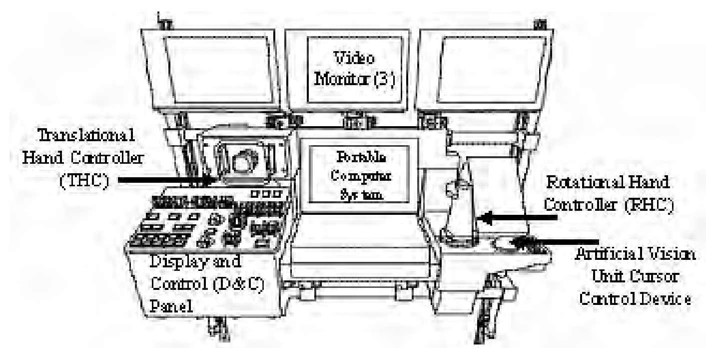
Mobile Transporter

The Mobile Transporter (MT) provides structural data and video links between the Station and MBS and mobility for robotic systems, payloads and EVA crew.

NASA Development

During operations, one RWS is active (prime) with the other in a monitor or powered-down mode:

- The active RWS has primary control of MSS functions, while the backup provides emergency stop, display of additional camera views, and system feedback status.
- If the prime RWS fails, the second can transition from monitor to active mode.
- RWS controls include hand controllers, automated pre-stored inputs, and a joint-by-joint hand controller.



Robotic Workstation

The Robotic Workstation (RWS) provides the operator interface needed to control and receive data from the SSRMS.

NASA Development

The ERA has many similarities to the SSRMS including power, data and video transfer capability by end effectors and ability of either end effector to act as a base-point while the other does payload handling:

- Uses include maintenance of solar arrays, radiator deployment, ORU installation/replacement and external element inspection.

- Control is either through an EVA Man-Machine Interface (EMMI) or IVA Man-Machine Interface (IMMI) without use of hand controllers.

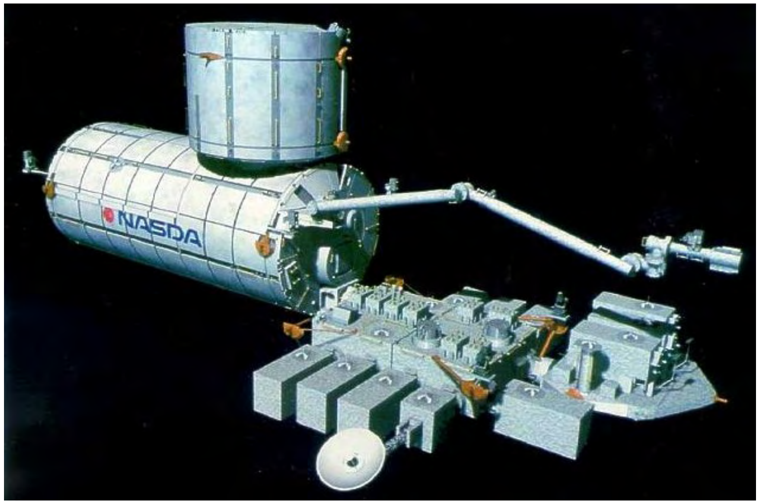
Primary functions of the European Robotic Arm (ERA) are to provide EVA support for installation and maintenance of equipment on the Russian segment.

European Robotic Arm

European Space Agency Development

The JEMRMS provides essential services in manipulating equipment units that must be attached and detached to the Exposed Facility (EF):

- The Main Arm is comprised of two boom sections (32.5 ft total length) containing 6 joints.
- A "snare" end effector located at the operating end attaches to grapple fixtures (similar to the Shuttle RMS).
- The Small Fine Arm is a dexterous manipulator used to support fine-tuned tasks.

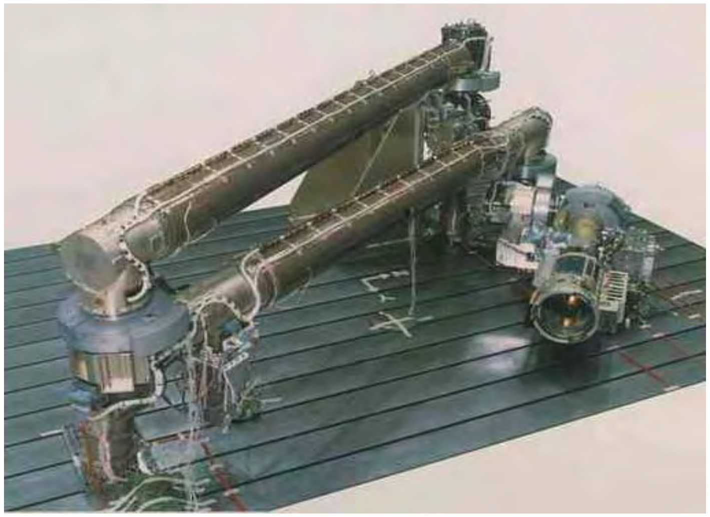


JEM Remote Manipulator System (JEMRMS)

The JEMRMS provides a Main Arm (MA) and Small Fine Arm (SFA) that work together.

