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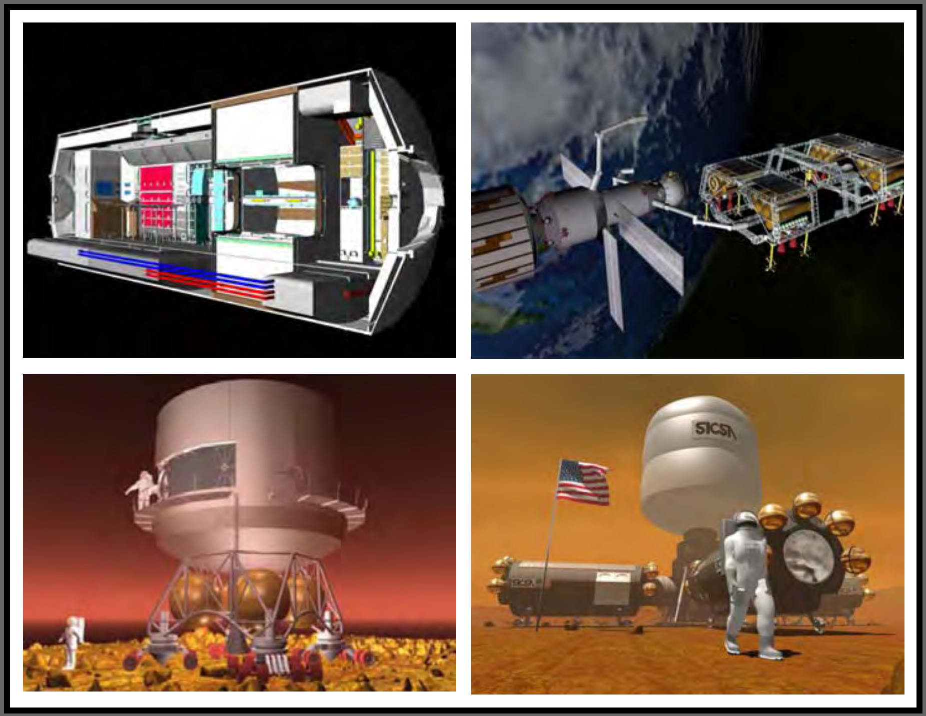
SICSA SPACE ARCHITECTURE
SEMINAR LECTURE SERIES

PART IV : SPACE MISSION AND FACILITY ARCHITECTURES



www.sicsa.uh.edu

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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.

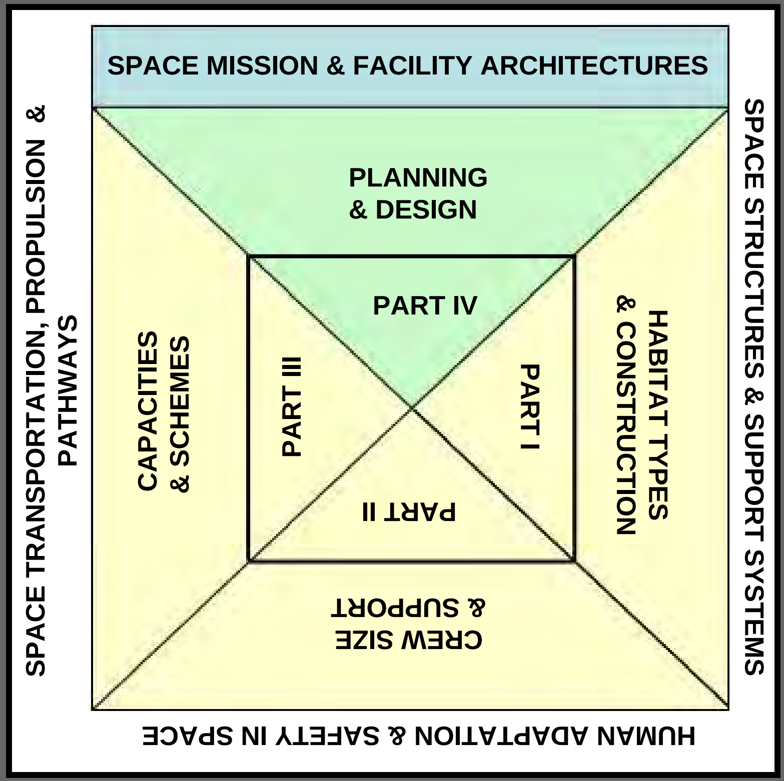
This report is offered in a PowerPoint format with the dedicated intent to be useful for academic, corporate and professional organizations who wish to present it in group forums. The document is the fourth in a series of seminar lectures that SICSA has prepared as information material for its own academic 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:	GROUP TWO:
Part I : Space Structures and Support Systems	Part V : The History of Space Architecture
Part II : Human Adaptation and Safety in Space	Part VI : The Nature of Space Environments
Part III : Space Transportation, Propulsion and Pathways	Part VII : Environmental Planning and Systems
Part IV : Space Mission and Facility Architectures	Part VIII : Shelter Design and Construction

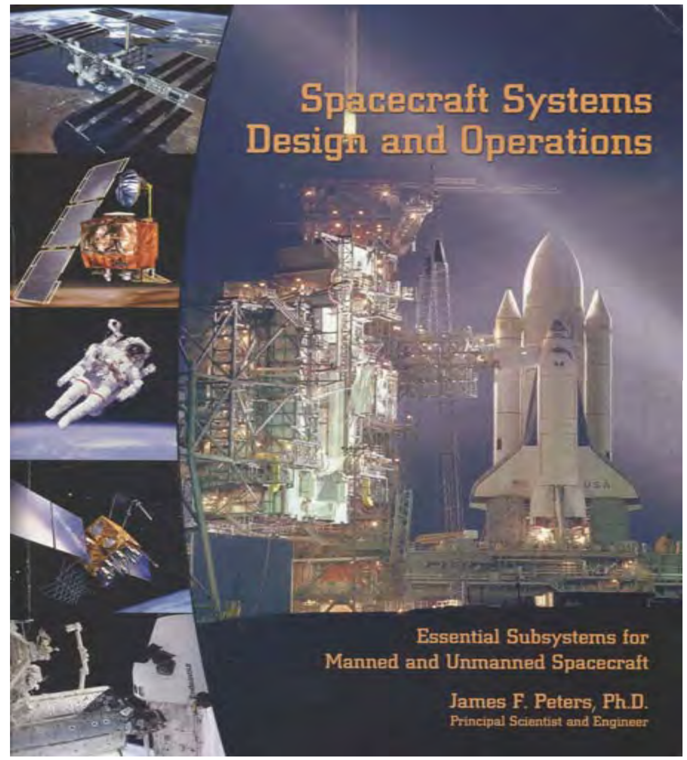
This lecture series provides comprehensive information, considerations and examples to support planning of human space missions and facilities:

- Part IV (this report) presents a “systems of systems” approach that connects together, applies and develops topics addressed in the three other parts :
  - Planning and design analyzes, selects and elaborates habitat types and construction features of essential Space Structures and Support Systems (Part I) based upon mission requirements.
  - Planning and design is guided by and is responsive to requirements for Human Adaptation and Safety in Space (Part II).
  - Planning and design is governed by capabilities, efficiencies and constraints associated with available Space Transportation, Propulsion and Pathways (Part III) which determine mission capabilities and schedules.



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

MS-SPACE ARCHITECTURE
SICSA

"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

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

Section A : Background

SPACE MISSIONS AND
FACILITY ARCHITECTURES

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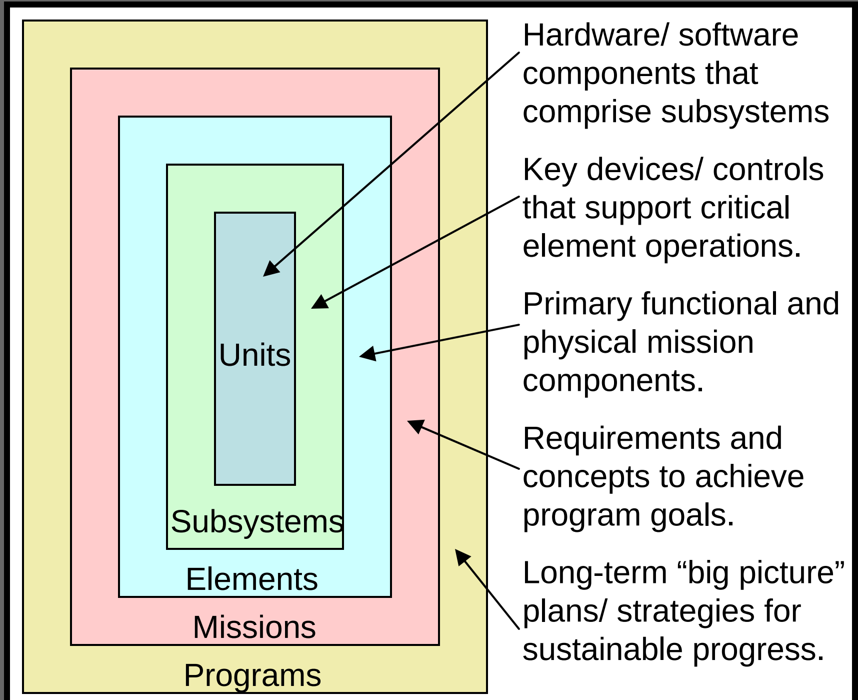
SECTION A: BACKGROUND

"Architectures" define and organize goals, requirements, strategies, concepts and components within coherent structures of logic and function that can be assessed and acted upon:

- They correlate priorities with means to achieve them.
- They present conceptual options and proposals involving programmatic policies/ budgets/ schedules, transportation and vehicle design, orbital trajectories and logistical systems.
- They establish functional interrelationships between mission objectives and human/ robotic operations and support accommodations.
- They co-exist within different levels of scale as systems within systems, and as interdependent systems of systems.



Hierarchy of Integrated Architectures

Systems of Systems

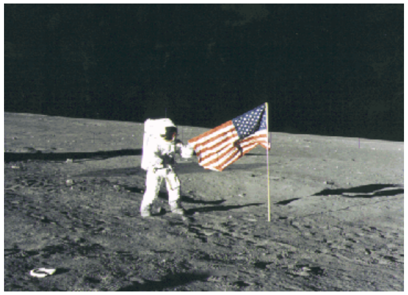
Current space program goals to explore the Moon, Mars and beyond through human and robotic campaigns embody large technological challenges which include the following:

- **Reduce costs and risks for space access :**
  - Develop a new Crew Exploration Vehicle system (CEV) to replace the Shuttle.
  - Develop transportation for crews/ cargo between LEO and the Moon and Mars.
  - Develop a Lunar Surface Access Module (LSAM) and Mars Surface Access Module (MSAM).
  - Develop a fail-safe crew Earth return capability addressing all abort contingencies.
- **Establish Moon/ Mars settlements :**
  - Develop communication satellite networks and precursor surveyor systems.
  - Use the Moon as a testbed/ laboratory for demonstrating Mars capabilities.
  - Apply and test ISRU technologies/ processes to reduce Earth resource dependence.
  - Create and test surface habitats, mobility systems and robotic aids.
- **Solve important scientific questions :**
  - The presence of accessible water and other precious materials on the Moon/ mars.
  - Evidence of previous or present life on Moon / Mars.
  - Lessons regarding the early history of Earth and its future.
  - Abilities of humans to safely adapt/ perform on extended missions beyond LEO.
- **Extend human presence into the Solar System :**
  - Robotic survey and precursor missions staged from Earth and space bases.
  - Development of advanced spacecraft to carry people and cargo over vast distances.
  - Lengthen human missions through advanced life support systems and ISRU applications.
  - Mitigate health/ safety risks from space radiation and debris hazards.

Representative Technology Challenges

Public opinion has important influences over NASA's planning of space program goals and achievements :

- Attitudes directly impact NASA budgets :
  - Accomplishments promote national pride and willingness to invest dollars.
  - Catastrophic accidents, technical failures, cost overruns and delays have opposite effects.
  - Businesses and jobs created by space programs generate public advocacy.
  - Scientific/ technological spin-offs and educational programs extend the support base.
- Sustained public support is essential :
  - Space program planning must be directed to exciting long-term visions.
  - Initiatives must appeal to a broad spectrum of stakeholder advocates.
  - The public desire for adventure must be counterbalanced by risk management.
  - Accomplishments must be substantial and regularly staged to hold public interest.



First Man on Moon

Skylab

Hubble Space Telescope

The Importance of Public Opinion

Leadership to establish and implement an effective space exploration program blueprint must overcome major planning impediments :

- **Reliable/ sustainable funding is uncertain :**
  - The volatile/ changing political, national and geopolitical landscape creates budgetary risks.
  - Long-term plans/ schedules are inconsistent with short Congressional cycles.
  - Space program funding must compete with a variety of other urgent national priorities.
  - NASA has been generally unsuccessful in attracting commercial partners/ users.
- **Competing priorities produce inefficiencies :**
  - Congressional districts influence roles and expenditures allocated to various centers.
  - Distribution of roles/ responsibilities assigned to different centers are sometimes duplicative.
  - Organization resource realignments and cutbacks often interrupt important initiatives.
  - Changing administrative policies and interests impair continuity.
- **Program setbacks/ delays are costly :**
  - Public reactions to catastrophic events can jeopardize programs.
  - Small subsystem failures can have devastating consequences.
  - Program development overruns can erode public/ political support.
  - Dependence upon contributions and performance of international partners creates uncertainties.
- **Experimental programs are risky by nature :**
  - Priority changes frequently work against efficient and productive R&D effects.
  - Competing science and technology priorities produce innovation, but often at high costs.
  - “Break-through” developments are difficult to predict and incorporate into plans.
  - Access to space for reliable in-place demonstration and testbed applications is limited.

Key Planning Impediments

Features of Merit (FOMs) identify key program planning and evaluation criteria, typically including priorities that follow :

- **Program Success :**
  - Near-term and long-range goals/ objectives
  - Scientific and technological advancements
  - Space exploration and development progress
  - National security applications/ benefits
- **Safety and Reliability :**
  - Risk minimization/ mitigation at all stages
  - Fail-safe emergency response countermeasures
  - System reliability and maintainability
  - Mission abort/ crew rescue contingencies
- **Affordability and Cost Effectiveness :**
  - Responsiveness to budgets and schedules
  - System development cost control
  - Launch facility and flight optimization
  - Reducing mission resupply requirements
- **Extensibility :**
  - "System-of Systems" modularity
  - Incremental technology upgrades
  - Elements that enable future campaigns
  - Commercial business opportunities

Features of Merit

Space exploration success will be subject to evaluation by a variety of different interest groups and perspectives :

- **Near-term and long-range goals/ objectives :**
  - Satisfy “stakeholder” requirements (the public, scientific community, education entities, business interests and military)
  - Optimize use of US and international assets
- **Scientific and technological advancements :**
  - Achieve longer lunar/ planetary stay times
  - Access multiple sites of interest
  - Accomplish comprehensive mission tasks
  - Develop/ test critical enabling systems
- **Space exploration and development progress :**
  - Understand new space environments
  - Identify in-situ resources and benefits
  - Apply/ test in-situ resource collection and processing
  - Demonstrate human and robotic capabilities
- **National security applications/ benefits :**
  - Utilize military launch/ enabling technologies
  - Develop cooperative communication networks
  - Coordinate scientific investigations
  - Protect sensitive information and systems

Program Success

Representative FOMs for Lunar / Mars Exploration

Safety and reliability is vital to the crew, to the mission and to the future of "the program" :

- **Risk minimization/ mitigation at all stages :**
  - Earth launch and crew return
  - Trans-lunar/ trans-Mars Injection (TLI /TMI)
  - Surface descent and ascent (crew and cargo)
  - Trans-Earth Injection (TEI)
- **Fail-safe emergency response countermeasures :**
  - Solar proton storms
  - Space debris hazards
  - On-board fires and pressure failures
  - Crew accidents/ injuries and illnesses
- **System reliability and maintainability :**
  - Backup systems for all critical failures
  - Parts and spares for vital equipment
  - Tools and maintenance accommodations
  - Fault error detection and response protocols
- **Mission abort/ crew rescue contingencies :**
  - Anytime Earth return from any orbit
  - Rescue for stranded surface astronauts
  - Safe havens for habitat failures
  - Return to base for stranded EVA crews.

Safety and Reliability

Representative FOMs for Lunar / Mars Exploration

Affordability and cost effectiveness will determine how much can be accomplished, when and whether the program will have sustained public support :

- **Responsiveness to budgets and schedules :**
  - Budget timelines for enabling technology
  - Correlation with Congressional funding cycles
  - Milestone achievements for public support
  - Launch and development facility optimization
- **System development cost control :**
  - Establishing practical performance standards
  - Standardization of component systems
  - Utilization of demonstrated hardware
  - Outsourcing to proven commercial suppliers
- **Launch facility and flight optimization :**
  - Leverage use of existing facility capabilities
  - Select most efficient/ safe orbital trajectories
  - Develop more efficient advanced propulsion systems
  - Demonstrate automated rendezvous/ refueling
- **Reducing mission resupply requirements :**
  - Minimize crew size and consumables
  - Minimize EVAs and airlock resupply
  - Demonstrate/ utilize in-situ resources
  - Extend surface missions to reduce rotations

Affordability and Cost Effectiveness

Representative FOMs for Lunar / Mars Exploration

Planning for extensibility requires a holistic long-term vision of what is possible and necessary for continued space exploration and development :

- **"System-of systems" modularity :**
  - Develop long-range "Mars and beyond" plan
  - Design/ utilize common Moon/ Mars elements
  - Emphasize a "kit of parts" equipment approach
  - Provide versatility to adapt to evolutionary needs
- **Incremental technology upgrades :**
  - Apply a "plug-n-play" system scheme
  - Utilize standard interfaces for upgrades
  - Use ISS as a testbed for the Moon
  - Use the Moon as a testbed for Mars
- **Enabling elements for future campaigns :**
  - Regenerative closed life support systems
  - Advanced propulsion systems
  - Nuclear and other power systems
  - Robotics and surface mobility devices
- **Commercial business opportunities :**
  - New launch vehicles and resupply services
  - Possible Moon-based astronomy
  - In-situ resource utilization and power
  - Space advertising and tourism

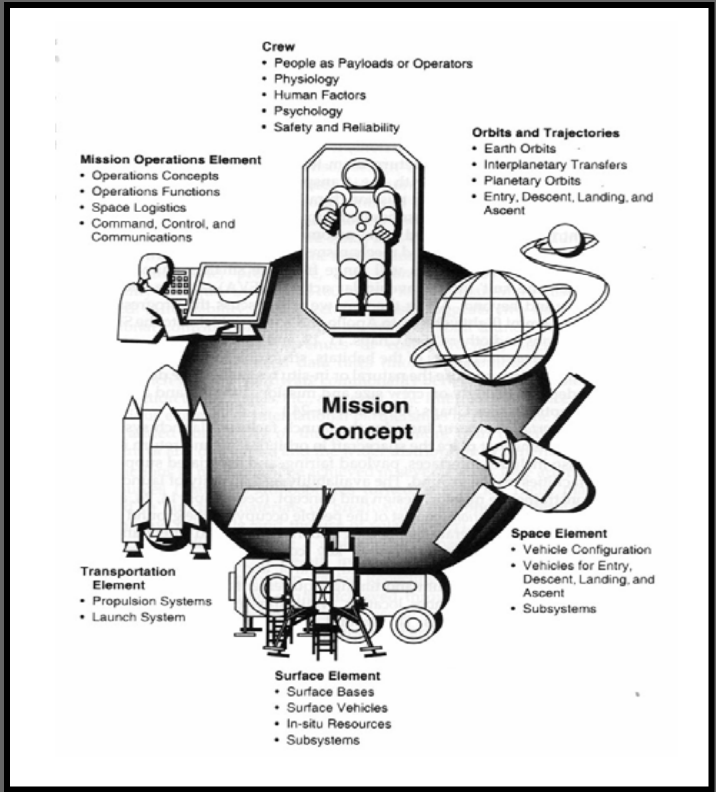
Extensibility

Representative FOMs for Lunar / Mars Exploration

HUMAN SPACEFLIGHT

Mission architectures conceptualize requirements and responses to program development challenges :

- Mission plans define broad campaign objectives, requirements and constraints :
  - What needs to be accomplished, when and how.
  - Physical and functional elements to be addressed.
  - Critical design drivers that will influence success.
  - Concept approaches subject to option trade studies.
- Mission elements are the primary plan components that must be developed and integrated :
  - They establish crew mission priorities.
  - They correlate transportation options and needs.
  - They establish orbit trajectories and schedules.
  - They identify habitat facility requirements.

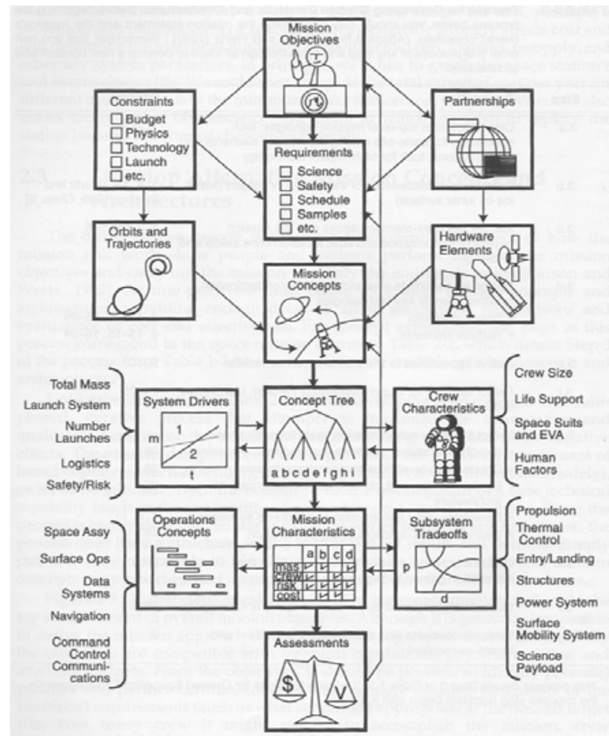


Plans & Key Elements

HUMAN SPACEFLIGHT

Trade Study Steps :

1. Define broad mission objectives:
   - How does the mission support the program?
2. Define requirements and constraints:
   - What governs option selections/ evaluations?
3. Propose alternative concepts/ architectures:
   - What broad approaches are possible?
4. Identify design drivers and critical requirements:
   - Which key parameters will influence success?
5. Select a baseline concept and architecture:
   - What philosophy/ approach appears most promising?
6. Define "top-level" element requirements:
   - What are their operating modes and subsystems?
7. Compare concept benefits with alternate approaches:
   - What lessons can be learned and applied?
8. Iterate and integrate the design:
   - What revisions and requirements are necessary?

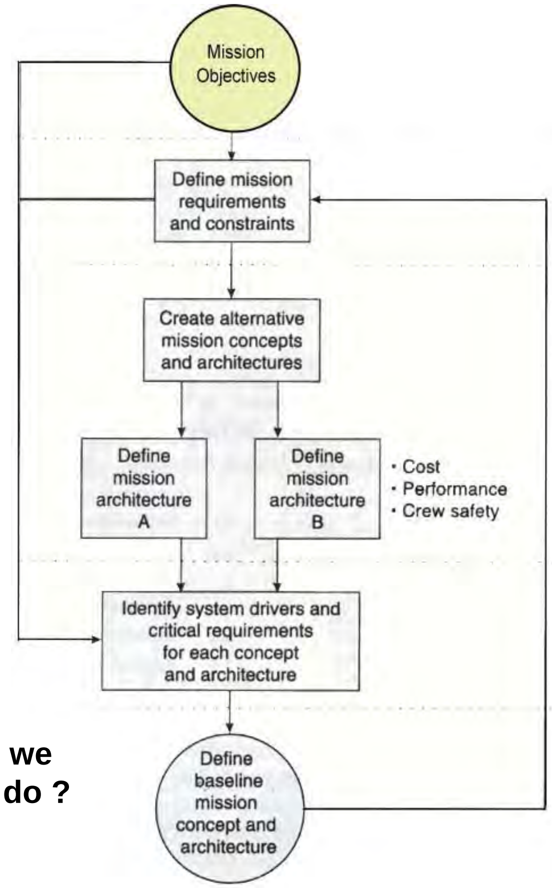


Planning Process & Considerations

The first step in developing a mission concept is to define mission objectives which clarify broad goals that must be achieved:

- Space missions typically have primary and secondary objectives:
  - Primary objectives emphasize what a particular element or system must do to be effective and useful.
  - Secondary objectives frequently include desired political, social/ cultural and economic outcomes that are also important.
  - While primary objectives usually tend to be stable, secondary objectives may shift in response to evolutionary needs.

Adapted from Larson & Wertz (1992)



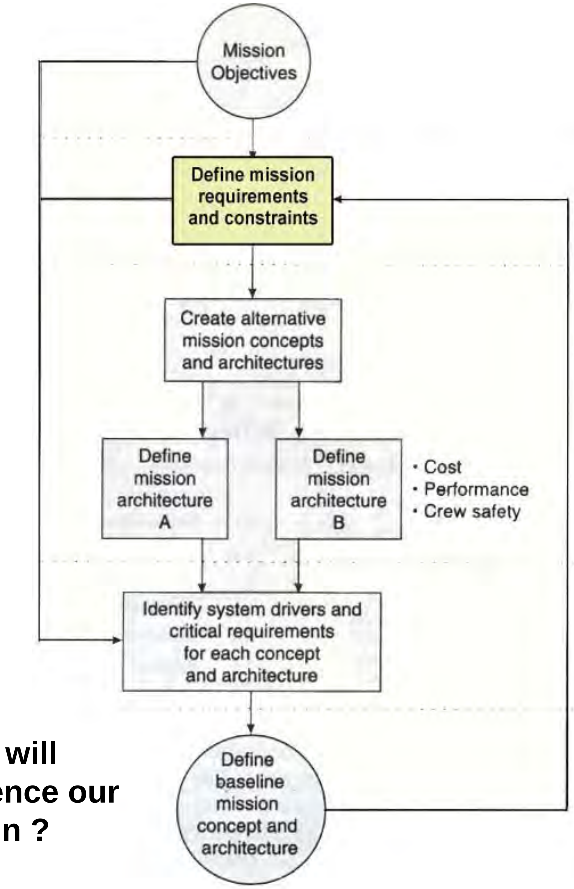
What are we trying to do ?

Establishing Objectives

After broad mission objectives have been established, they must be transformed into requirements and constraints that will influence operations and performance:

- Three general areas of consideration are primarily addressed:
  - Functional requirements define how well the mission concept must perform to meet its objectives.
  - Operational requirements determine how the mission concept must be conducted, and how elements and users must interact to achieve broad objectives.
  - Constraints that limit budgets, schedules and approaches for carrying out the mission.

Adapted from Larson & Wertz (1992)



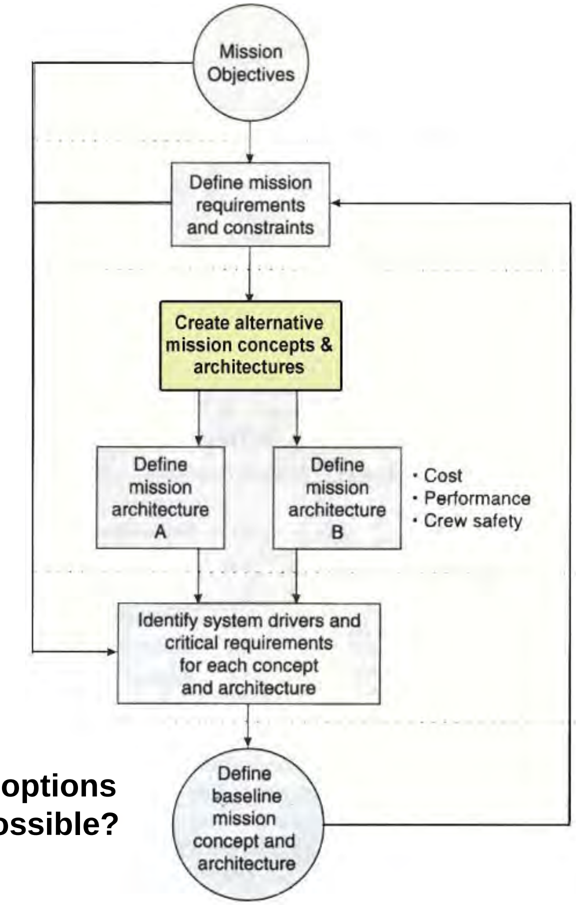
What will influence our design ?

Defining Requirements

Developing top-level mission concepts typically involves the following considerations:

- **Crew safety :** Designs that emphasize system reliability and means for crew aborts and escapes.
- **Technology maturity :** Use of proven systems to reduce development time/ cost and failure risks.
- **Degree of life support system closure :** Determining resupply logistics based upon crew size/ mission length.
- **Tasking and scheduling :** Influenced by assumptions regarding crew vs. use of automated systems.
- **Communications :** How to transfer and manage information between crew-ground and other elements.
- **Timelines :** Overall schedule from concept definition through production, operations, and end-of-life.

Adapted from Larson & Wertz (1992)



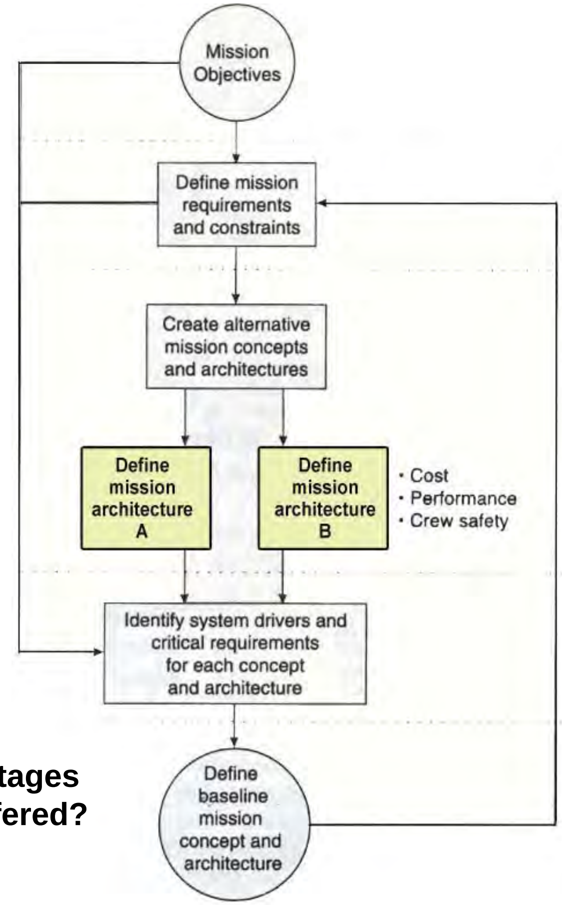
What options are possible?

Exploring Possibilities

Alternative mission concepts must be proposed and compared to determine special attributes, advantages and disadvantages of each, including cost, performance and safety. Representative considerations include :

- Crew size influences upon facility volume:
  - Number/ skills needed; EVAs planned; and consumables, equipment and robotic support.
- Transport vehicles and habitat facilities:
  - Launch capacities vs. living quarters and lab volumes/ mass and resupply requirements.
- Orbits and transfer trajectories:
  - Travel, dwell and return times/ windows, abort/ rescue strategies and propellant costs.
- Mission operations approach:
  - Communications infrastructure, crew rotations, and logistics schedules based upon elements used.

Adapted from Larson & Wertz (1992)



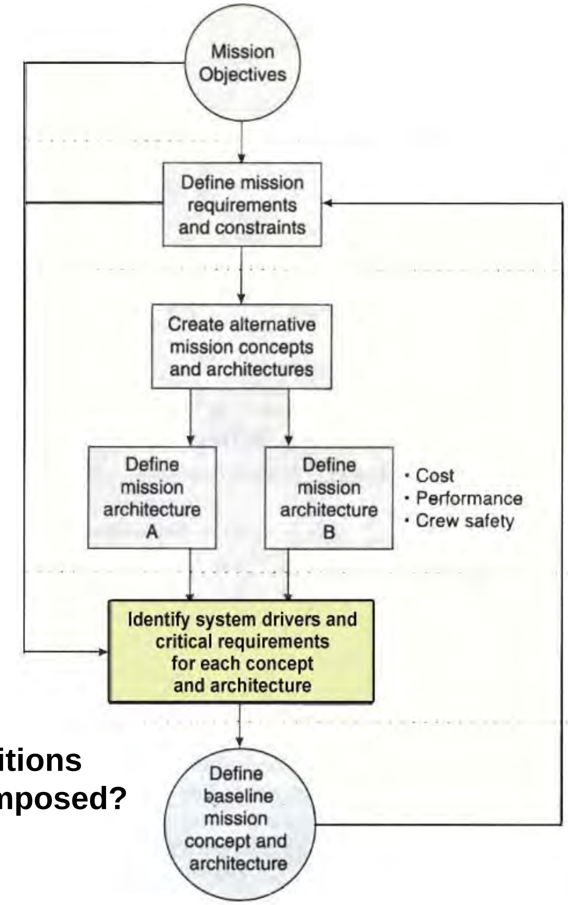
What advantages are offered?

Comparing Approaches

Trade study comparisons of alternative mission architectures provide a basis for determining special system drivers and requirements that may not have been previously apparent. Potential insights may include a better understanding of :

- Number of crew members influencing habitable volume, ECLSS/ consumables, power and task/EVA schedules.
- Number of launches influencing costs and schedules driven by requirement vs. vehicle payload capacities.
- Mass delivery amounts, destinations and schedules driven by transportation elements, trajectories and launch/ return windows.
- Habitat and logistics design constraints including launch payloads, orbital assembly, and lunar/ planetary surface landing/ deployment.

Adapted from Larson & Wertz (1992)



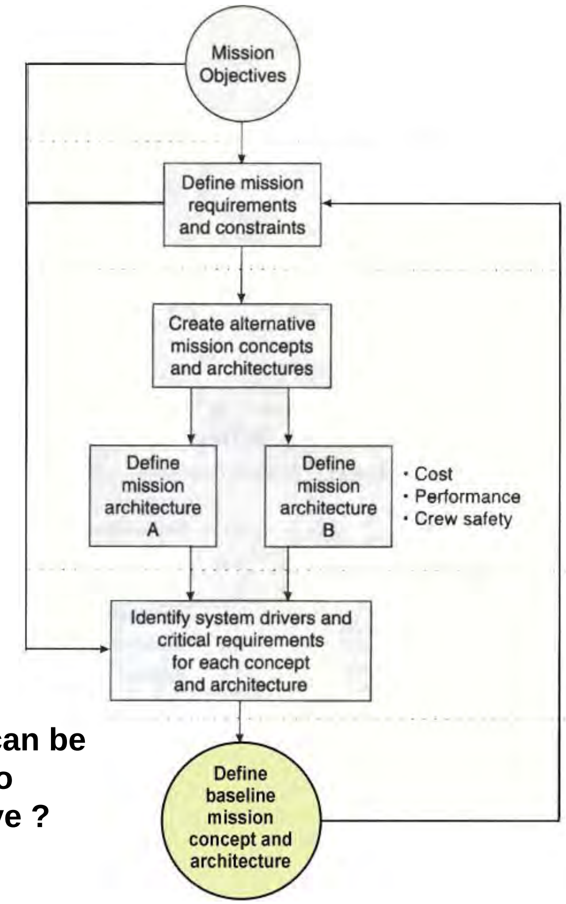
What conditions are imposed?

Defining Design Critical Factors

BACKGROUND

MISSION ARCHITECTURES

Adapted from Larson & Wertz (1992)



What can be done to improve ?

Mission planning is fundamentally an interactive process which involves a large number of ongoing trade studies at all architecture levels. A primary objective is to develop a final baseline to guide definitive element design:

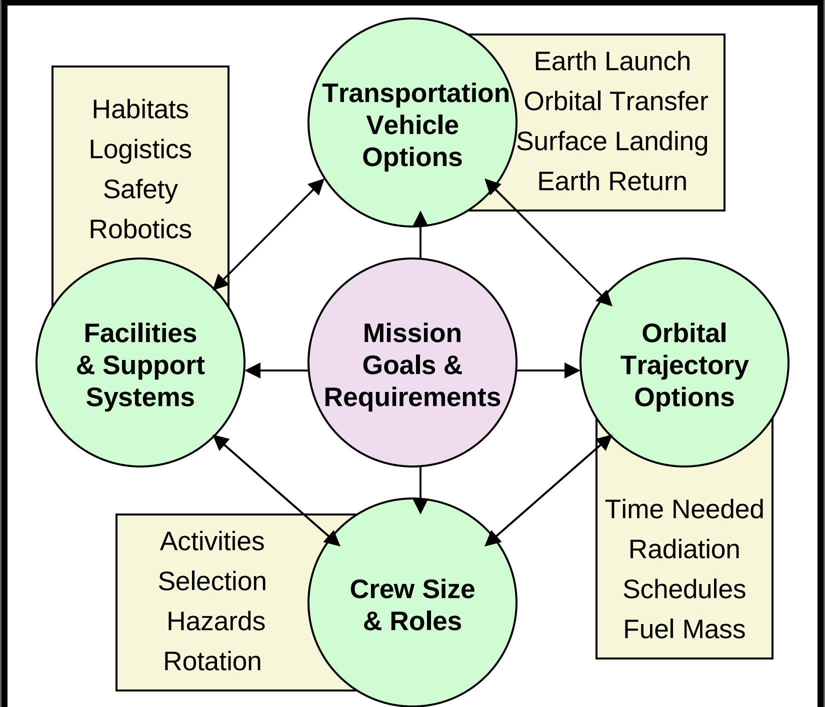
- Baseline concepts/ architectures provide information that enables reassessments/ refinements of earlier mission requirements and constraints:
  - They support improved understanding of element design and operating parameters.
  - They enable more realistic estimates of mission costs and risks.
  - They indicate which general element concepts will most likely meet foundation mission objectives.

Creating Baselines

SICSA's characterization of element architectures as a separate category within broader mission architectures is a departure from other reference sources that lump them together. This is done to give special attention to interrelationships between element selection and design decisions.

Four general types of interdependencies are of particular importance in developing architectures for human missions.