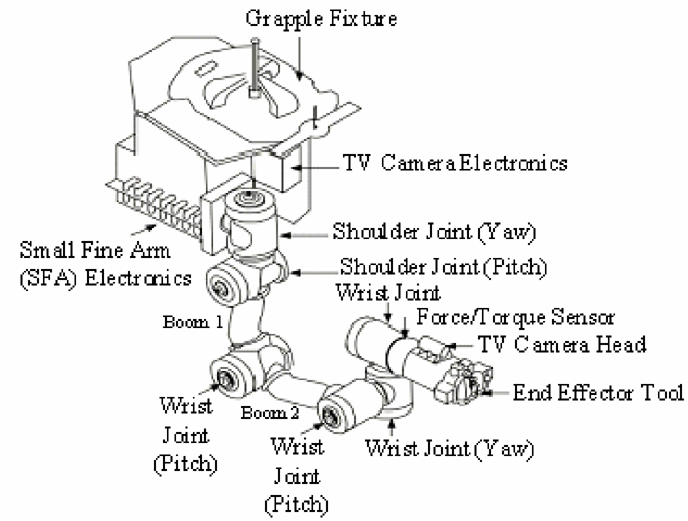
National Space Development Agency, Japan

SPACECRAFT SYSTEMS DESIGN & OPERATIONS



The Small Fine Arm (SFA) Dexterous Manipulator has two sections (6ft. total length).

SFA Boom and joints

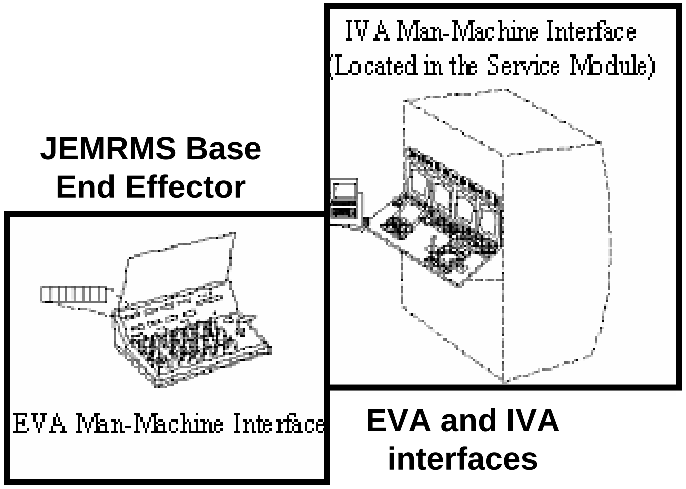


The SFA is positioned by and operated from the Main Arm through IVA/EVA interfaces.

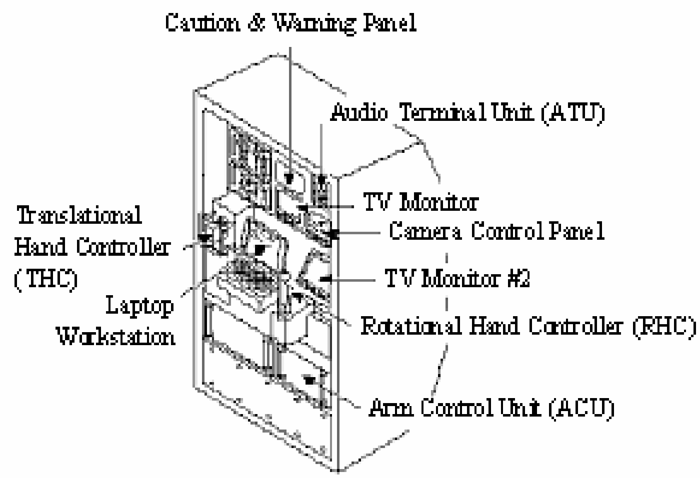
SFA Sub-system Components

National Space Development Agency, Japan

SPACECRAFT SYSTEMS DESIGN & OPERATIONS



The Main Arm grapple fixture provides power, data and video to the SFA.

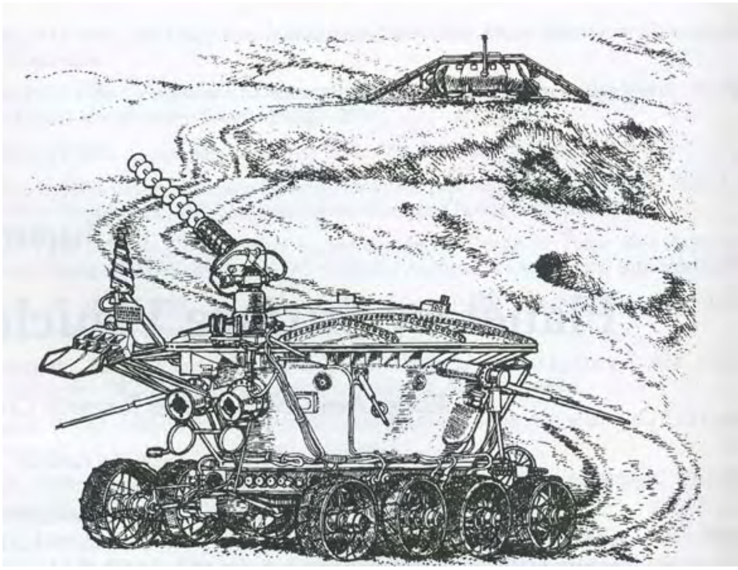


The JEMRMS Console located inside the pressurized JEM provides manual, auto trajectory and single-joint modes.

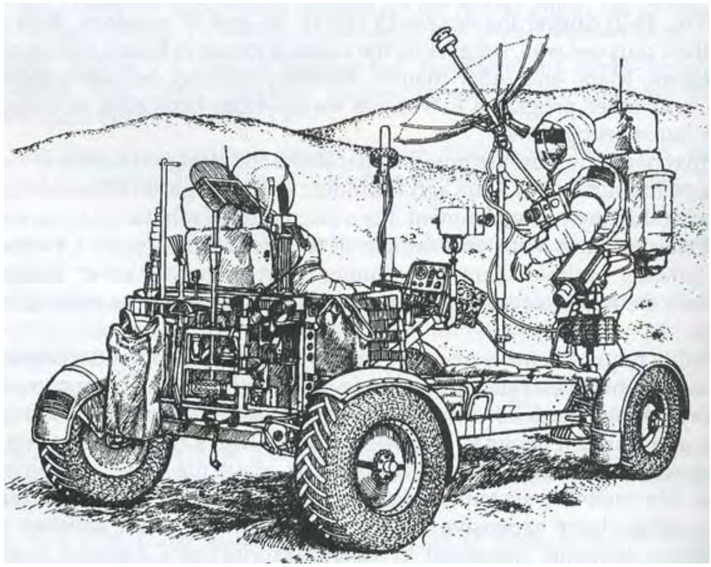
JEMRMS Control Console

National Space Development Agency, Japan

HUMAN SPACEFLIGHT



Lunakhod Rover used for Russian unmanned missions in 1970 and 1973



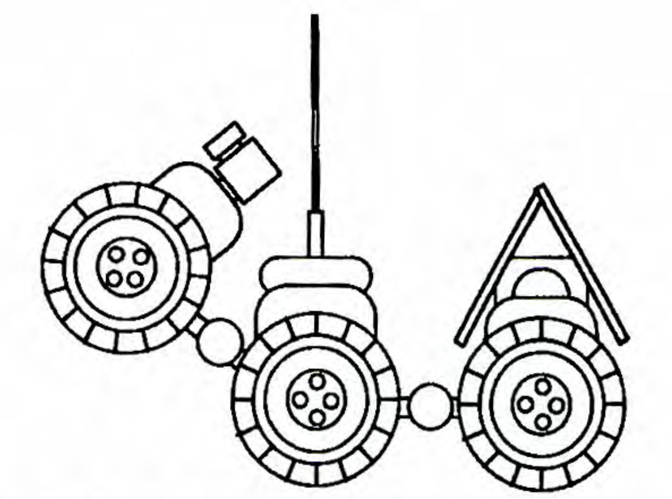
US Lunar Rover used for Project Apollo 15, 16 and 17 missions

Surface Mobility Systems

ROBOTIC SYSTEMS

LUNAR/PLANETARY APPLICATIONS

HUMAN SPACEFLIGHT



Articulated Chassis Mobility System
Example: Russian Marsokhod (prototype)

Chassis: 1-5 m long, articulated frame

Mobility System: 6-wheel electric motor drive

Operation: Remote control

Power: Batteries, radioisotopes or solar cells

Range: A few kms, depending on energy available

Speed: Moderate, power-limited on level terrain

Energy Efficiency: Moderate on smooth terrain

Towing: Not recommended

Complexity: Moderate

Lifetime: Days to months

Payload: Limited by size and articulation interference

Terrain: Good climbing ability

Applications: Rocky terrain

Surface Mobility System Concepts

Screw Drive Mobility Vehicle
Example: Snowmobile

Chassis: 3-5 m long, rigid frame
Mobility System: Counter-rotating helixes
Operation: Human driver
Power: Batteries, fuel cells or RTG
Range: A few kms, depending on energy available
Speed: Moderate, good on soft soil
Energy Efficiency: Moderate on smooth terrain
Towing: Very good on proper surface
Complexity: Moderate
Lifetime: Indefinite with fuel and maintenance
Payload: Good on soft terrain
Terrain: Soft surfaces
Applications: Local to base or special uses