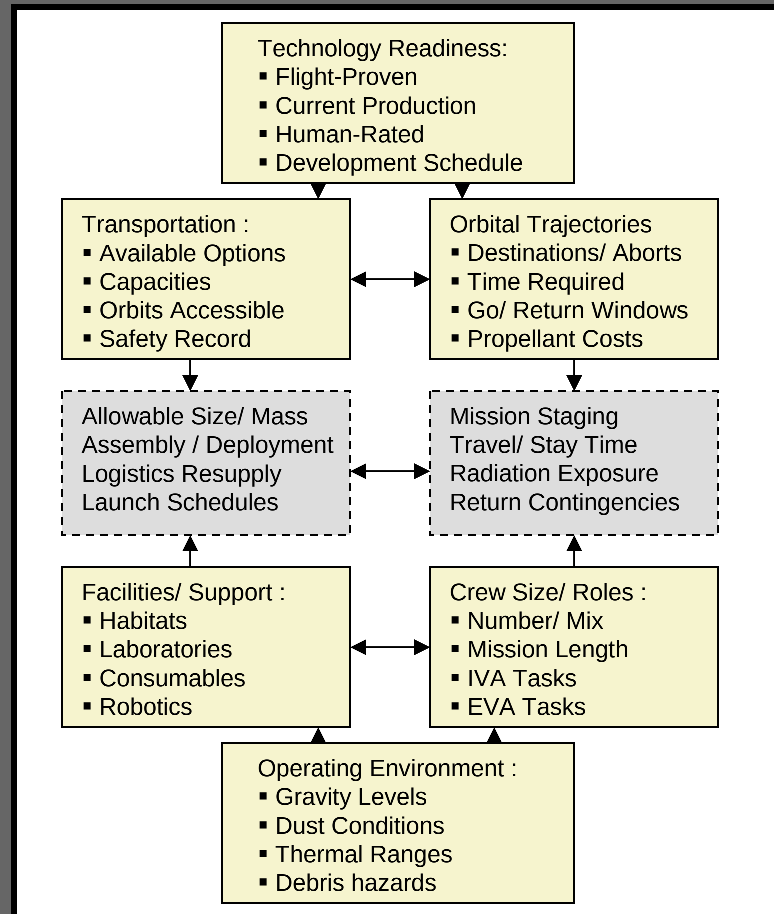
- Transportation vehicle options that size and constrain facilities, operations and schedules.
- Orbital trajectory options that determine time, risks and costs to deliver people and cargo.
- Crew size and role assumptions that influence what can be accomplished on each mission.
- Facilities and support systems that will be needed to support human and robotic functions.



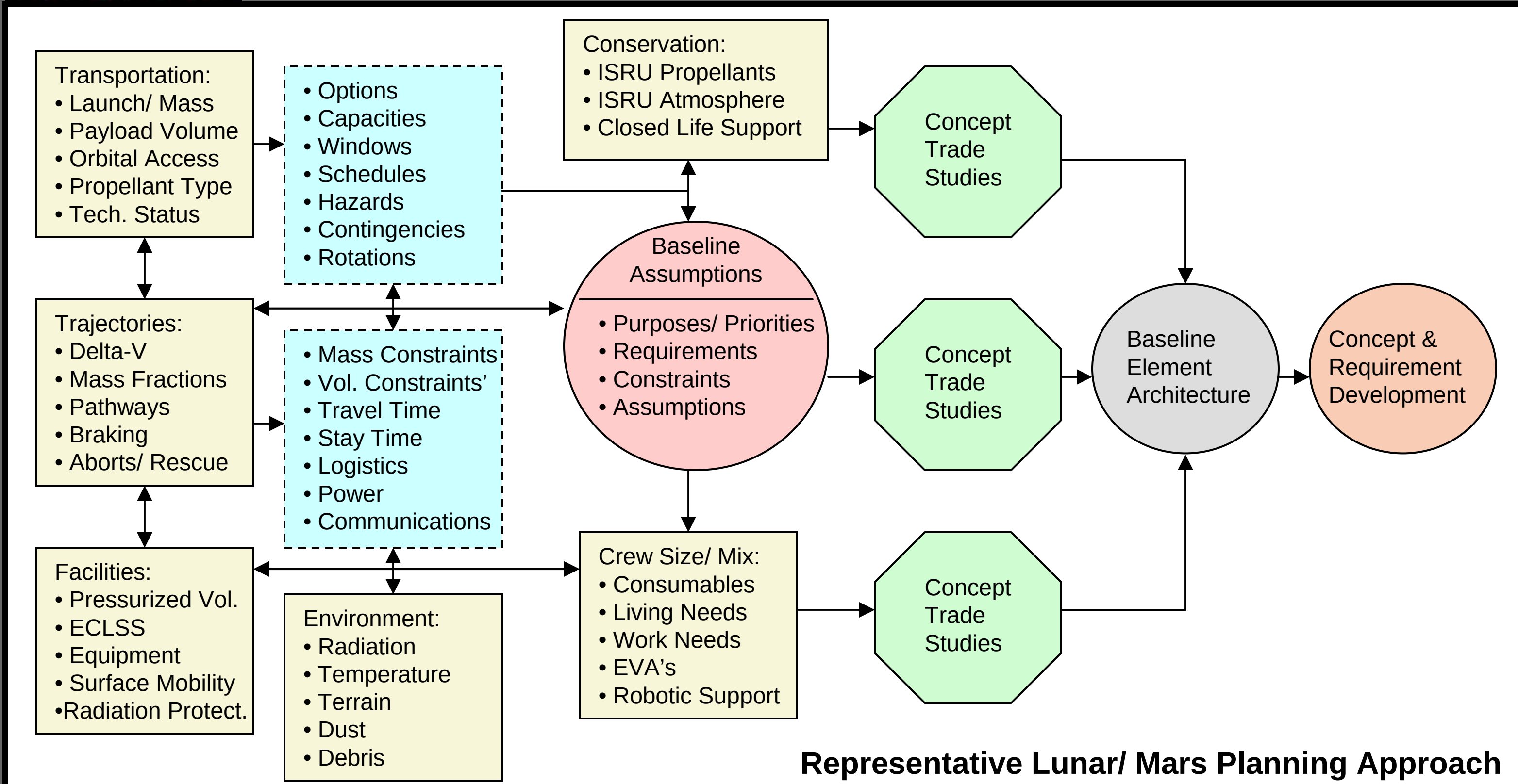
Interdependent Design Determinants

First order baseline assumptions must address a variety of interrelated mission drivers:

- Transportation Vehicles :
  - Launch from Earth to LEO
  - Transfers to lunar and Mars orbits
  - Surface landing/ ascent and Earth reentry
- Orbital Trajectories :
  - Pathways to Moon and surface sites
  - Pathways to Mars and surface sites
  - Abort opportunities and strategies
- Crew Size/ Roles :
  - Scientific activities (EVA and IVA)
  - Mission operations and health maintenance
  - Housekeeping and equipment maintenance/ repair
- Facilities/ Support :
  - Pressurized habitats and laboratories
  - Logistics delivery and stowage
  - Robotic aids and surface mobility systems



First Order Considerations



Representative Lunar/ Mars Planning Approach

First Order Relationships

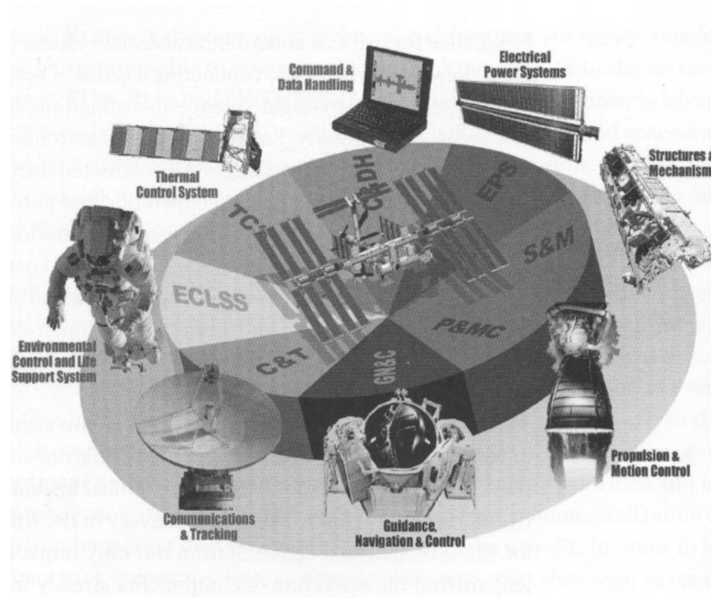
Destination Environment:	Transport Vehicle Options:	Orbital Trajectories:	Crew Size & Mix:
▪ Terrain features influencing landing & surface mobility.	▪ Thrust characteristics vs. engine/ tank size.	▪ Influences on vehicle selection & efficiencies.	▪ Food & water consumption correlated with stay time.
▪ Gravity levels influencing operations & transport.	▪ Propellant storage & engine restart capabilities.	▪ Influences on solar radiation & debris exposure.	▪ Pressurized volume to support living and work.
▪ Thermal ranges impacting equipment systems.	▪ Propulsive vs. aerobraking @ destination and Earth.	▪ Influences upon abort & Earth return systems.	▪ Mass/volume impacts on launch/ landing options.
▪ Dust, influences on EVAs & equipment maintenance.	▪ Propulsive vs. parachute landing on Mars.	▪ Influences upon mission windows/ schedules.	▪ Atmosphere/ equipment to support EVAs.
▪ In-situ resources for propellant & atmosphere.	▪ Lander thrust ejecta influences on site planning.	▪ Influences on travel and surface stay times.	▪ Power requirements to support crew operations.
▪ Proximity to equator for ascent efficiency.	▪ Surface mobility vehicles and operations.	▪ Influences on access to priority sites.	▪ Sizing of abort/ crew return vehicles.

Representative Strategic Planning Determinates for Human Lunar/ Mars Missions

Planning Drivers

Major space elements such as transportation vehicles, orbital habitats and surface modules rely upon many interdependent systems for safe and reliable operations. Included are:

- Structures and mechanisms that contain habitat pressure and utility-element interfaces.
- Electrical power systems that supply, manage and distribute energy for all equipment and operations.
- Thermal Control Systems (active and passive) to control onboard temperatures within specific ranges.
- Environmental Control & Life Support Systems to maintain proper humidity and air purity levels.
- Command & Data Handling to manage computing and information distribution functions.
- Guidance, Navigation & Control to keep orbital spacecraft on desired flight paths.
- Propulsion & Motion Control to maintain orbital spacecraft in proper orientation attitudes.
- Communications & Tracking to link the spacecraft to ground and space mission control networks.

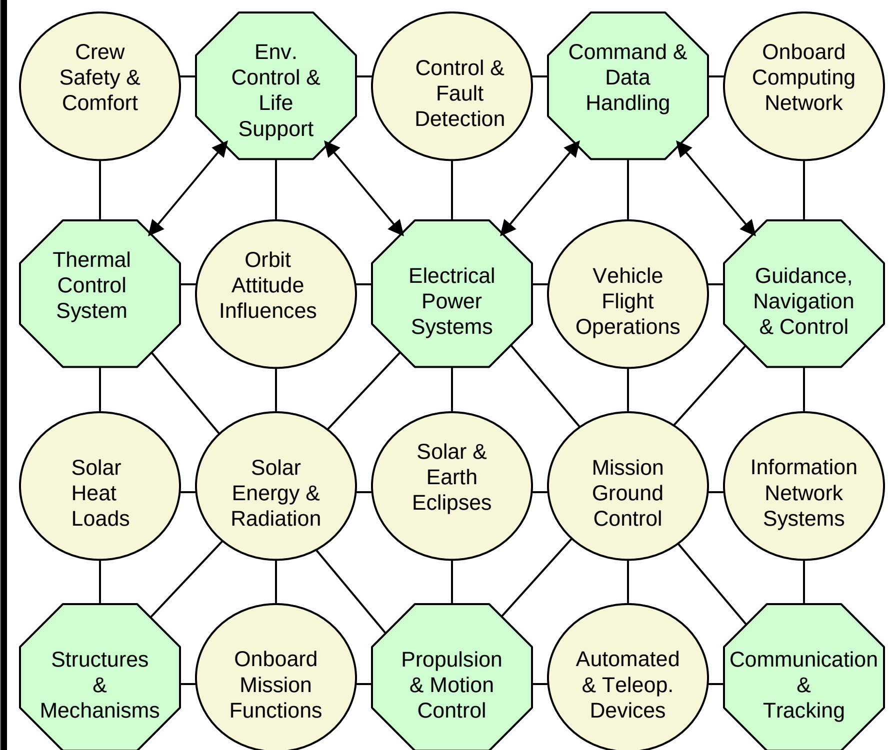


Essential Subsystems

Systems of Subsystems

Space architecture entails optimization of interdependent relationships between systems at all levels through holistic integrated planning. For example:

- Photovoltaic power and heat loads impacting structures, ECLSS and thermal control systems are impacted by spacecraft orientation to the Sun managed by Propulsion and Motion Control.
- ECLSS may share/ exchange water and oxygen with power fuel cells, and use power and thermal control radiators to dump waste heat.
- Power and information management/ distribution must be integrated with all other functions, including motion control, guidance/ navigation, and communication/ tracking networks.



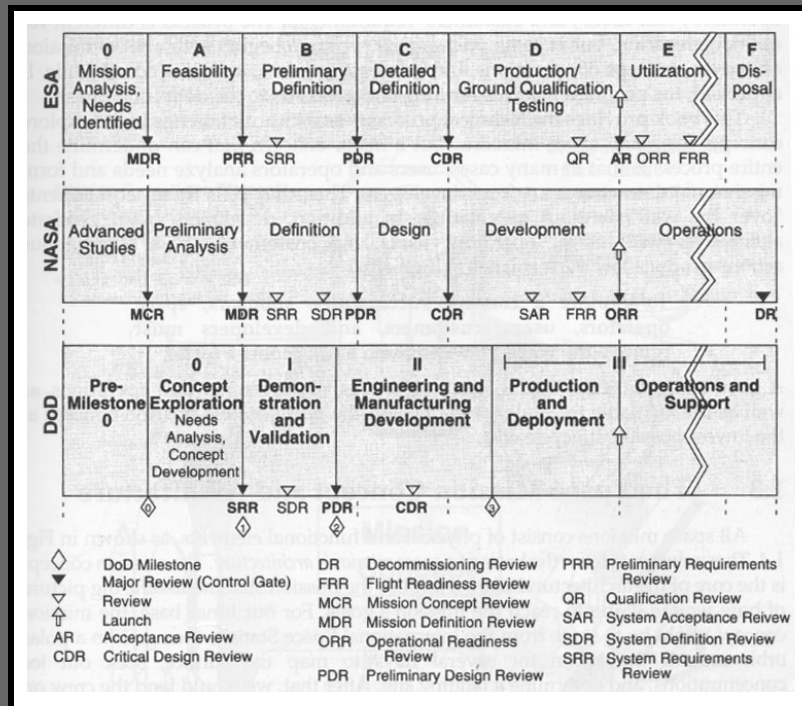
Interdependent Relationships

Integrated Planning

HUMAN SPACEFLIGHT

NASA's planning, design, development and test evaluations for major program elements, subsystems and scientific equipment items involves four general phase stages:

- Phase A is based upon identified mission support needs and makes preliminary assessments of feasibility, performance parameters, budgets and development schedules.
- Phase B/C undertake design and ground tests/ simulations to demonstrate proof of concept and determine necessary requirements, improvements and costs.
- Phase D develops and tests prototypes using ground and flight experiments (if possible) to determine operational readiness.



Planning, Development & Evaluation Phases

BACKGROUND

SUBSYSTEM ARCHITECTURES

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Phase A – Preliminary Analysis :

- A preliminary design and project plan is developed which may satisfy the following :

– Description and performance requirements.

– When and how the item will be used.

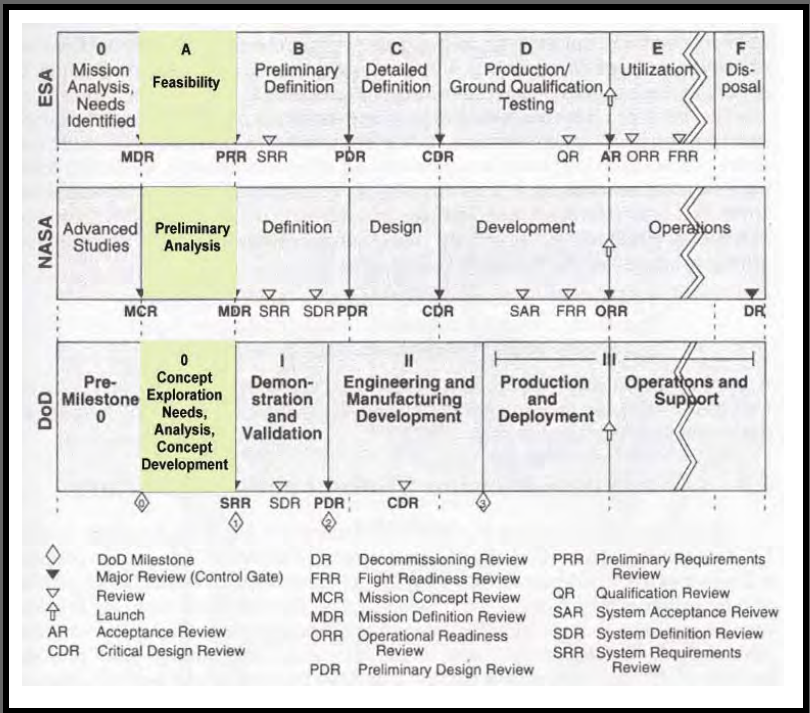
– What flight activities will be necessary.

– Which components will be developed vs. purchased.

– What tests and qualifications must be conducted.

– Essential interfaces with other systems.

– Projected design and development costs.



Phase A Activities/ Products

BACKGROUND

SUBSYSTEM ARCHITECTURES

Phase B – Definition :

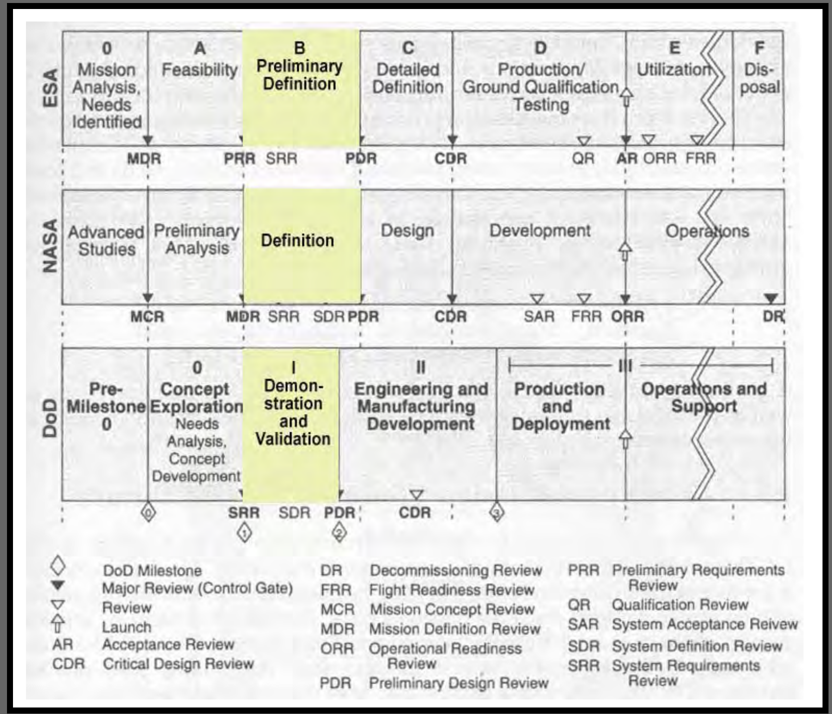
- The preliminary plan is converted into a baseline technical solution :

– Detailed requirements and schedules are determined.

– Specifications are prepared to initiate R&D.

– System requirement, design and outside “non-advocate” reviews are conducted to introduce new ideas and proposed modifications.

– A subcommittee from NASA Headquarters will evaluate/ approve value, costs, engineering design and safety.



Phase B Activities/ Products

HUMAN
SPACEFLIGHT

Phase C – Design :

- Final schedules are negotiated and determined for the system through a process called Assembly, Test and Launch Operations (ATLO):

– System components/ prototypes are developed and tested on Earth and/ or in space.

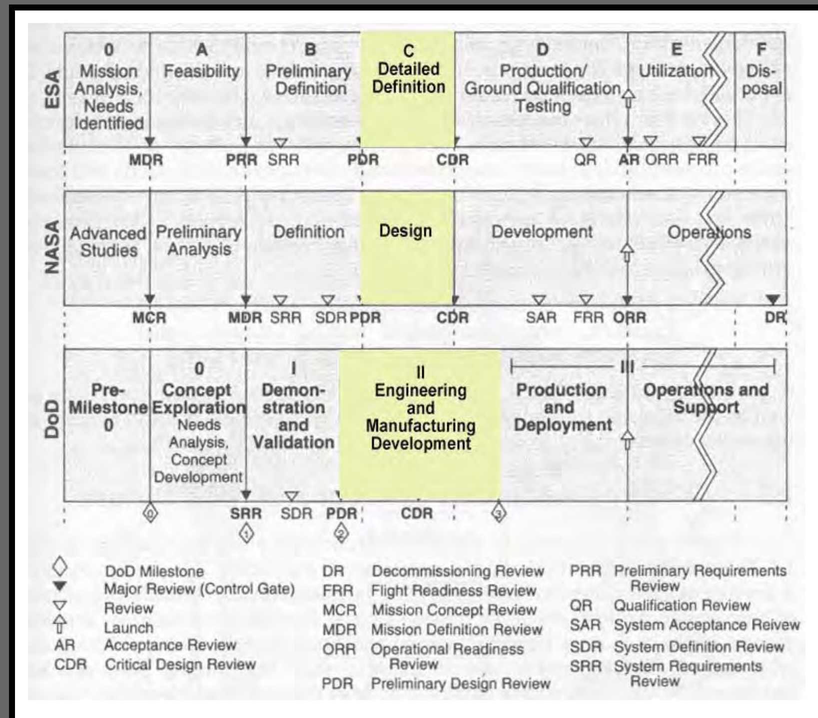
– Ground systems to support operations are developed in parallel and demonstrated along with systems tests.

- Phase C typically lasts until 30 days after launch, and major reviews are often conducted during the R&D phase:

– Preliminary Design Reviews (PDRs)

– Critical Design Reviews (CDRs)

– Test Readiness Reviews (TRRs)



Phase C Activities/ Products

Phase D – Development :

- This phase involves test system or prototype development for ground qualification testing and often overlaps Phase C :

– Proof of performance experiments and simulations are conducted for ground qualification tests.

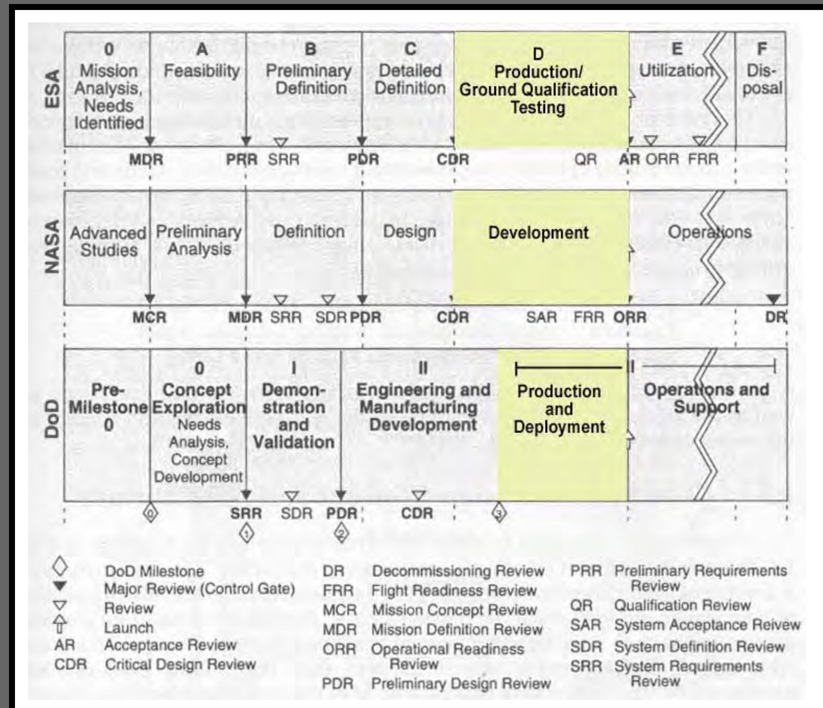
– Flight tests are conducted if possible through evaluations often referred to as Mission Operations & Data Analysis (MO&DA).

- Phase D typically involves major reviews :

– System Acceptance Reviews (SARs)

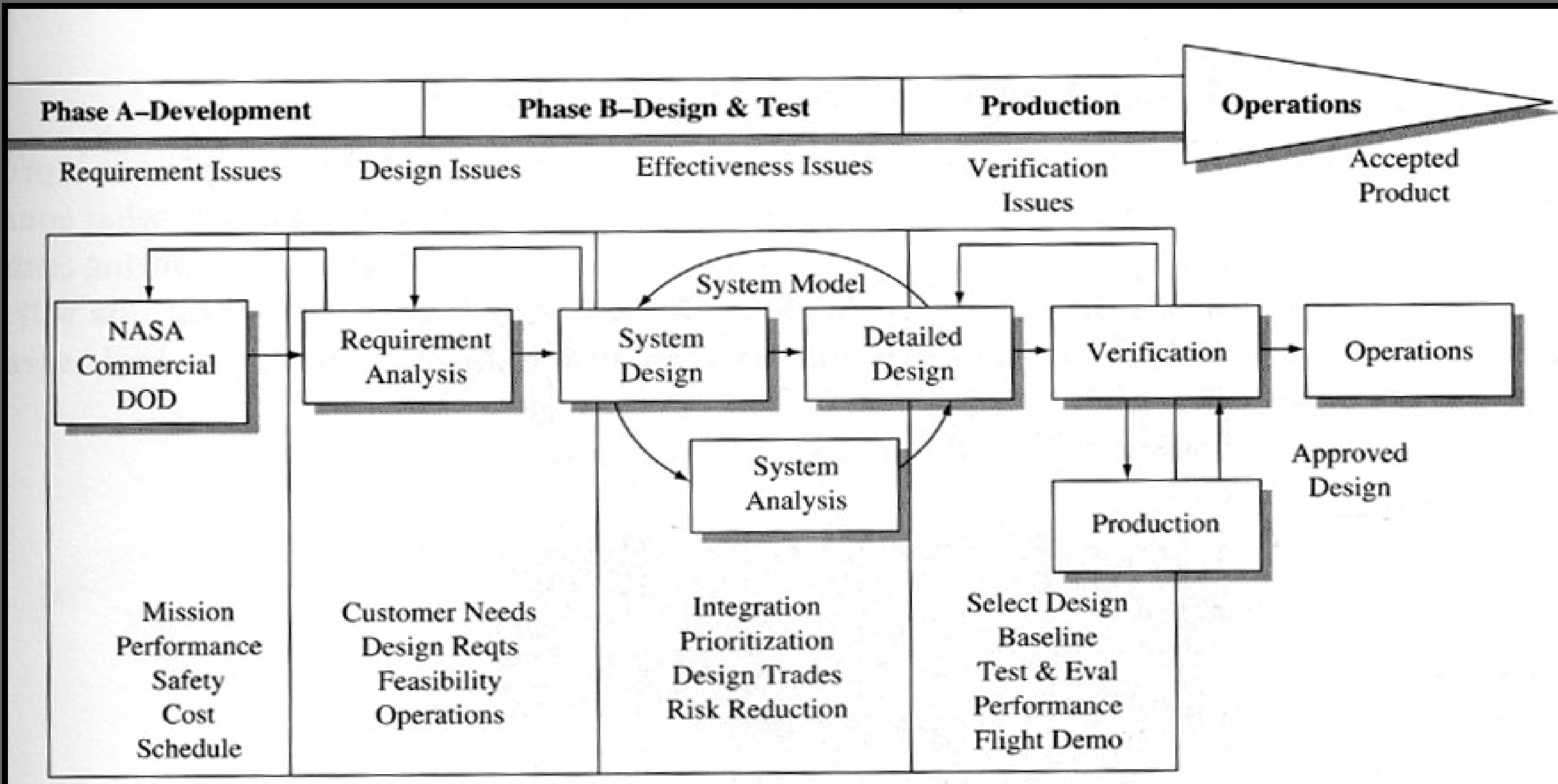
– Flight Readiness Reviews (FRRs)

– Operational Readiness Reviews (ORRs)



Phase D Activities/ Products

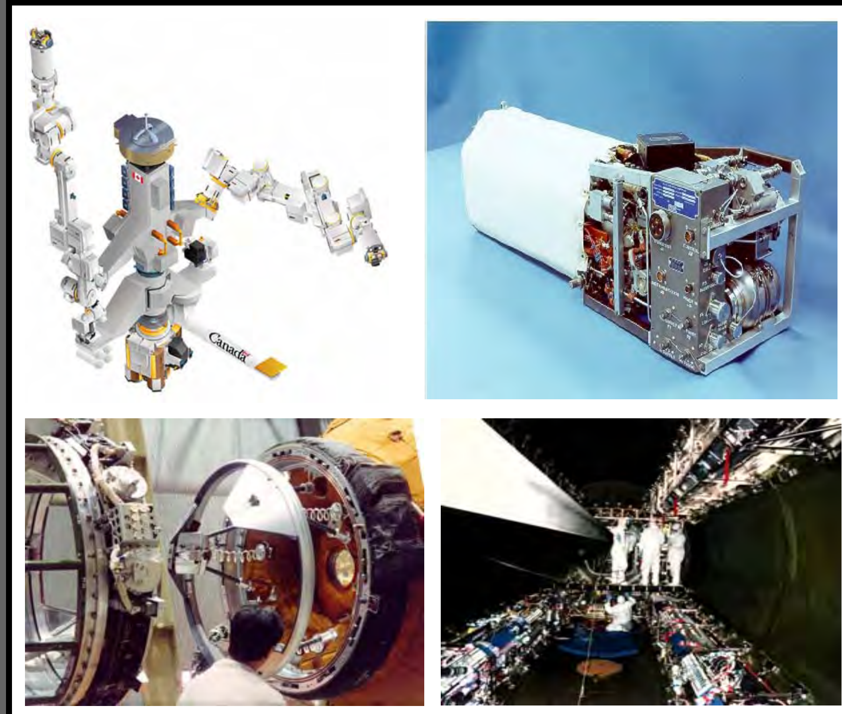
SPACECRAFT SYSTEMS DESIGN & OPERATIONS



Product Life Cycle Overview

The term “unit” is used as a greatly oversimplified generic category for general illustrative purposes, and encompasses an enormous variety of subsystem components. Many of these parts can be accurately viewed as system and subsystem architectures within larger system and subsystem architectures. They include:

- Equipment racks and functional units, including experiment racks, crew personal hygiene compartments, and robotic workstations.
- Utility assemblies and interfaces that distribute and control fluids, gases and data.
- Operational Replacement Units (ORUs) that are designed with plug-in features enabling rapid and easy change-out of an experiment or critical functional equipment system.
- Hardware and devices, including truss structures, hatches, robotic systems and mechanical connections.



Subsystems of Subsystems

Structures & Mechanisms:	Thermal Control Systems:	Propulsion & Motion Control:	Guidance, Navigation & Control
▪ Pressurized elements ▪ Viewports & airlocks ▪ Utility systems/ interfaces ▪ Berthing/docking mechanisms ▪ Trusses/ attachments ▪ Robotic systems/workstations	▪ Passive insulation/ coatings ▪ Fluid loops/ pumps/ valves ▪ Electric heaters ▪ Heat pipes & cold plates ▪ Active & passive radiators ▪ Multiplexers/ demultiplexers	▪ Propellant tanks ▪ Rocket engines ▪ Auxiliary/ nuclear power ▪ Orbital maneuvering systems ▪ Reaction control systems ▪ Hydraulic systems	▪ Computer systems ▪ Celestial trackers ▪ Attitude sensors ▪ Attitude actuators ▪ Control moment gyros ▪ Antennas/ GPS
Electrical Power Systems:	**Env. Control /Life support:**	**Command & Data Handling:**	**Communications & Tracking:**
▪ Photovoltaic arrays ▪ Radioisotope generators ▪ Batteries & fuel cells ▪ Power conditioning ▪ Distribution busses ▪ Fault detection systems	▪ Atmosphere supply/ distribution ▪ Trace contaminate control ▪ Ventilation/temp./hum. control ▪ Fire detection/ suppression ▪ Waste collection/ treatment ▪ Regenerative life support	▪ Computer networks ▪ Crew interface computers ▪ Multiplexers/ demultiplexers ▪ Flight control systems ▪ Caution & warning systems ▪ Telemetry systems	▪ Data relay satellites ▪ Tracking/ data network ▪ External/ interior antennas ▪ Audio/ visual systems ▪ Data distribution ▪ Robotic workstations

Representative Support Systems

Space experience has demonstrated that failures of even the simplest, smallest and least expensive of all architecture units can have devastating impacts that result in lost lives, mission delays and erosion of public support for entire space programs.

- Effective planning requires a holistic approach:

– Design requirements and concepts must be correlated with special conditions and risks imposed upon crews and spacecraft systems.

– System reliability, maintenance, repair and replacement decisions must address all possible failure contingencies.

– Space architecture fundamentally involves conceptualizing, evaluating and integrating systems at all levels.

Space Shuttle Challenger Accident

A Holistic Imperative

A substantial amount of information relevant to this section can be found in Part I of this Space Architecture Seminar Lecture Series titled Space Structures and Support Systems. That reference material, along with Part II titled Human Adaptation and Safety in Space are intended as foundation presentations to support clearer understanding of this and other Part III Sections. Additional reference and information sources follow:

Astore, W., Giffen, R., Larson, W. *Understanding Space: An Introduction to Astronautics*. 2nd Edition. The McGraw-Hill Companies, Inc., 2000.
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Larson, W., Pranke, L. *Human Spaceflight-Mission Analysis and Design*. 1st Edition. McGraw-Hill, 1996.
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“The NASA Access-to-Space Study Summary.” Part I, July, 1993. NASA.
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Wertz, J., Larson, W. *Reducing Space Mission Cost*. Microcosm/ Kluwer Publisher, 1999.
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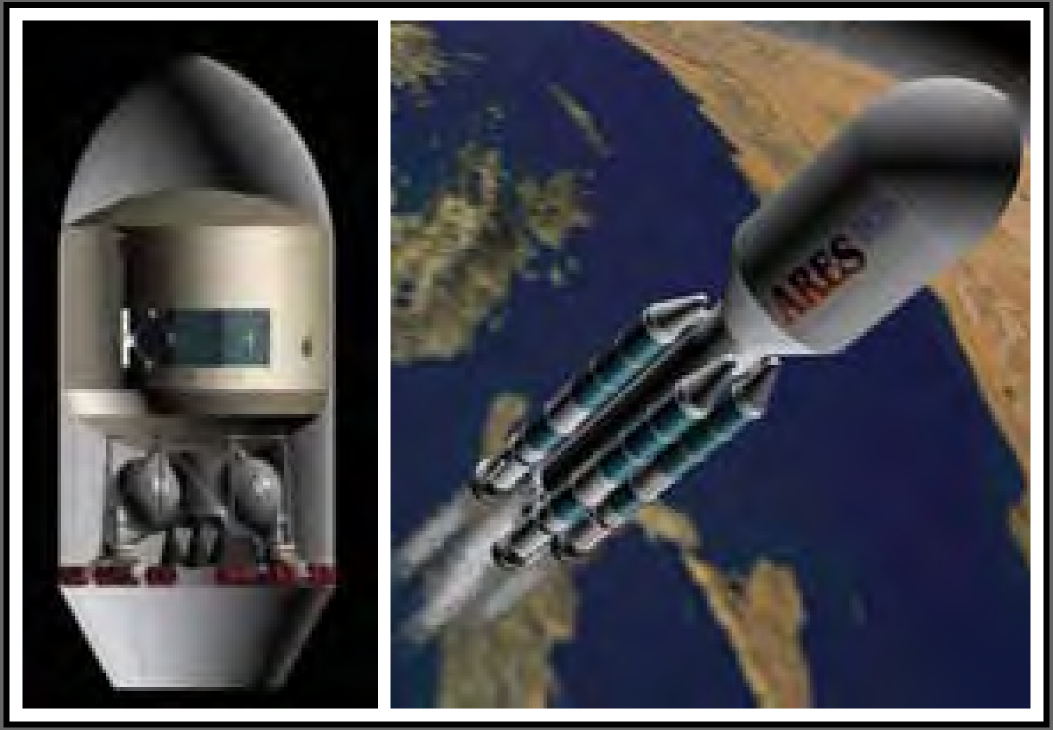
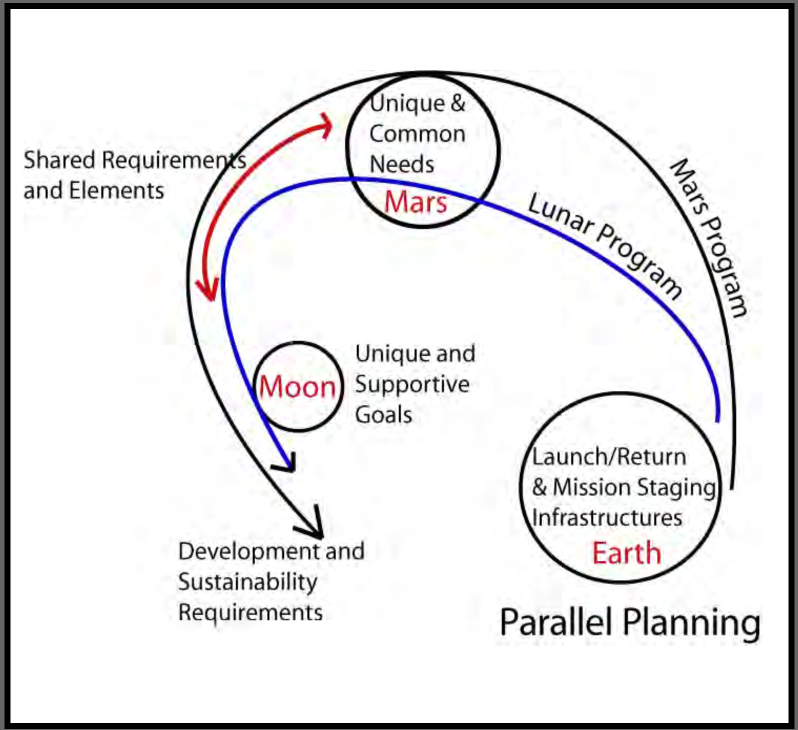
BACK TO THE LIST OF CONTENTS