HUMAN SPACEFLIGHT

Dune Buggy / Golf Cart Rover
Example: Lunar Rover

Chassis: 3-5 m long, rigid frame

Mobility System: 4-wheel electric motor drive

Operation: Human driver

Power: Batteries, fuel cells or RTG

Range: A few kms, depending on energy available

Speed: Moderate to high

Energy Efficiency: High on smooth terrain

Towing: Not recommended

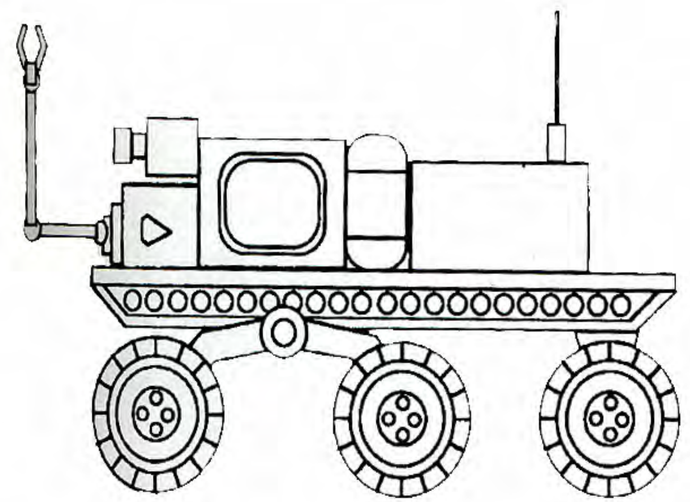
Complexity: Moderate

Lifetime: Indefinite with fuel and maintenance

Payload: Low to high, depending on vehicle

Terrain: All surfaces, limited by wheel size

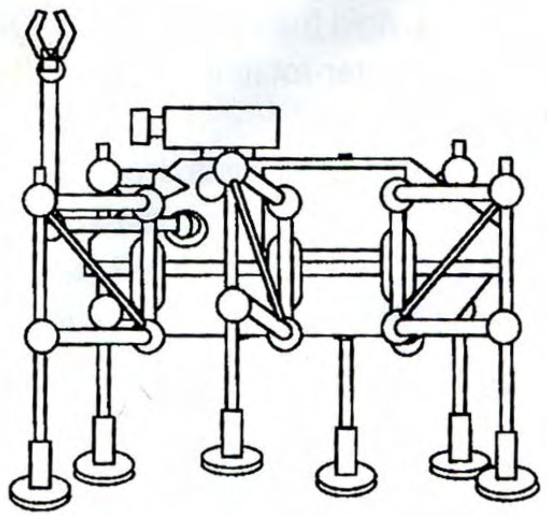
Applications: Local to base, short excursions



Six-wheel, Four wheels Articulated Vehicle
Example: Mars Pathfinder Rocky Rover

Chassis: 0.1-1 m long, rigid frame
Mobility System: 6 wheels, 4 articulated
Operation: Automated or human driver
Power: Batteries, fuel cells or RTG
Range: Depends on vehicle size, stored energy
Speed: Good to excellent, power limited
Energy Efficiency: Good on smooth terrain
Towing: Not recommended
Complexity: Moderate
Lifetime: Energy or maintenance- limited
Payload: Good , depends on vehicle size
Terrain: Smooth or rough surfaces
Applications: Exploring unpredictable terrain

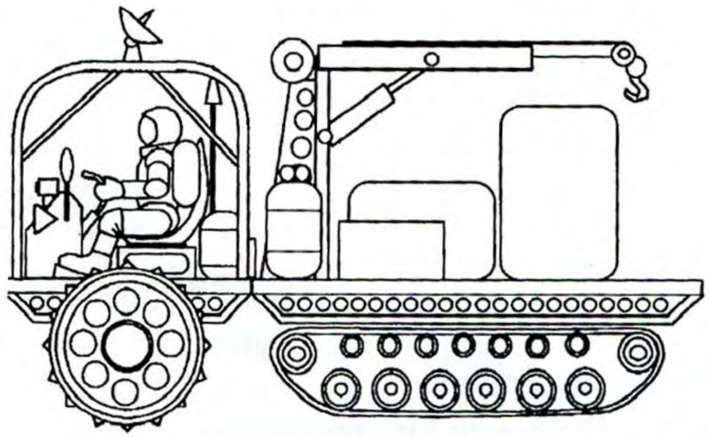
HUMAN
SPACEFLIGHT



Walking Mobility System
Example: Dante

Chassis: 1-5 m long, rigid frame or body
Mobility System: Computer-controlled legs
Operation: Remote control
Power: Batteries, fuel cells or solar
Range: A few kms, depending on energy available
Speed: Low
Energy Efficiency: Low due to vertical movement
Towing: Not recommended
Complexity: Very high, not well developed
Lifetime: High maintenance system
Payload: Low due to high ground pressure
Terrain: Solid, rough, rocky but without cracks
Applications: Best in steep, dangerous areas