SECTION B: TRANSPORT OPTIONS & CAPACITIES

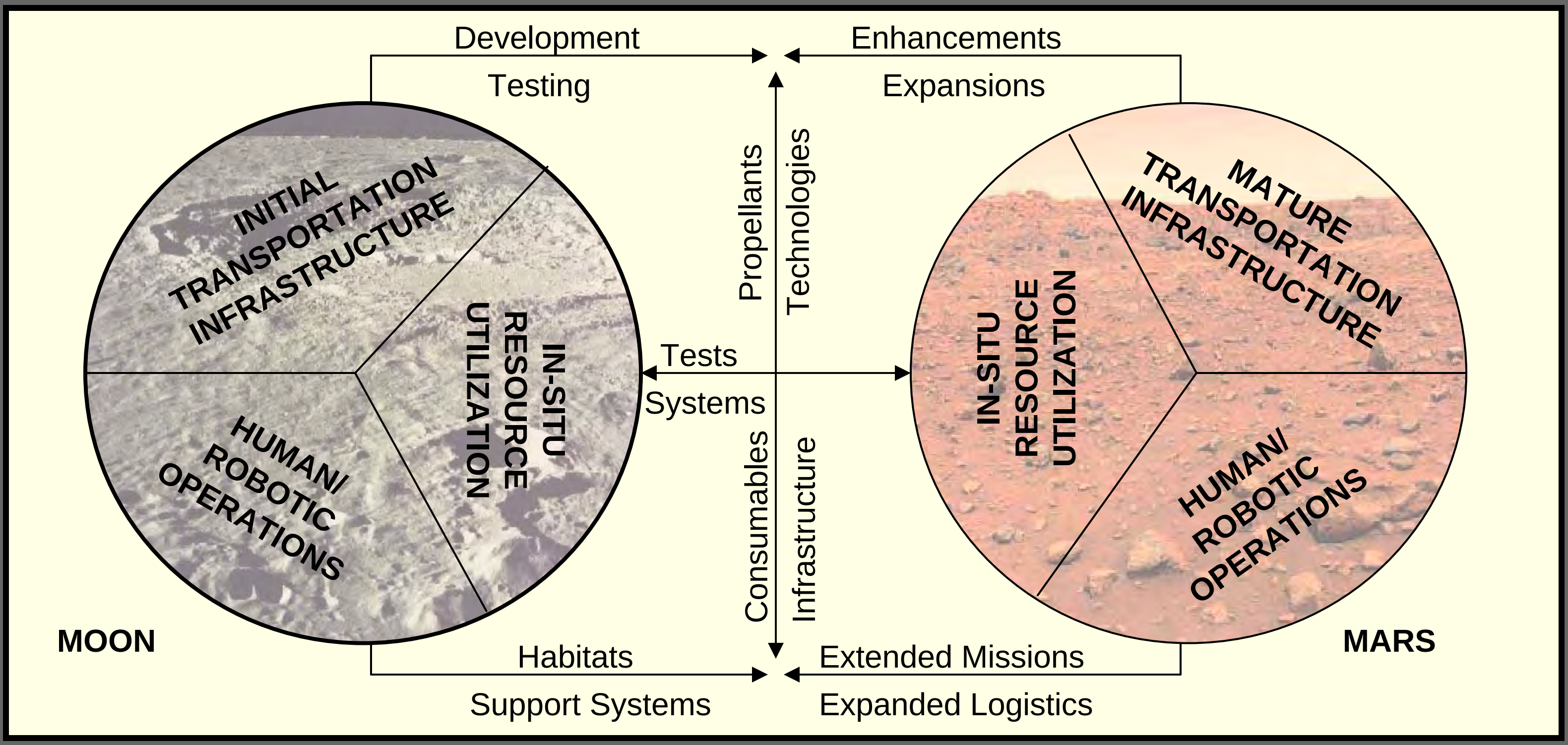


Frequent and affordable access to the Moon to establish a permanent human presence, and practical means to transfer crews and cargo on longer voyages to Mars, will demand transportation systems which are much more efficient than those presently available :

- The logical approach to meet these challenges is to apply a “Mars-back” planning methodology that investigates technical and operational pathways to the ultimate and most difficult destination, and then “reverse engineers” ways that lunar elements can be seamlessly integrated into holistic exploration/ development strategies:
  - Mars program planning must address needs which are both common and unique relative to lunar mission goals and means.
  - Lunar program planning must consider possible ways these missions can facilitate and advance broader exploration goals through development and testing of enabling concepts and systems.



“Mars-back” Planning Approach



Integrated/ Parallel Planning

TRANSPORT OPTIONS AND CAPACITIES

BACKGROUND

	Similarities and Differences	
	Moon	Mars
Surface Landing	Communication satellite relay needed	Possible relay from elliptical parking orbit
	Short Earth-Moon communication delay	Longer Earth-Mars communication delay
	No atmosphere/ dust storms	Dust storms can limit visibility
	Parachutes are not possible	Parachutes are not practical for large items
Ascent Return	Possible propellant from regolith	Possible propellant from atmosphere
	Less gravity/ Delta-V	More gravity/ Delta-V
	Frequent return opportunities	Limited windows/ abort options

Outbound Issues

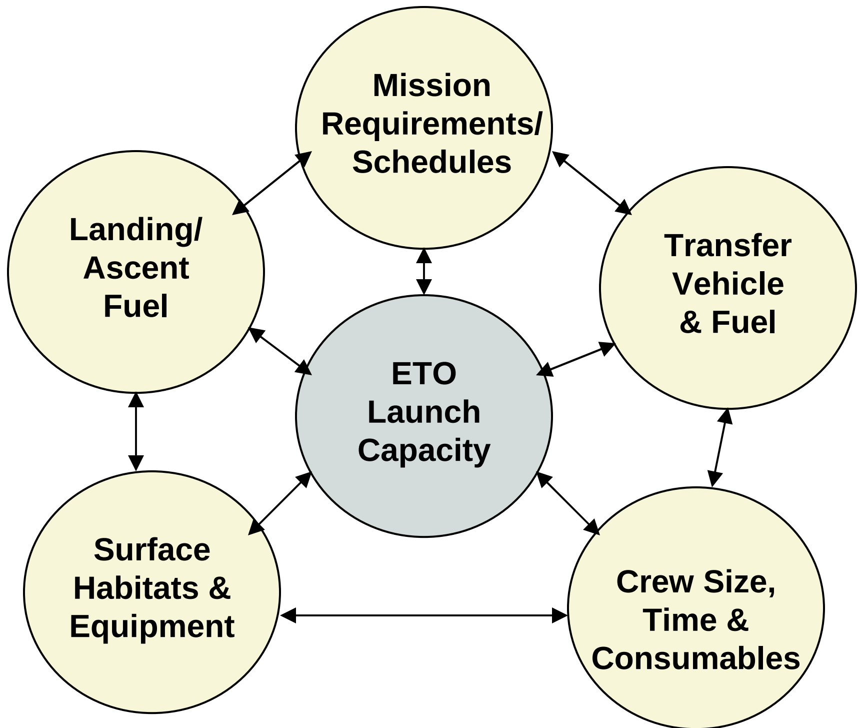
	Similarities and Differences	
	Moon	Mars
Launch	Substantial cargo mass for surface infrastructure	Additional cargo mass for crew transfer
	Rapid turn around for short/ frequent missions	Limited launch opportunities/windows
Orbital Transfer	Possible staging from LEO or LI	Possible staging from LEO or LI
	Possible propellant source for Mars	Possible propellant resupply at LI
	Short travel exposures to space radiation hazard	Long periods of space radiation hazards
	No aerobraking to conserve propellant	Aerocapture/ aerobraking is possible
	Apollo legacy mission experience benefits	More time for systems to fail

Return Issues

Comparison of Lunar & Mars Considerations

Just as it is essential that transportation requirement definition and system planning be guided by "big picture" Moon/ Mars program goals, it is also important that mission-driven payload requirements be considered from the very beginning :

- Unlike Apollo missions which minimized surface payload requirements and stay times, future exploration voyages will need to deliver substantial infrastructure and logistics cargo:
  - Early attention must be directed to the minimum practical volume of these elements (including habitats and major equipment items) necessary to support long-term mission goals as a basis for sizing launch, transfer and landing vehicles.
  - Practical requirements and constraints of payload elements and vehicle options must be planned and correlated in parallel.



Sizing the Systems

Mission - driven Influences

Transportation capacities have fundamental influences upon most aspects of mission planning and element design :

- Mass and volume correlations between ETO launch capacities and surface landing systems and payloads are of particular importance :
  - Heavy Lift Vehicle (HLV) capabilities can enable use of relatively large-diameter modules (possibly 30ft. or more) which can be landed and utilized in a vertical orientation (center axis up).
  - HLVs can launch surface landers attached to modules and other payloads, avoiding a need to dock/ assemble these elements together in orbit.
  - Surface modules that are compatible with Medium Lift Vehicles (MLVs) must be oriented horizontally for landing and utilization (conditions driven by descent, CG, footprint stability and functional layout optimization).
  - MLV modules and landers are likely to require separate launch manifesting in the same or different booster shrouds, necessitating orbital rendezvous and docking.

SICSA Heavy-lift and Medium-lift Concepts

ETO Launch/ Payload Correlations

TRANSPORT OPTIONS AND CAPACITIES

SICSA HLV Lander/ Module Concept

SICSA MLV Lander/ Module Concept

HLV & MLV Landing Implications

TRANSPORT OPTIONS AND CAPACITIES

Referring to Part III of this lecture series (Space Transportation, Propulsion and Pathways), there are a variety of different factors that influence capacities, performance and applications of particular systems for various exploration mission segments :

- Earth launch, transfer, landing and ascent system considerations and options are discussed in Section A : Transportation Systems.
- Influences of different propulsion approaches and applications upon capacities and efficiencies are presented in Section B : Propulsion Systems.
- Propellant mass, trip time and crew safety/ consumable implications of different vehicle trajectories are elaborated in Section C : Pathways and Destinations.

ETO Cap./ Launch:
- Vehicle Size/ Type
- Attitude/ Inclination
- Propellant I_{sp}
- Staging Destination
- Abort Strategy

Transfer System:
- Trajectory
- Mass Fraction
- Propellant I_{sp}
- Braking Strategy
- Return/ Abort

Landing System:
- Descent Altitude
- Mass Fraction
- Propellant I_{sp}
- Gravity Level
- Abort Strategy

Ascent System:
- Liftoff Mass
- Rendezvous Orbit
- Propellant I_{sp}
- Gravity
- Abort Strategy

Summary Top-level Considerations

Transportation Segment Influences

The mass (and volume) capacity of a selected ETO launch system, in combination with mission goals and requirements, will determine the number of launches (N launches) that will be necessary to deliver particular payloads (PL mass) that are baselined for a specific mission:

ETO mass capacity x N launches =
TS mass + LS mass + AV mass + PL mass
where :
ETO mass cap.= Earth to orbit capacity/ launch
N launches = Number of launches required/ mission
TS mass = Transfer system mass required/ mission
LS mass = Landing system mass (without AV mass)
AV mass = Ascent vehicle mass for crew return
PL mass = Payload mass (mission total)
so that :
PL mass (maximum) =
ETO mass cap. x N –(TS mass+LS mass+AV mass)

Transfer System (TS mass) =
- Crew module & consumables
- Vehicle structure
- Engines & thrusters
- Propellant (outbound and return)

Landing System (LS mass) =
- Landing stage structures
- Engines & thrusters
- Propellant (landing only)

Ascent Vehicle (AV mass) =
- Crew ascent module
- Ascent stage structures
- Engines & thrusters
- Propellant (ascent only)

Payloads (PL mass) =
- Habitats & equipment
- Crew consumables
- EVA resupply
- EVA support (transport & equip.)

Summary Top-level Considerations

ETO Launches Required for Surface Deliveries

Example 1 : A lunar cargo mission to deliver a surface habitat module using a low-energy conjunction class transfer trajectory :

- Determine the maximum module mass if it is to be launched ETO by a single HLV, where :
  - ETO mass capacity = 100 MT (HLV to LEO)
  - TS mass = 3MT x PL mass (the module)
  - LS mass = PL mass (1:1 ratio)
  - AV mass (not applicable for one-way cargo)

PL mass (maximum) (habitat module) $= \dfrac{\text{TS mass + LS mass}}{\text{ETO mass capacity}}$

$= \dfrac{\text{3(PL mass) + PL mass}}{\text{100 MT}}$

so that :

habitat module $= \dfrac{\text{4 (PL mass)}}{\text{100MT}}$ = 25MT (max.)

Hypothetical Cargo Mission

Example 2 : A round-trip crew mission to the lunar surface using a fast opposition class trajectory :

- Determine the number of HLV ETO launches required, where :
  - ETO mass capacity = 100 MT (HLV to LEO)
  - TS mass = 5MT x PL mass (total) based on outbound mass (5:1 ratio)
  - PL mass (tot.) = 33 MT (including an 8MT crew transfer vehicle and 25MT descent/ ascent vehicle constituting LS mass and AV mass)

Rewriting the formula :

N launches $= \dfrac{\text{5(PL mass) + PLmass}}{\text{ETO mass capacity}}$

so that :

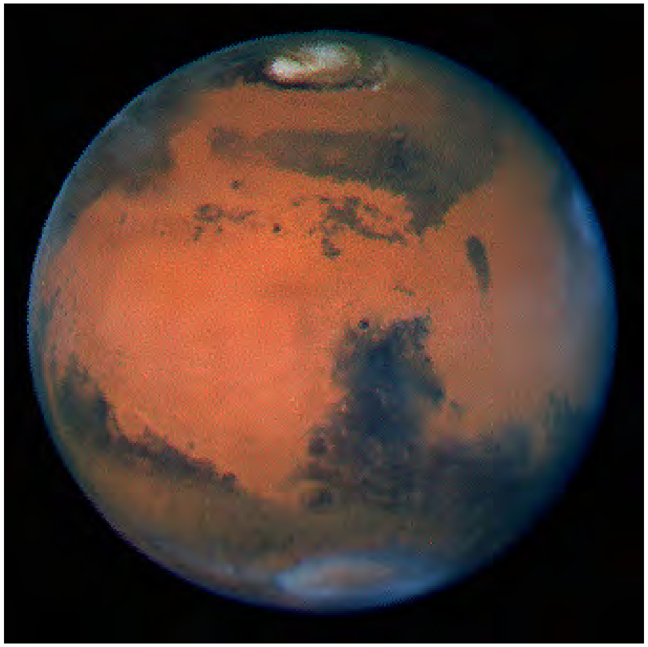
N launches $= \dfrac{\text{5(33MT) + 33MT}}{\text{100 MT}} = \dfrac{\text{198MT}}{\text{100MT}}$ = 2

Hypothetical Crew Mission

Mission Examples

US Government-mandated space goals are to establish a permanent human presence on the Moon, and proceed to Mars :

- With Mars as the ultimate destination, it is essential to pursue plans that lead us there without technical interruptions or programmatic detours.
  - Since the Moon is designated to lie along that development pathway (although not necessary on a common trajectory), it is important to integrate technical and operational benefits of lunar missions into Mars.
  - In plans to replace the tiny and ageing Shuttle with upgraded Earth-to-Orbit (ETO) ISS servicing capabilities, it is important that this new system also support the LEO staging of even more advanced lunar/ Mars exploration vehicles.



Keeping Our Eyes on the Ball

Taking the Long View

TRANSPORT OPTIONS AND CAPACITIES

As discussed in Part III, Sections B and C, a vehicle's velocity at any given time will be influenced by a variety of conditions to impact trip time and propellant mass consumption :

- A vehicle can use the force of its thrusters to change its Delta-V (hence its orbit) by applying Newton's 2nd Law of Motion according to the formula shown opposite.
- The point in a particular orbital trajectory at a particular time will determine its velocity within that orbit (slowest at apogee and fastest at perigee).
- Gravitational influences of large planetary bodies such as the Sun, Earth, a planet or the Moon can be beneficially used to reshape orbits, causing vehicles to accelerate or decelerate.
- Aerocapture/ aerobraking at planets with atmospheres can greatly reduce propellant needs for orbit insertion.

Newton's 2nd Law of Motion is used to calculate the rate of acceleration (a) in relation to net force (F) and the total system/ payload mass according to the formula :

$$a = \frac{F}{m}$$

Where :

$$\text{Mass} = \frac{\text{Weight}}{g} = \frac{\text{Total weight (lbs)}}{32\ \text{ft/sec}^2} = \text{“slugs”}$$

(A slug is a unit of mass in the English system of measurement)

- Assuming that a fully loaded Space Shuttle weighs 4.4 million lbs with 3 main engines and 2 SRBs rated at 375,000 lbs each :
  - Downward gravitational force of its weight (Fa) = 4.4 million lbs
  - Upward force (Fa) of its total rockets is about 7.7 million lbs
  - Net upward force (F) is about 3.3 million lbs.

$$a = \frac{F}{m} = \frac{3{,}300{,}000\ \text{lbs}}{140{,}000\ \text{slugs}} = 24\text{ft/sec}^2 = 16\text{mph/sec}$$

Thrust & Orbit Influences on Velocity & Fuel Mass

Part III, Section B of this lecture series discussed the importance of a vehicle's propulsion system type and the specific impulse (I_{sp}) particular to the propellant it uses in determining thrust and fuel mass efficiency according to the formula :

$$I_{sp} = F/g_o m$$

where :
I_{sp} = specific impulse (s)
F = thrust (N)
M = propellant mass-flow rate (kg/s)
g_o = gravity constant = 9.81 m/s^2 (applies on all planets)

A higher number is better, meaning that more thrust can be delivered for a given amount of propellant.

Propellant	I_{sp}	Propellant	I_{sp}
Solid: 18% Al, 71% NH_4ClO4, 11% HTPB	307	Kerosene/ N_2O_4	311
Monopropellant: 92% H_2O_2,8% H_2O	181	Kerosene/ 92% H_2O_2, 8% H_2O	315
Monopropellant: N_2H_4	218	Kerosene, Liquid O_2	337
Monomethyl hydrazine/ N_2O_4	328	Kerosene/ N_2O	299
Liquid H_2/ Liquid O_2	448	Nuclear/ H_2 propellant	1013

Representative Propellants

I_{sp} Influence on Fuel Mass/ Efficiency

HUMAN SPACEFLIGHT

As discussed in Part III, Section B, propulsion system selection processes match application requirements with technology attributes:

- Chemical liquid rockets offer good launch/ orbital insertion thrust and can be restarted for repeated use. Liabilities are mechanical complexity and difficulties in storing cryogenic propellants during long duration space missions.
- Solid fuel rockets are simpler than liquid, and propellants can be stored indefinitely. A big limitation is that once ignited, they cant be throttled back, topped off or reused.
- Hybrid rockets use a solid fuel core and liquid oxygen as an oxidizer. They haven't yet found mainstream and established heritage, but new solid propellants using synthetic polymers are improving burn continuity and thrust.
- Nuclear systems might support long distance/ duration human exploration missions, either to super heat hydrogen gas propellant, or to power electric drive systems. Scale-up challenges, mass and radiation hazards present issues.

Technology	Applications	Advantages	Disadvantages
Chemical Liquid Monopropellant Bipropellant	Launch Orbit insertion/ maneuvers Landing/ ascent	• High thrust • Heritage • Restartable	• Complicated combustion • Fuel storage problems
Solid Hybrid	Launch Orbit insertion	• High thrust • Heritage	• not restartable
Nuclear Solid core Liquid core Gas core	Orbit insertion/ maneuvers	• High specific impulse	• Unproven • Radiation • Low thrust/ weight
Electric Electro-thermal Electromagnetic Electrostatic	Orbit insertion/ maneuvers	• Very high specific impuloe	• Radiation • System mass • Low thrust levels • Limited heritage

General Applications & Attributes

Propulsion System Types & Features

A Mass Fraction (MF) is the proportion of propellant mass to the total propulsion system mass (MF=Mprop/ Mtotal). This means that as Mass Fractions become larger, there is less remaining mass available for payloads.