HUMAN SPACEFLIGHT



Flat-Bed, Open-Cab Utility Vehicle

Chassis: 5-10 m long, rigid or pivoted frame

Mobility System: Wheels and/or tracks

Operation: Human driver

Power: Batteries, fuel cells or RTG

Range: Up to 100 km, depends on energy availability

Speed: Moderate to good

Energy Efficiency: Moderate with tracks

Towing: Excellent, especially with tracks

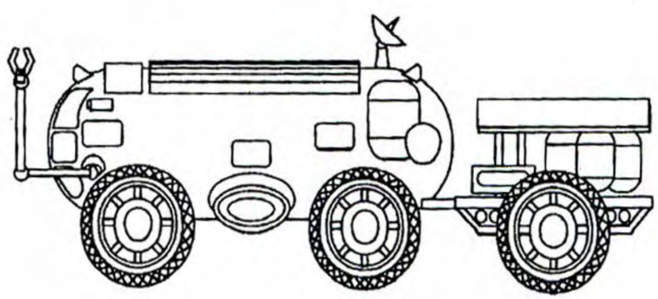
Complexity: Moderate

Lifetime: Indefinite with fuel and maintenance

Payload: High fraction of total mass

Terrain: Smooth to moderately rough

Applications: Lifting and hauling heavy loads



Long-range, pressurized, Planetary Rover
(Shown with optional power system trailer)

Chassis: 5-10 m long, pressurized shell

Mobility System: 4 –wheel electric motor drive

Operation: Human driver

Power: Fuel cells or RTG

Range: 1000 km, depends on power available

Speed: Good on smooth terrain, power-limited

Energy Efficiency: Good on smooth terrain

Towing: Very good on proper surface

Complexity: High (with life support)

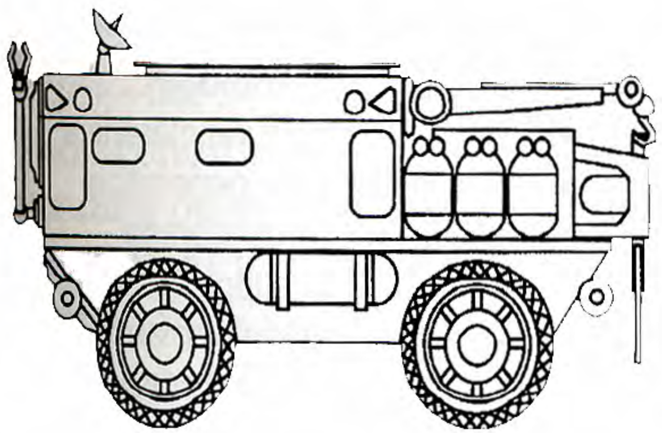
Lifetime: Indefinite with fuel and maintenance

Payload: 2-4 crewmembers, significant science

Terrain: Moderately rough, moderate slopes

Applications: Long-duration exploration sorties

Surface Mobility System Concepts

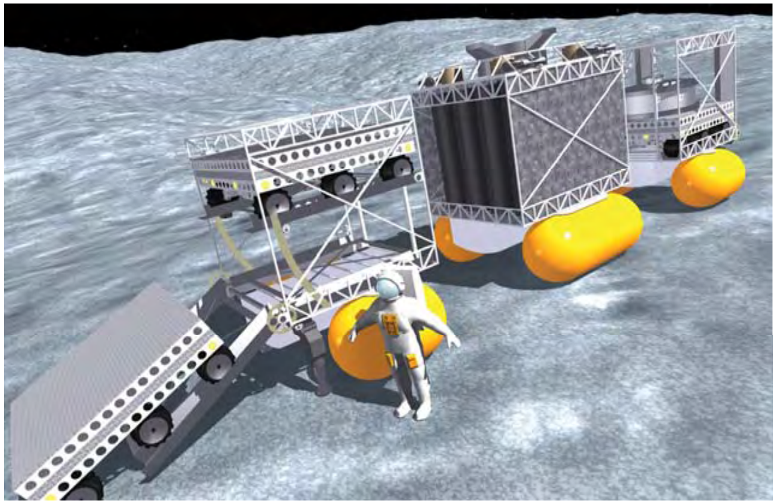


All-purpose Pressurized Utility Vehicle

Chassis: 5-10 m long, pressurized shell
Mobility System: 4-wheel electric motor drive
Operation: Human driver
Power: Batteries, fuel cells or RTG
Range: 200 km, depends on power available
Speed: Good on smooth terrain, power-limited
Energy Efficiency: Good on smooth terrain
Towing: Very good on proper surface
Complexity: High (with life support)
Lifetime: Indefinite with fuel and maintenance
Payload: 2-3 crew, cargo, moderate science
Terrain: Moderately rough, moderate slopes
Applications: Hauling, crew transport, construction