- **Conventional Systems :**

  - Mass fractions decreases as propellant mass increases (economies of scale).

  - Mass fractions typically increase as the rocket stage numbers increase (because stages usually get smaller as they "go up the vehicle").

  - The average mass fraction for liquid rockets is about 0.17, while systems using gas propellants tend to be much heavier with mass fractions near 0.7.

  - Solid rockets tend to have somewhat lower mass fractions than liquid, but their mass fractions typically get better as their sizes increase.

- **Other Systems**

  - Hybrid rockets tend to have mass fractions that are slightly higher than liquids because their fuel packaging density is lower, but they waste quite a lot of unburned fuel (17%).

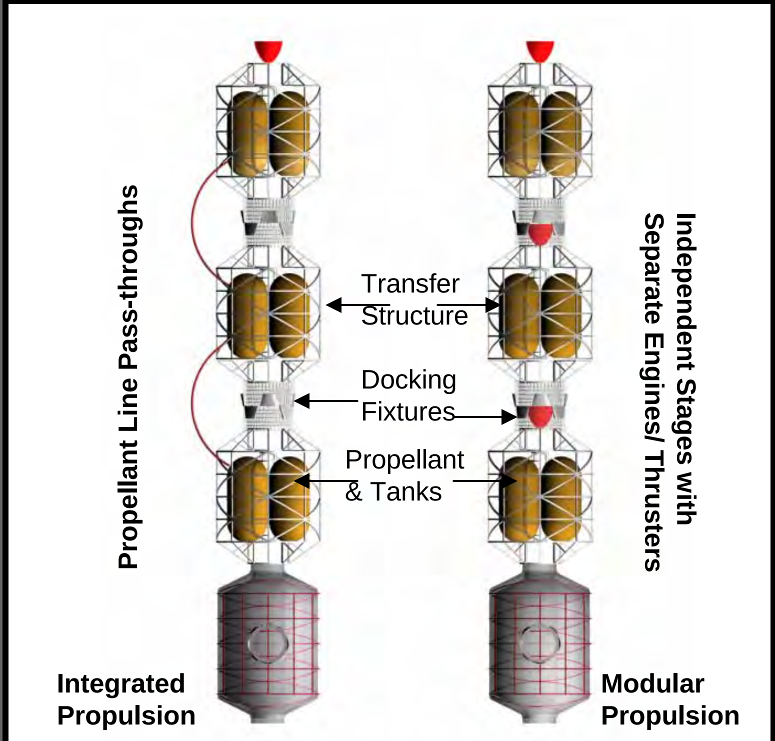
  - Nuclear rockets have similar mass fractions to liquids except that the reactor mass can be very substantial (500 kg is typical). Their radiation shields can also add significant mass (about 3,500 kg/m^2).

  - Nuclear electric systems can have relatively small propellant and tank masses due to high I_{sp} efficiencies, but their generating equipment may be proportionally larger along with nuclear power sources and shields.

Mass Fraction Considerations

Since it may not be possible to deliver all propellant needed for lunar/ Mars transfers to an Earth departure orbit in a single booster, it may be necessary to launch propulsion units separately and dock them together in LEO :

- An integrated propulsion approach would provide only the last unit in the "train" with an engine/ thruster assembly:
  - Propellant transfers would pass between all docked unit interfaces.
  - Mass advantages of a single engine/ thruster assembly would be offset by an inability to jettison spent unit tanks.
- A modular propulsion approach would provide each unit with an engine/ thruster assembly:
  - Advantages of being able to jettison empty tanks would be offset by duplicate engines/ thrusters.
  - Independent units would avoid risks of propellant leaks between units, would provide engine/ thruster redundancy in the event of failure, and would simplify orbital refueling.



Fixed vs. Jettisoned Units

Transfer Propulsion Staging

As a general weight guideline, engines, thrusters and other "dry" mass components constitute about 15% of the total fueled mass of chemical propulsion systems :

- Interplanetary transfer vehicle dry mass and propulsion efficiencies will be influenced by ETO launch capabilities as well as the integrated vs. modular propulsion staging approach that is used :
  - HLV boosters will be able to deliver more propellant mass to the departure orbit with fewer launches and Automated Rendezvous and Docking (ARAD) maneuvering requirements.
  - Larger propellant units made possible using larger boosters are likely to offer more efficient propellant/ dry mass economies of scale.
  - The integrated propulsion design approach that provides only a single engine/ thruster will offer a launch and Earth departure mass advantage, but will present a tank mass entry orbit braking penalty at the destination.

Example : Assume that a propellant mixture of nitrogen-tetroxide (oxidizer) and monomethyl-hydrazine (fuel) is to be used in a ratio of 1.6:1, with a total mass of 3,041 kg for an application :

- Determine the tank sizes of each :

1) Since 1.6:1 = 62% oxidizer and 38% fuel :
   oxidizer = 3,041 kg x 0.62 = 1,885 kg
   fuel = 3,041 kg x 0.38 = 1,156 kg

2) Given: nitrogen tetroxide density = 1,434 kg/m^3
   1,885 kg/ 1,434 kg/m^3 = 1.3 m^3 (tank)
   Given: monomethyl hydrazine density=870kg/m^3
   1,156 kg/ 870 kg/m^3 = 1.3m^3 (tank)

3) Using a formula for spherical volume,
   Volume = 4/3 pi r^3
   1.3m^3 = 4/3 pi r^3

So that radius = 0.68m and diameter = 1.36m

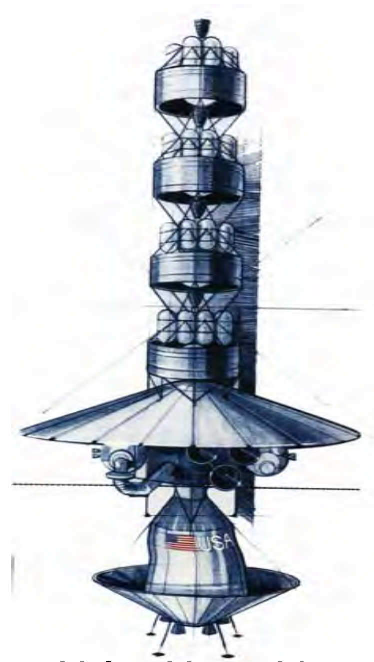
Sizing Propellant Tanks

Propulsion Stage Mass/ Volume

IMAGINING SPACE

Part III of this lecture series discusses a variety of design and operational strategies that can be applied to minimize propulsive mass requirements for interplanetary missions :

- Deployable aerobrakes can provide non-propulsive braking for atmospheric deceleration into Mars and Earth orbits, offering substantial propellant savings with modest structural mass penalties (Section A).
- Orbital refueling depots at L1 or other strategic locations can use propellant delivered from the Earth and/ or Moon using energy-efficient orbits to resupply Earth crew returns from Mars (Sections A and C).
- Fly-by orbits can take advantage of gravitational influences of large planetary bodies that reshape trajectories to accelerate/ decelerate vehicles. Weak Stability Boundaries (WSBs) are an example (Section C).
- Cycler orbits such as the VISIT and UP-DOWN Escalator concepts can reduce launch/ transfer mass using "cargo freighters" in inertial space trajectories (Section C).



Vehicle with Earth/ Mars Aerobrakes

Design & Operational Approaches

A. Stay time is estimated from approximate launch windows.

B. Times for sprint/ VISIT and conjunction missions are similar.

C. Times for sprint/ Escalator and opposition missions are similar.

D. Payload fractions for high-thrust ignore structure mass. All non-payload mass is propellant (plus heat shields if provided, adding about 15% dry mass).

E. Payload fractions for low-thrust vehicles include structure and propellant.

F. Cyclers don't require propellant to transfer their own mass, but consumables and other mass must be accelerated to dock with the cycler.

Mission Type	Mission time (days)				Round-trip Payload Fraction
	Out	Surface	Return	Total	
High-thrust, conjunction with aerobraking	224	487	224	935	0.136[D]
High-thrust, conjunction without aerobraking	224	487	224	935	0.036[D]
High-thrust, fast-transit with aerobraking	120	623	120	863	0.045[D]
High-thrust,fast-transit without aerobraking	120	623	120	863	0.005[D]
High-thrust, opposition with aerobraking	241	40	185	466	0.020[D]
High-thrust, opposition without aerobraking	241	40	185	466	0.001[D]
Low-thrust, fast	165	644	165	974	0.027[E]
Low-thrust, slow	493	200[A]	493	1186[A]	0.037[E]
Cycler, UP/DOWN escalator	224[B]	487[B]	224[B]	935[B]	0.136[F]
Cycler, VISIT	120[C]	623[C]	120[C]	863[C]	0.045[F]

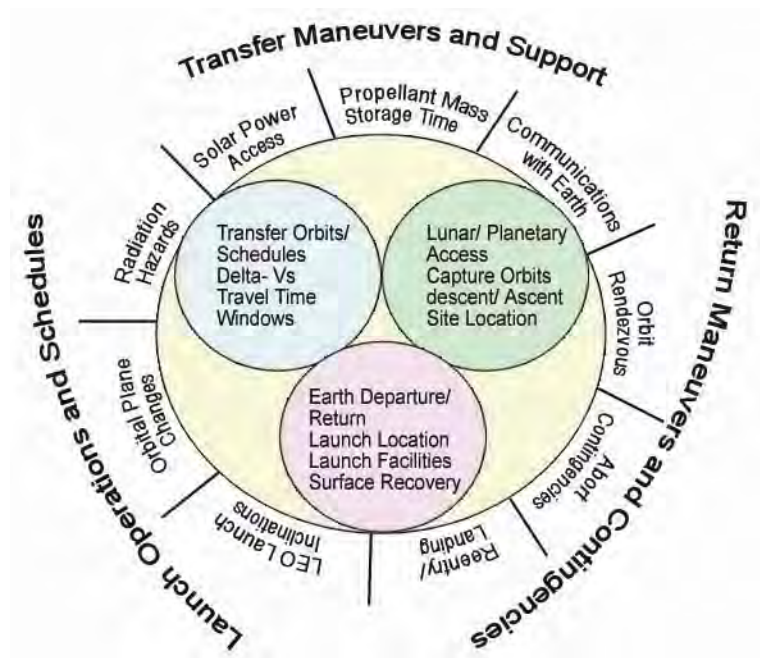
SYSTEM/ Orbit Influence Comparisons

TRANSPORT OPTIONS AND CAPACITIES

SUMMARY CONSIDERATIONS

Part III, Section C of this lecture series discusses important needs and conditions that transportation planning must address:

- Each pathway segment presents a variety of special considerations:
  - Correlations of launch latitudes with necessary Earth and transfer orbit plane changes influencing fuel-costly maneuvers.
  - Transit periods through the Earth's trapped radiation belts and transfer trajectory exposures to potential solar proton storms that present hazards to crew and electronic systems.
  - Transfer and surface periods without line-of-site connections to photovoltaic solar power and Earth for communications.
  - Extended orbital pre-departure, transfer, surface operations and return periods that require means to prevent boil-off of stored gaseous propellants.
  - Contingency plans to ensure a way back in the event of a missed orbital rendezvous or any critical system failures.



Mission Pathway Segment Influences

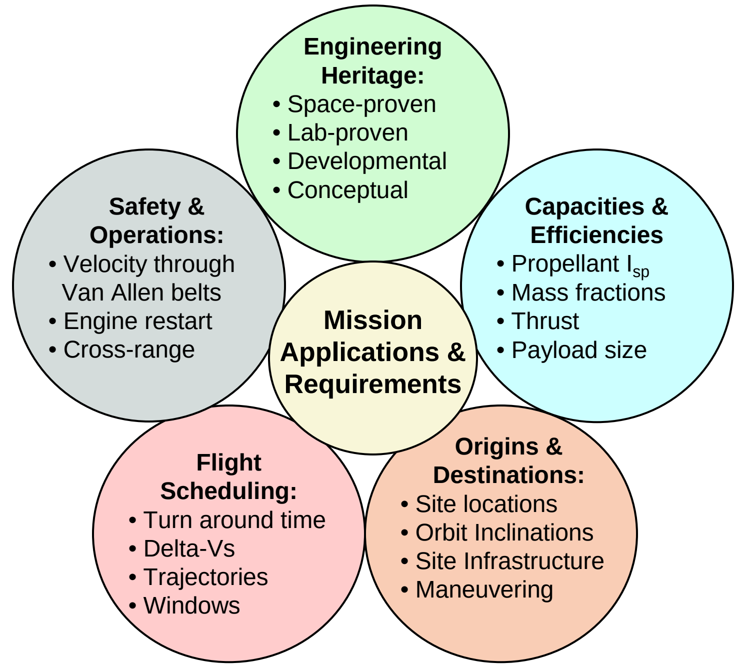
Priority Planning Issues

TRANSPORT OPTIONS AND CAPACITIES

SUMMARY CONSIDERATIONS

None of the transportation vehicles needed for future lunar/ Mars exploration presently exist, and must be developed in response to evolving program and mission definition plans :

- Responses will need to take many fundamental considerations into account:
  - System selection and design must optimize use of available and proven technologies for nearest-term requirements, but also begin development and testing of next generation options to optimize efficiencies and performance.
  - Planning must correlate realistic vehicle capacities with mission-driven mass and volume delivery requirements which are determined in parallel.
  - Destination priorities must be determined as a basis for establishing launch site locations/ infrastructures to support vehicle choices.
  - Vehicle design , launch features and trajectories will determine mission windows and schedules.
  - All of these and other factors will influence safety and operation planning vital to program success.



System Selection and Planning

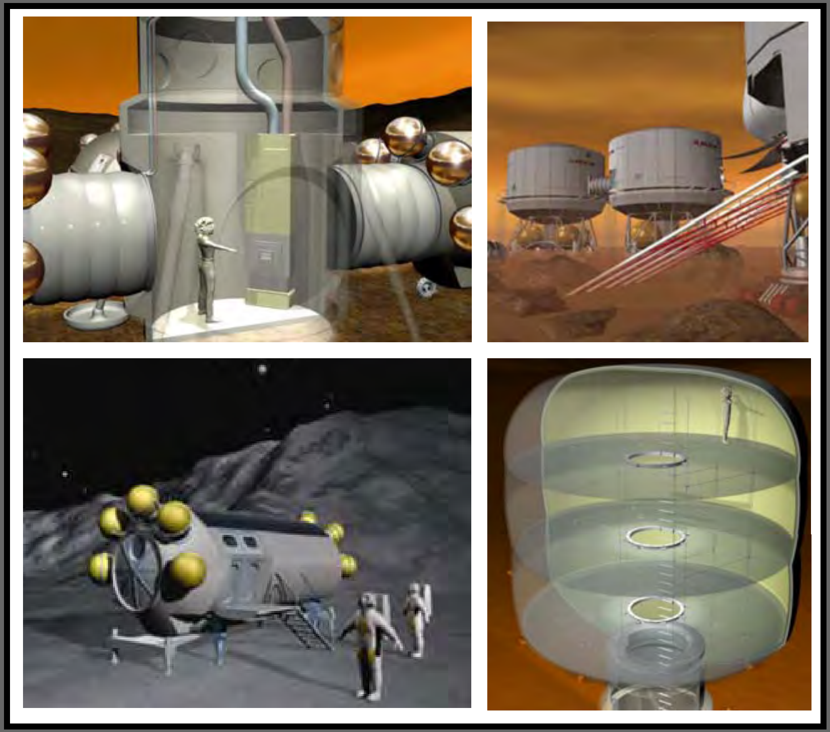
Assessing Option Features

SUMMARY CONSIDERATIONS

More detailed information about many topics discussed in this section, along with references and additional information sources, is offered in Part III of this lecture series. This section also draws upon important material available in the book “Human Spaceflight : Mission Analysis and Design”, Wiley J. Larson and Linda K. Pranke Editors, published by McGraw Hill Higher Education, Space Technology Series, which is a highly recommended reference.

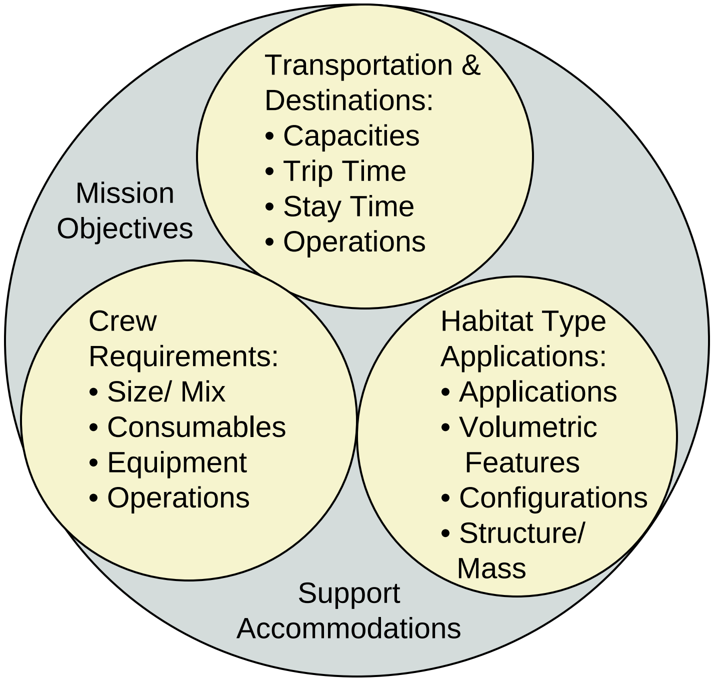
BACK TO THE LIST OF CONTENTS

SECTION C: HABITAT TYPES AND FEATURES



Habitat module design requirements and options are driven by space program mission objectives and capabilities/ constraints of available transportation systems :

- General design features will depend upon what the modules will be used for, the nature of their space operation environments, how they are to be transported and deployed, and unique advantages and limitations presented by their construction.
- Special functional accommodation requirements will be influenced by crew size and composition, how long they will occupy the habitats, what duties they will be performing, the living and work facilities they will require, and their related consumable and equipment needs.
- All of these factors are highly interdependent, and must be addressed in parallel, simultaneously considering issues and information items presented in all preceding parts of this lecture series.



Interdependent Factors

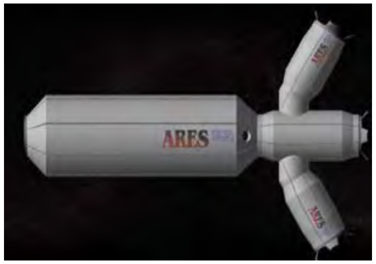
Parallel Planning Considerations

As NASA continues to examine requirements for Crew Exploration Vehicle (CEV) designs, these decisions will directly influence habitat module sizing, configurations and deployments :

- CEV capabilities and constraints will have fundamental impacts upon a variety of module planning considerations ,including:
  - Allowable module mass and volume dictated by launch vehicle capacities to LEO or to other transfer departure locations.
  - The number of launch/ orbital assembly operations required to accomplish mission objectives (influenced by launch payload constraints and transfer staging strategies).
  - Methods and constraints imposed by decelerations/ insertions into destination entry orbits and surface landing placements.
  - Influences of landing accommodations and other module design features upon surface relocations, element configurations and preparations for use.