SICSA has conceptualized a multipurpose rover platform that can be adapted for a variety of functions using augmentation devices:

- All applications use a common wheeled platform system that incorporates battery power and automation/telerobotic control systems.
- In most cases, the functional augmentation devices are installed on the platforms prior to launch/landing, and are too large to be changed out on the surface by EVA crews.
- Multiple units can be launched together within a 12ft. diameter rocket shroud.



SICSA has investigated ways to deliver rovers and other large logistics payloads to lunar/Mars surfaces in support of human missions.

Logistics Carrier with Rovers

SICSA Multipurpose Rover Platform

Spool/ Winch:

- -spool carries power cable from RTG to module
- -winch for moving modules
- -extendable rods anchor the rovers for pulling

Cargo Carrier:

- -flexible cargo area adapts to modular containers of varying size
- -removeable guard rails secure payloads
- -automatically controlled

SICSA Multipurpose Rover Platform

Mobile Drilling Rig:

-hydraulic lift for multi-angle drilling
-revolving chamber with chuck bits extract core samples
-storage tubes provide assorted bits and core samples

Crew Transport:

-life support system located within each seat
-versatile storage areas with perimeter guards
-manual, teleoperated or automated control

SICSA Multipurpose Rover Platform

Mobile Power System:

- -automatically controlled
- -can provide power for rover fleet or backup power for habitats
- -maintenance tools and air supply stowage in chassis

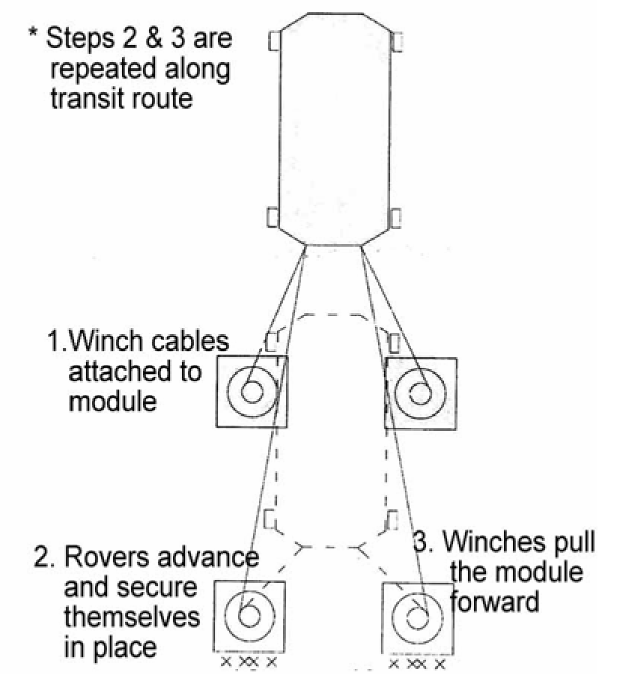
Crane:

- -360 degree range of movement for boom
- -box truss for light-weight telescoping structure
- -retractable outriggers for stability

SICSA Multipurpose Rover Platform

SICSA has proposed a special operational approach to enable a pair of rovers to move and position a large surface module under low-gravity conditions that greatly reduce wheel traction:

- Winch spindle cables are attached to the wheeled module through automated or crew-assisted interfaces.
- The two rovers advance forward along a pathway that avoids large rocks and other surface barriers, and then anchor themselves in place.
- Winches are used to pull and align the module along the pathway, and the procedure is repeated.



Surface Towing Approach

SICSA Multipurpose Rover Platform

Additional information relevant to this section can be found in Part II, Sections B, C, D and I of this SICSA Space Architecture Lecture Series titled Human Adaptation and Safety in Space, along with other publications listed below:

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AA	Antenna Assembly
ACS	Atmosphere Control and Supply or Attitude Control System
ACU	Audio Communication Unit, or Arm Control Unit
ADS	Audio Distribution System
AEHF	Advanced Extremely High Frequency
AFRSI	Advanced Flexible Reusable Surface Insulation
AOA	Abort Once Around
APAS	Androgynous Peripheral Attach
APC	Aft Power Controller
APCU	Assembly Power Converter
APU	Auxiliary Power Unit
ARS	Atmosphere Revitalization System
ATCS	Active Thermal Control System
ATVC	Ascent Thrust Vector Control
AV	Avionics
BC	Bus Controller
BCA	Battery Charger Assembly
BCDU	Battery Charge/ Discharge Unit
BEE	Base End Effector
BGA	Beta Gimbal Assembly
BIA	Bus Interface Adaptor
BSP	Baseband Signal Processor
BTU	Bus Terminal Unit
C&C	Command and Control
C&C MDM	Command and Control Multiplexer/ Demultiplexer
C&T	Communication and Tracking
C&TS	Communication and Tracking System
C&W	Caution and Warning
CAS	Common Attach System
CB	Control Bus
CBM	Common Berthing Mechanism
CC	Central Computer
CCA	Communication Carrier Assembly
CCAA	Common Cabin Air Assembly
CCPK	Crew Contaminant Protection Kit
CCTV	Closed Circuit Television
CCU	Crew Communication Umbilical
CDMK	Carbon Dioxide Monitoring Kit
CELSS	Controlled Ecological Life Support System
C&DH	Command and Data Handling
CDRA	Carbon Dioxide Removal Assembly
CHRS	Central Heat Rejection System
CMG	Control Moment Gyroscope
CO_2	Carbon Dioxide

ACRONYMS

CPC	Control Post Computer
CPU	Central Processing Unit
CRPCM	Canadian Remote Power Control Module
CSA	Canadian Space Agency
CSA-CP	Compound Specific Analyzer-Combustion Products
CTRS	Conventional Terrestrial Reference System
CVIU	Common Video Interface Unit
CWC	Contingency Water Collection
CWS	Caution and Warning Software
D&C	Display and Control
DA	Distribution Assembly
DBS	Digital Broadband System
DC	Direct Current
DCSU	Direct Current Switching Unit
DDCU	Direct Current-to-Direct Current Converter Unit
DDU	Digital Display Unit
DPS	Digital Processing System
DSC	Digital Signal Conditioner
EACP	EVA Audio Control Panel
EATCS	External Active Thermal Control System
ECLSS	Environmental Control and Life Support System
ECU	Electronics Control Unit
EE	End Effectors
ELV	Expandable Launch Vehicle
EETCS	Early External Thermal Control System
EF	Exposed Facility
ELV	Expandable Launch Vehicle
EMMI	EVA Man-Machine Interface
EMU	Extravehicular Mobility Unit
EPS	Electrical Power System
ERA	European Robotic Arm
ESA	European Space Agency
ESSMDM	Enhanced MDM
ETCS	External Thermal Control System
ETVCG	External Television Camera Group
EVA	Extravehicular Activity
EVVA	Extravehicular Visor Assembly
FAA	Federal Aviation Administration
FCC	Federal Communication Commission
FCS	Flight Control System
FDIR	Fault Detection, Isolation, and Recovery
FDS	Fire Detection and Suppression
FGB	Functional Cargo Block

ACRONYMS

ACRONYMS

FRCI	Fibrous Refraction Composite Insulation
FRGF	Flight Releasable Grapple Fixture
GEO	Geosynchronous Earth Orbit
GF	Grapple Fixture
GN_2	Gaseous Nitrogen
GN&C	Guidance, Navigation, and Control
GPC	General Purpose Computer
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
Hab	Habitation Module
HC	Hand Controller
HDR	High Data Rate
HGA	High Gain Antenna
HRFM	High Rate Frame Multiplexer
HRSI	High-Temperature Reusable Surface Insulation
HX	Heat Exchanger
IAA	Intravehicular Antenna Assembly
IEA	Integrated Equipment Assembly
IFHX	Interface Heat Exchanger
IMMI	IVA Man-machine Interface
IMU	Inertial Measurement System
IMV	Intermodule Ventilation
IP	International Partner
ISPR	International Standard Payload Rack
ISS	International Space Station
ITCS	Internal Thermal Control System
ITS	Integrated Truss Structure
IVA	Intravehicular Activity
JEM	Japanese Experiment Module
JEMEF	Japanese Experiment Module Exposed Facility
JEMPM	Japanese Experiment Module Pressurized Module
JEMRMS	Japanese Experiment Module Remote Manipulator System
JPL	Jet Propulsion Lab
JSC	Johnson Space Center
Lab	Laboratory Module
LAN	Local Area Network
LB	Local Bus
LCA	Lab Cradle Assembly, or Load Control Assembly
LCC	Launch Control Complex
LEO	Low Earth Orbit
LEE	Latching End Effector
LEM	Lunar Excursion Module
LGA	Low Gain Antenna