Launch Vehicle

Transfer Vehicle with Module



Surface Landing

Surface Configuration

Transportation Influences

MS-SPACE ARCHITECTURE
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Future habitats are likely to be needed for orbital as well as planetary surface applications, each presenting special conditions and requirements:

- Next-generation space stations may be deployed in orbits around the Earth, other planets , or Earth-Moon LaGrange points to serve as :
  - Fuel/ cargo resupply facilities and depots.
  - Centers for element assemblies and departures.
  - Places for space science and tourism.
- Crew transfer modules will be needed to transport people, consumables and equipment on long voyages to Mars, in lunar/ Mars parking orbits, and for Earth returns , potentially including :
  - Artificial gravity habitats to maintain crew health and performance.
  - Modules in permanent cycler orbits in the Earth-Moon and/ or Earth-Mars systems.
- Lunar and Mars surface habitats may include:
  - Initial exploration base camps.
  - Later, permanent and expanded settlements.

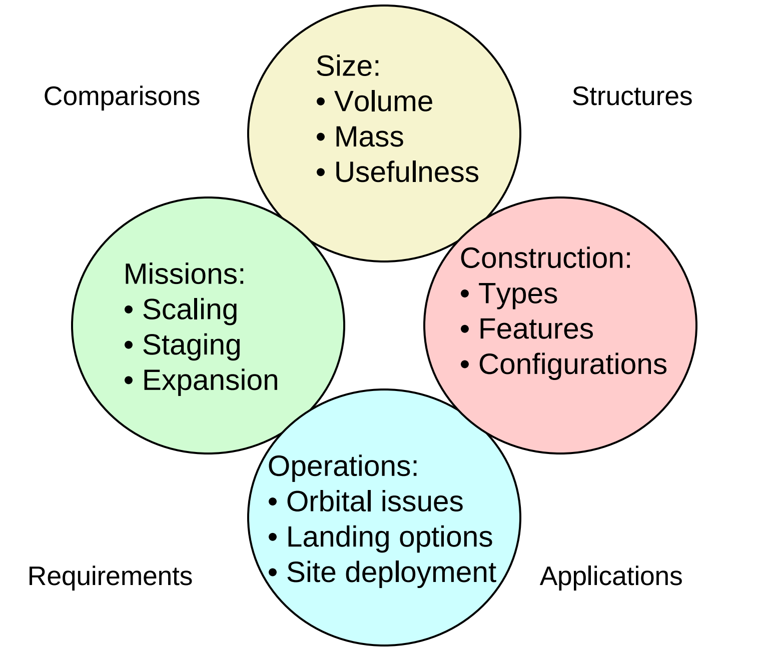
SICSA

Mars Base Development

Habitat Applications

Habitat system planning and design must be guided by a variety of key considerations:

- Module sizing must correlate allowable structure volume and mass, influenced by :
  - Pressure envelope design and construction.
  - The amount of useful interior space that will be available based upon geometric factors.
- Various construction approaches present inherent benefits and disadvantages, including:
  - The types of applications they are best suited to support.
  - Ways they can be configured in combinations to afford special advantages.
- Orbital and surface applications present unique planning and design issues:
  - Dynamic flight conditions impose special requirements.
  - Surface landing and deployment approaches have important structural and mobility implications.
- Ultimate solutions must address early and evolutionary requirements, demanding:
  - Versatility through modular design and upgrades.
  - Expandability to accommodate growth demands.



Element and Configuration Issues

Key Planning & Design Considerations

As discussed in Part I, Section B of this lecture series, habitats and other large space structures must be designed to withstand a variety of harsh and potentially destructive conditions that pose safety and operational hazards:

- Structures must be designed to mitigate effects of dynamic launch, orbital docking and deceleration/ landing loads and vibrations.
- They must be sized and engineered with necessary strength to contain internal pressure forces, and to accommodate extreme temperature changes.
- External surfaces must shield crews and equipment from harmful radiation, and provide protection from space debris hazards and contaminants.
- All of these challenges must be met without adding unacceptable launch and orbital transfer mass burdens.

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

Engineering Considerations

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

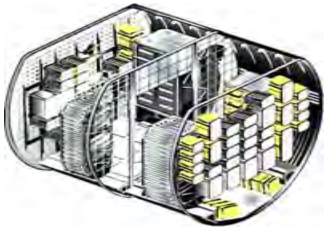
- They are simplest to design and deploy, and offer immediate operational capabilities.
- They offer good structural integrity and reliability, using materials that have been demonstrated in harsh space environments.
- They enable utility and equipment systems to be installed and checked out prior to 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

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

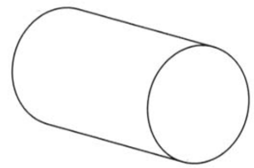
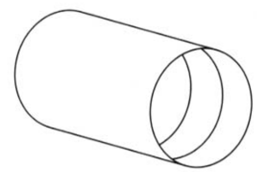
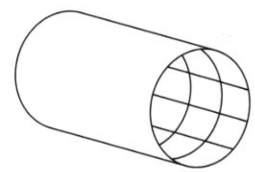
- Longerons are used to increase stiffness and load-carrying capabilities of pressure shell panels.
- Ring frames provide attachment points for longeorns and shell panels.
- Shell panels contain atmosphere pressurization loads.
- Window and hatch/berthing port frames provide pressure-tight interfaces.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

Primary Structure of a Typical Module

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.

Primary Structure Variations

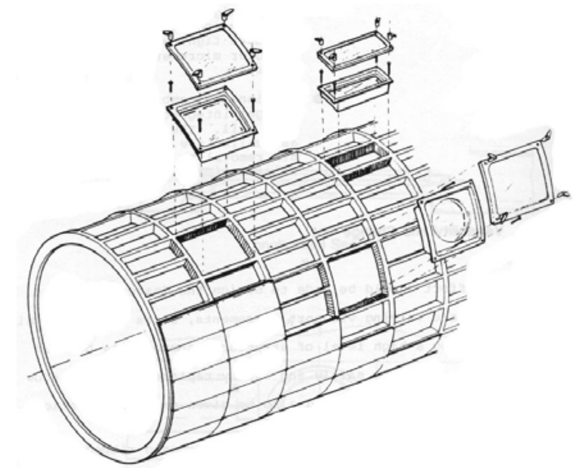
HABITAT TYPES AND FEATURES

CONVENTIONAL MODULES

BELL & TROTTI, INC

A big advantage of rigid, conventional modules is an ability to place penetrating assemblies such as windows wherever they are needed. (Much more information about viewports is presented in Part I, Section B of this lecture series).

- 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

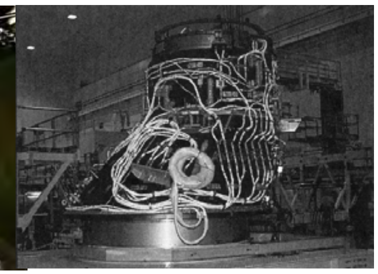
Viewport Systems

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

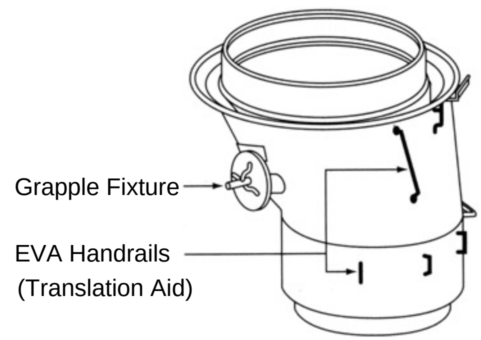
- Standoffs that provide attachment points for racks and passageways for electrical cabling, fluid lines and air distribution.
- Meteoroid debris shielding and window shutters.
- Crew and payload translation aids include internal and EVA handrails.
- Grapple fixtures for connections to other spacecraft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

Standoffs Inside the US lab

Internal Structure



Pressurized Mating Adaptor

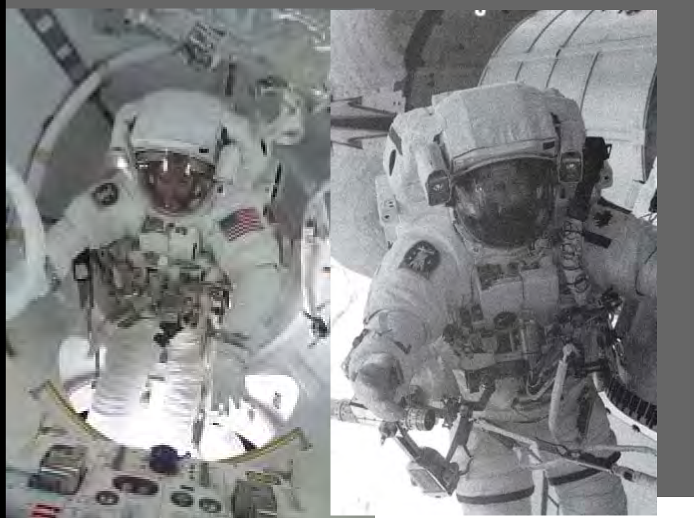


Handrails and translation aids are used by EVA crews, and grapple fixtures are used by robotic arms to install or move elements.

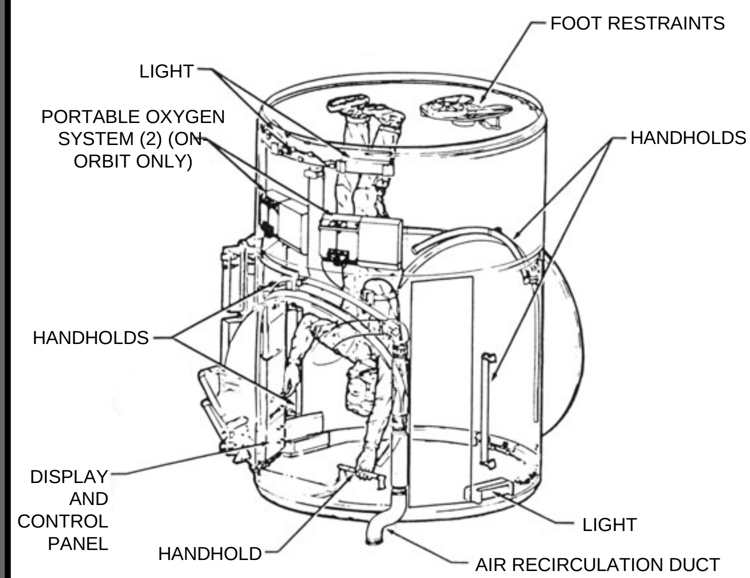
Pressurized Mating Adaptor

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)

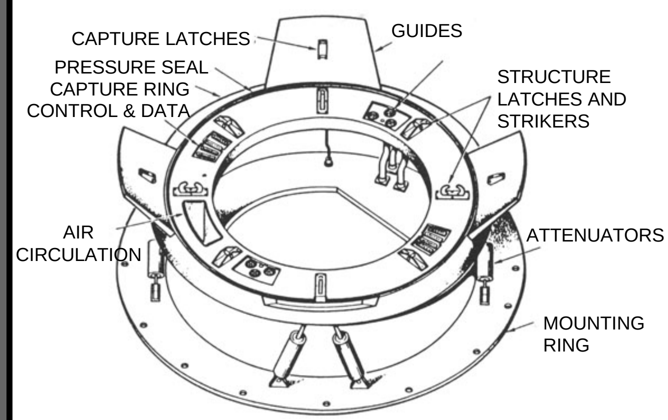


Space Shuttle Orbiter Airlock

Airlocks

Part I, Section B discusses various connections and pass-throughs that are used to transfer crews and cargo between modules and other modules or spacecraft:

- 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.



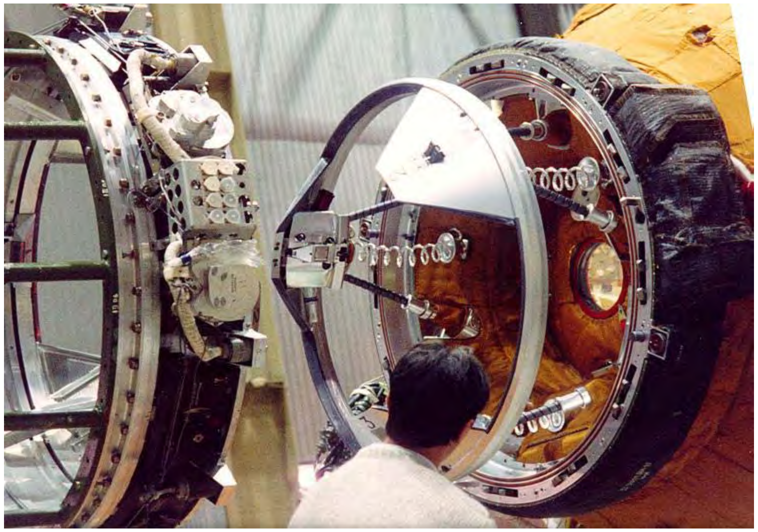
Guide vanes containing capture latches align the two elements upon contact, and they are tightly locked together by structure latches and strikers.

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.



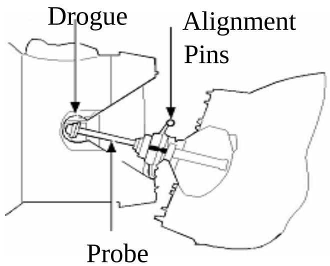
The Androgynous Peripheral Attach System (APAS) is a Russian design that is able to mate with an exact copy of itself.

Androgynous Peripheral Attach System

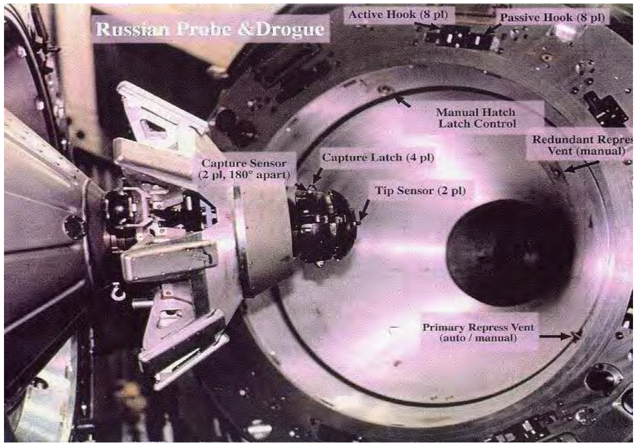
Orbiter – ISS/ Mir Docking System

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.

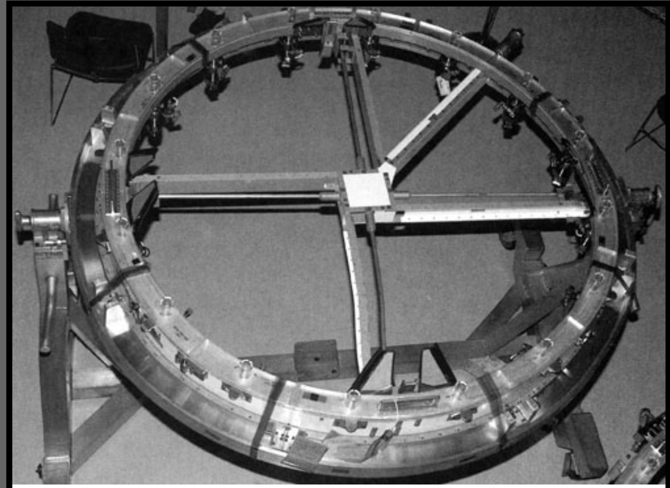


Probe/ Drogue Docking System

Russian ISS Segment Docking

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

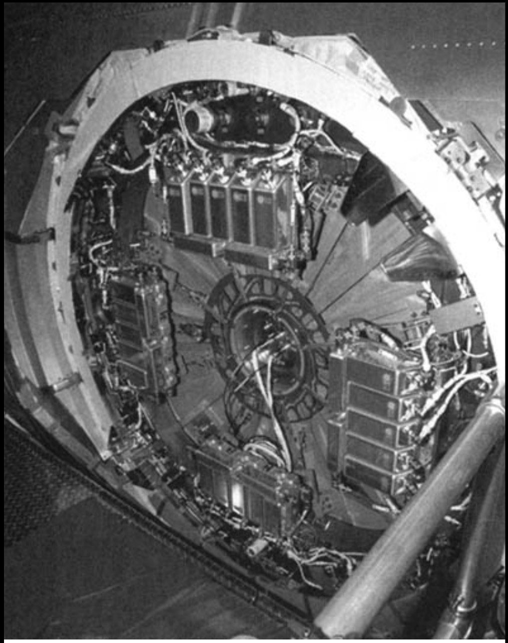
- A Manual Berthing Mechanism is located on the no.21 truss segment, and is manually operated by an EVA crew person to mate it with the passive side of a Common Berthing Mechanism (CBM).
- The CBM has both a passive and active half that connects one US module to another by means of capture latches, alignment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



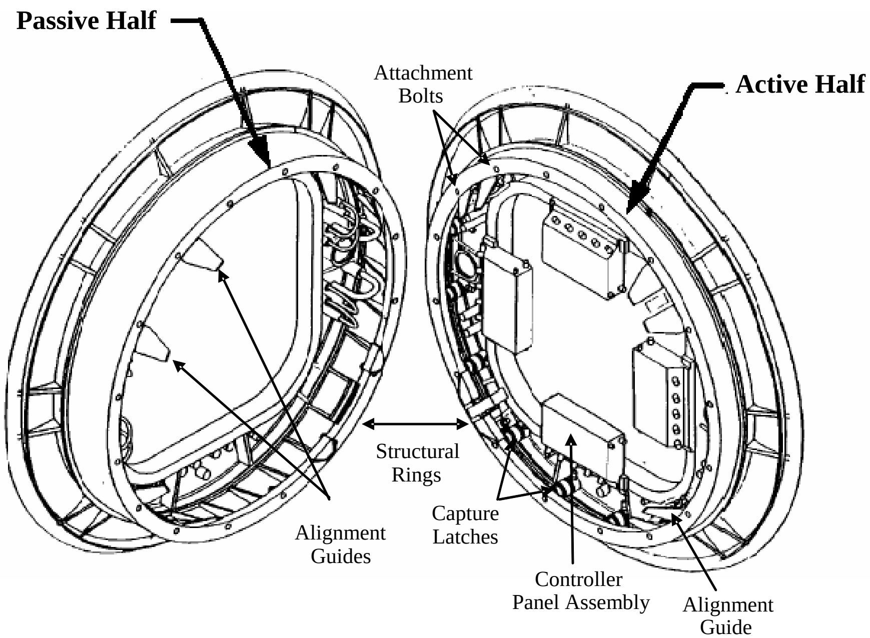
The Manual Berthing Mechanisms (MBM) serves as a temporary EVA attachment point that can mate with any passive CBM.

Manual Berthing Mechanisms

ISS Berthing Mechanisms



Active Half of a CBM



Common Berthing Mechanism

ISS Berthing Mechanisms

Part I, Section B of this lecture series presents alternatives that enable modules to be transported to destinations in compact forms, and then expanded at space destinations:

- Telescoping modules could apply a “gelatin capsule” approach that packages one hard shell segment within another for longitudinal extension:
  - This concept utilizes relatively conventional pressure vessel construction , with pre-integrated utility systems (or equipment interfaces located within the inner segment).
- Inflatable modules provide pliable/foldable laminated pressure containers that are pneumatically deployed at the destination:
  - This approach has been studied, tested and applied by US and Russian organizations.
- Hybrid systems can incorporate features of hard and inflatable systems to combine useful features of each:
  - They enable some pre-integration of utilities with expanded interior volume advantages.