LH_2	Liquid Hydrogen
LOR	Lunar Orbit Rendezvous
LOX	Liquid Oxygen
LRSI	Low Temperature Reusable Surface Insulation
LSS	Life Support System
LTL	Low Temperature Loop
LVLH	Local Vertical/ Local Horizontal
MA	Main Arm
MAS	Microbial Air Sampler
MBM	Manual Berthing Mechanism
MBS	Mobile Remote Servicer Base System
MBSU	Main Bus Switching Unit
MCA	Major Constituent Analyzer, or Motor Control Assembly
MCAS	MBS Common Attach System
MCC	Mission Control Center
MCC-H	Mission Control Center-Houston
MCC-M	Mission Control Center-Moscow
MCS	Motion Control System
MCU	MBS Computer Unit
MCV	Microbial Check Valve
MDM	Multiplexer/ Demultiplexer
Mev	Mega-Electron Volt
MGA	Medium Gain Antenna
MLI	Multilayer Insulation
MM/ OD	Micrometeroroid/ Orbital Debris
MMU	Mass Memory Unit
MPD	Magnetoplasmadynamics
MS	Margin of Safety
MO&DA	Mission Operations and Data Analysis
MPLM	Multi-Purpose Logistics Module
MSFC	Marshall Space Flight Center
MSS	Mobile Servicing System
MT	Mobile Transporter
MTL	Moderate Temperature Loop
NASA	National Aeronautics and Space Administration
NASDA	National Space and Development Agency (Japan)
NSP	Network Signal Processor
OCS	Onboard Computer System
OGA	Oxygen Generator Assembly
OMS	Orbital Maneuvering System
OPF	Orbiter Processing Facility
ORU	Orbital Replacement Unit
PAS	Payload Attach System
PASS	Primary Avionics Software System
PCS	Portable Computer System

ACRONYMS

PDGF	Power and Data Grapple Fixture
PDIM	Power and Data Interface Module
PLSS	Primary Life Support System
PM	Propulsion Module
PMA	Pressurized Mating Adapters
PPA	Pump Package Assembly
PRSD	Power Reactant Storage and Distribution
psia	Pounds per square inch absolute
psid	Pounds per square inch differential
PTCS	Passive Thermal Control System
PV	Photovoltaic
PVA	Photovoltaic Array
PVCU	Photovoltaic Control Unit
PVM	Photovoltaic Module
PVR	Photovoltaic Radiator
PVTCS	Photovoltaic Thermal Control System
PWP	Portable Work Platform
PYR	Pitch, Yaw, and Roll
QD	Quick Disconnect
QF	Quality Factor
RA	Radar Altimeter
RACU	Russian-to-American Converter Unit
RAD	Radiation Dose
RAIU	Russian Audio Interface Unit
RAM	Random Access Memory
RCS	Reaction Control System
REM	Radiation Equivalent to Man
RF	Radio Frequency
RFG	Radio Frequency Group
RGA	Rate Gyro Assembly
RHX	Regenerative Heat Exchanger
RIP	Reusable Interface Panel
RLV	Reusable Launch Vehicle
RMS	Remote Manipulator System
RPDA	Remote Power Distribution Assembly
RPY	Roll, Pitch, Yaw
RS	Russian Segment
RSA	Russian Space Agency
RTAS	Rocketdyne Truss Attach System
RTG	Radioisotope Thermoelectronic Generator
RWS	Robotic Workstation
S&M	Structures and Mechanisms
SARJ	Solar Alpha Rotary Joint
SAW	Solar Array Wing
SAWD	Solid Amine Water Desorbed
SCWO	Supercritical Water Oxidation
SEU	Single Event Upset
SFCA	System Flow Control Assembly

SM	Service Module
SNAP	Space Nuclear Auxiliary Power
SPDA	Secondary Power Distribution Assembly
SPDM	Special Purpose Dexterous Manipulator
SPP	Science Power Platform
SRB	Solid Rocket Booster
SSAS	Segment-to-Segment Attach System
SSMDM	Standard MDM
SSME	Space Shuttle Main Engine
SSRMS	Space Station Remote Manipulator System
SSSR	Space-to-Space Station Radio
STDN	Spaceflight Tracking and Data Network
STS	Space Transportation System
TCCS	Trace Contaminant Control Subassembly
TCS	Thermal Control System
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TEA	Torque Equilibrium Attitude
THC	Temperature and Humidity Control
TLM	Telemetry System
TOCA	Total Organic Carbon Analyzer
TPS	Thermal Protection System
TRK	Tracking System
UB	User Bus
UHF	Ultrahigh Frequency
UOP	Utility Outlet Panel
VBSP	Video Baseband Signal Processor
VDS	Video Distribution Subsystem
VHS	Very High Frequency System
VLVS	Valves
VOA	Volatile Organic Analyzer
WCLS	Water Coolant Loop System
WCS	Waste Collection System
WM	Waste Management
WORF	Window Observation Research Facility
WRM	Water Recovery and Management
WSB	Water Spray Boiler
XPOP	X-Axis Pointing Out of Plane
X-Axis	Perpendicular or Orbit Plane
YPR	Yaw, Pitch, and Roll
ZOE	Zone of Exclusion

ACRONYMS