Telescoping Modules

Inflatable Modules

Hybrid Modules

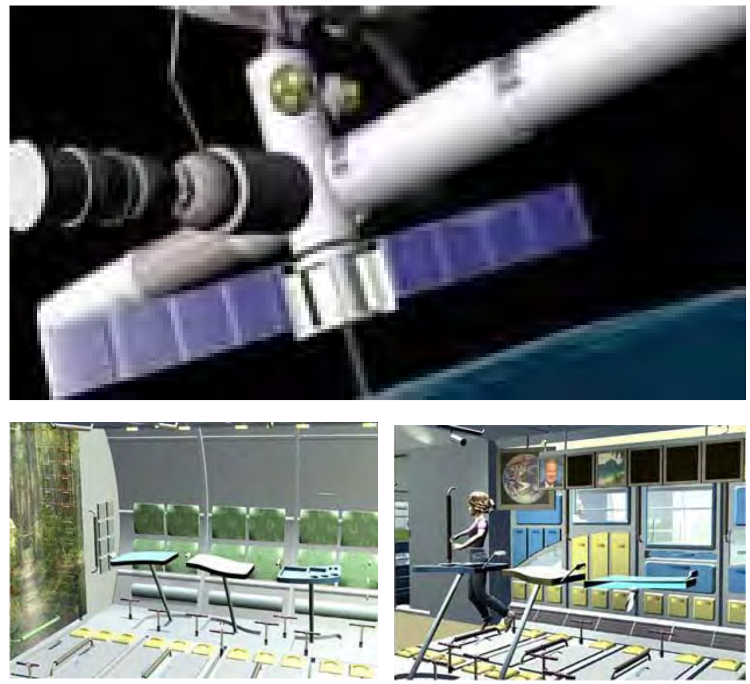
Expandable Structures

HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

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

- Similar to conventional modules, utiltiies and equipment can be integrated into the hard inner section for pre-launch operational checkouts.
- 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.



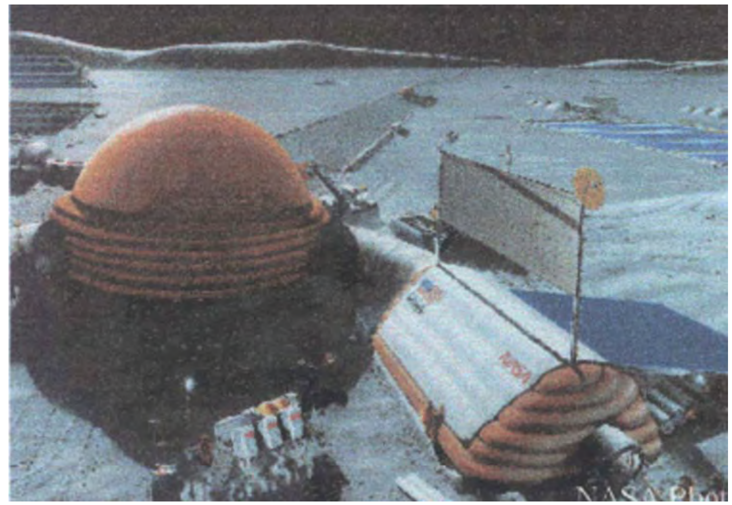
Life and Biological Sciences (LaBS) Facility

Telescoping Structures

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.

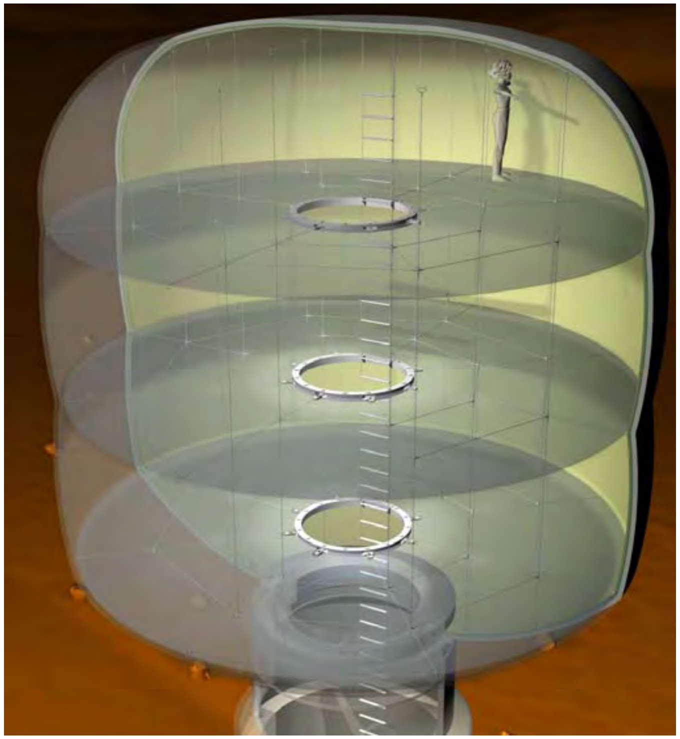


Possible inflatable system applications include lunar/ planetary facilities as well as smaller elements such as airlocks and transfer tunnels.

NASA Lunar Base Concept

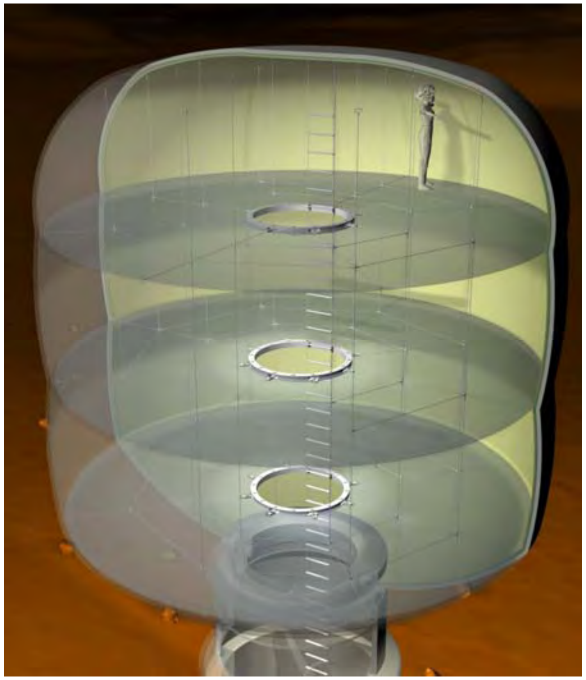
SICSA has studied and conceptualized inflatable space structures over a period of more than two decades. One proposed design deploys interior floors automatically:

- 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.

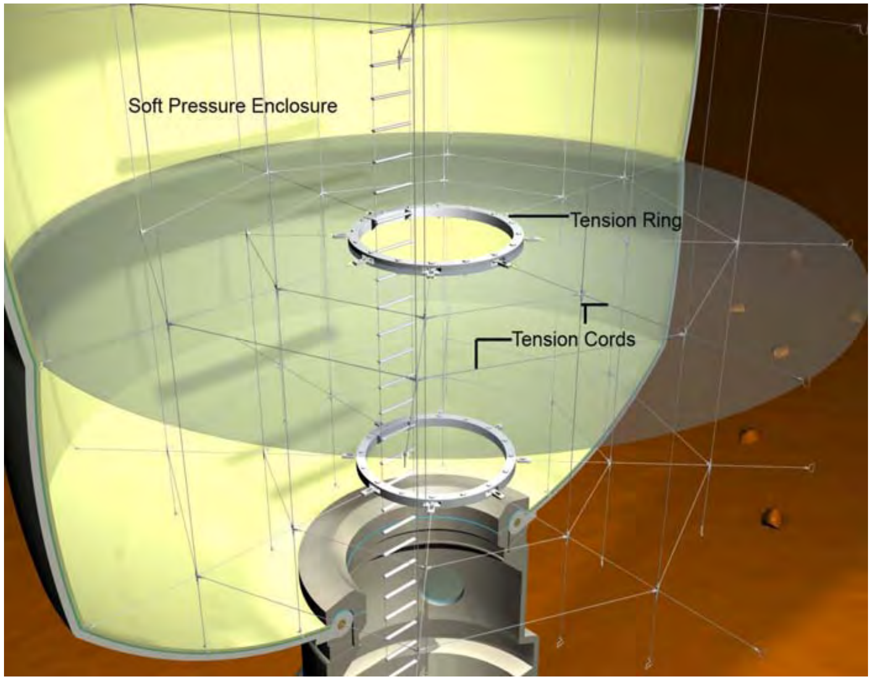


SICSA "Pop-Out" Interior Concept

Inflatable Structures-SICSA "Pop-out" Interior Concept

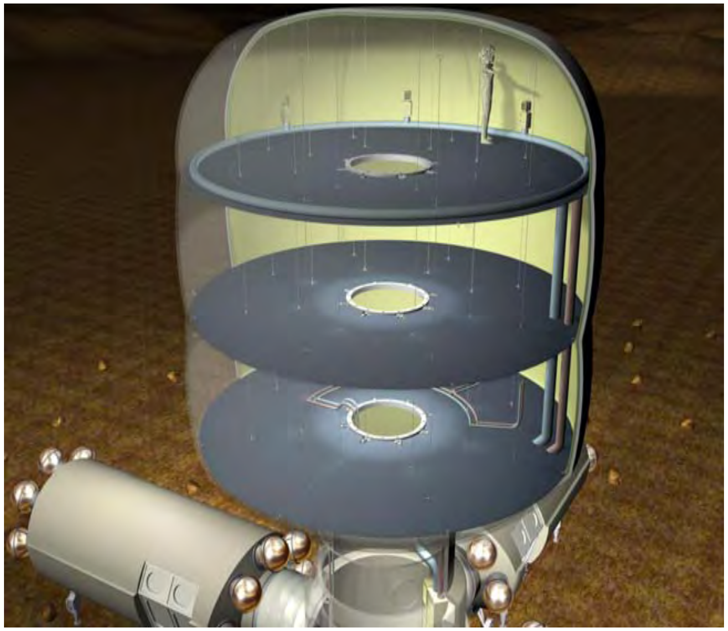


Pop-Out Internal Structure

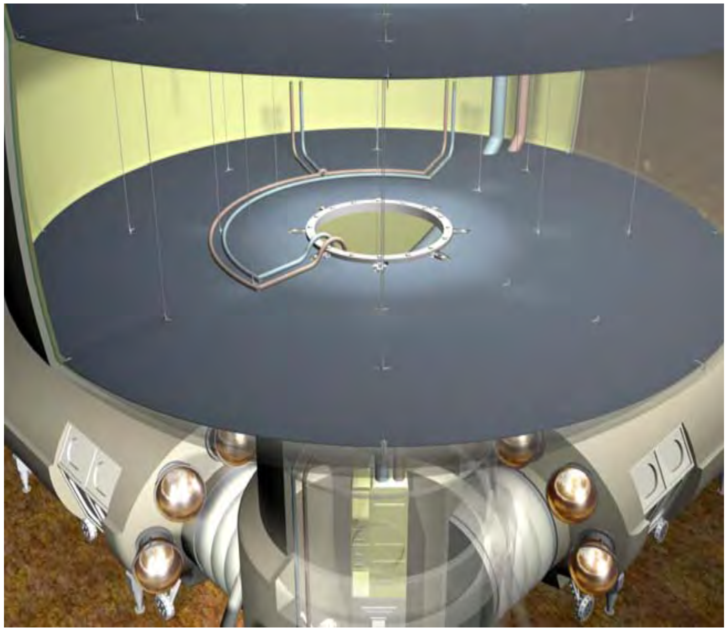


Typical Floor Structure

Inflatable Structures-SICSA "Pop-out" Interior Concept



Three Level Scheme

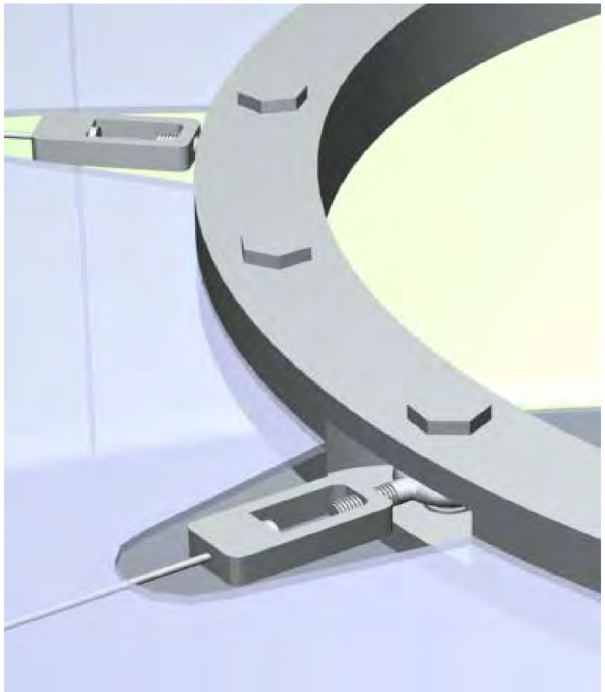


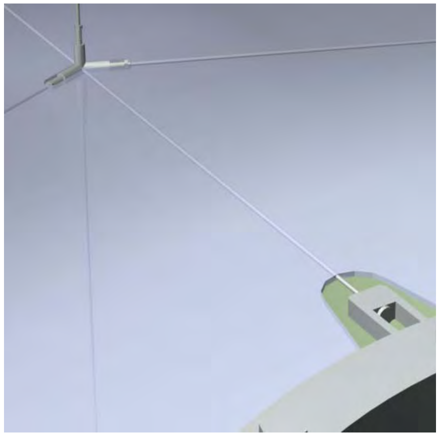
Lower Level Structure & Utilities

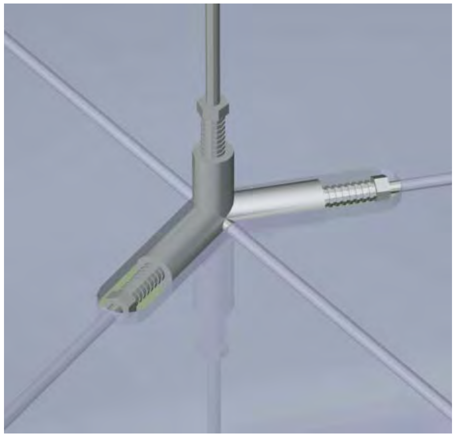
Inflatable Structures-SICSA "Pop-out" Interior Concept

HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

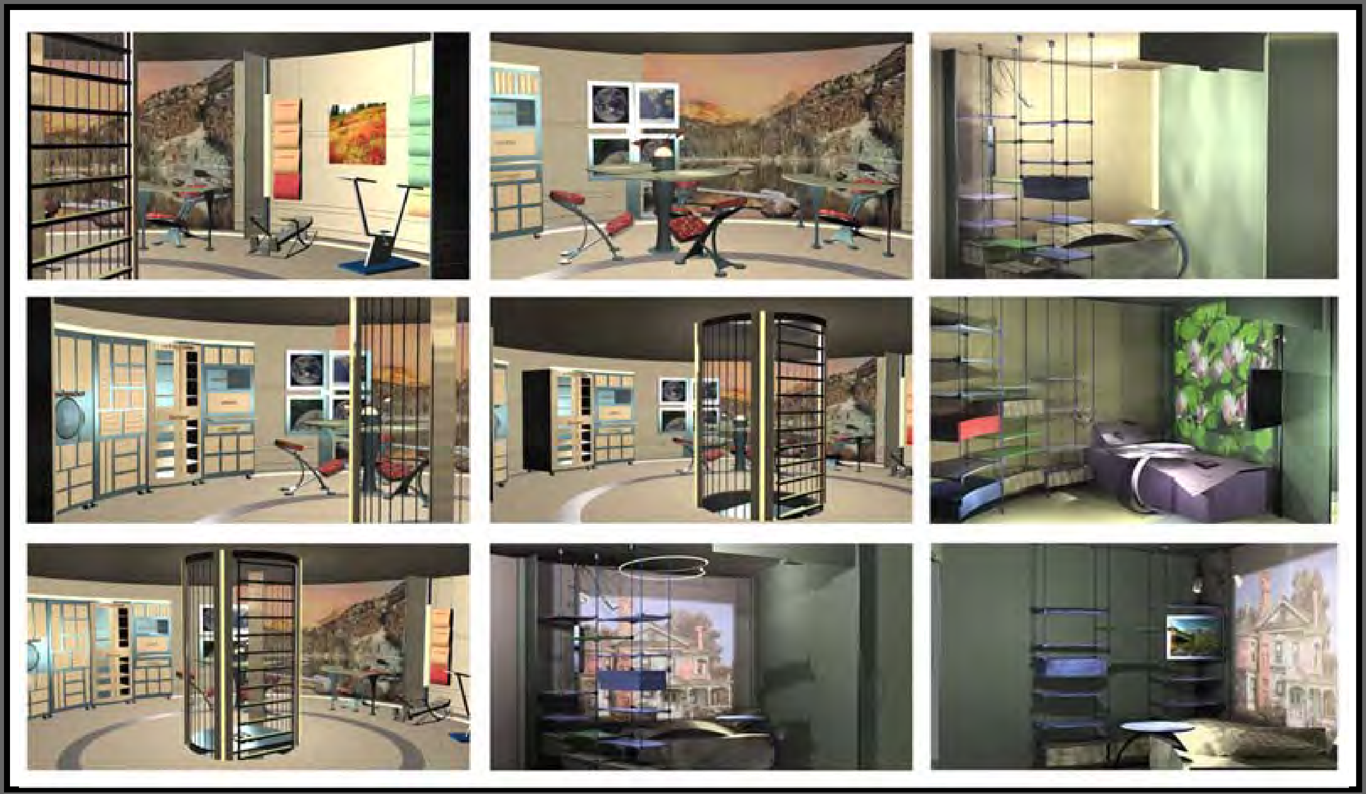






Central tension rings accommodate vertical circulation between interior levels and offer attachment fixtures for utility risers and equipment. Turnbuckles enable tension chords to be adjusted in order to minimize floor "trampoline" effects.

Inflatable Structures-SICSA "Pop-out" Interior Concept



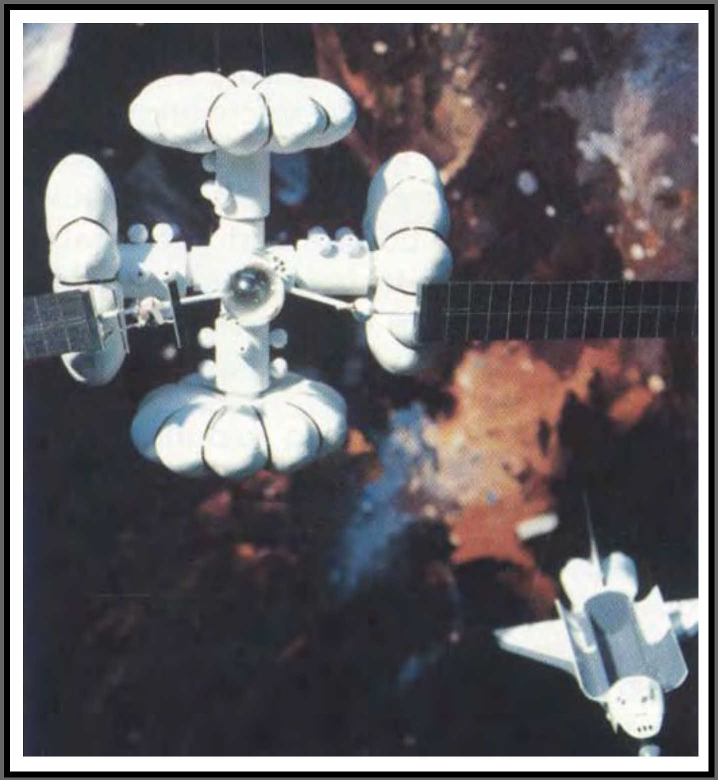
Inflatable Structures – SICSA Lunar/ MarsHab

HABITAT TYPES AND FEATURES

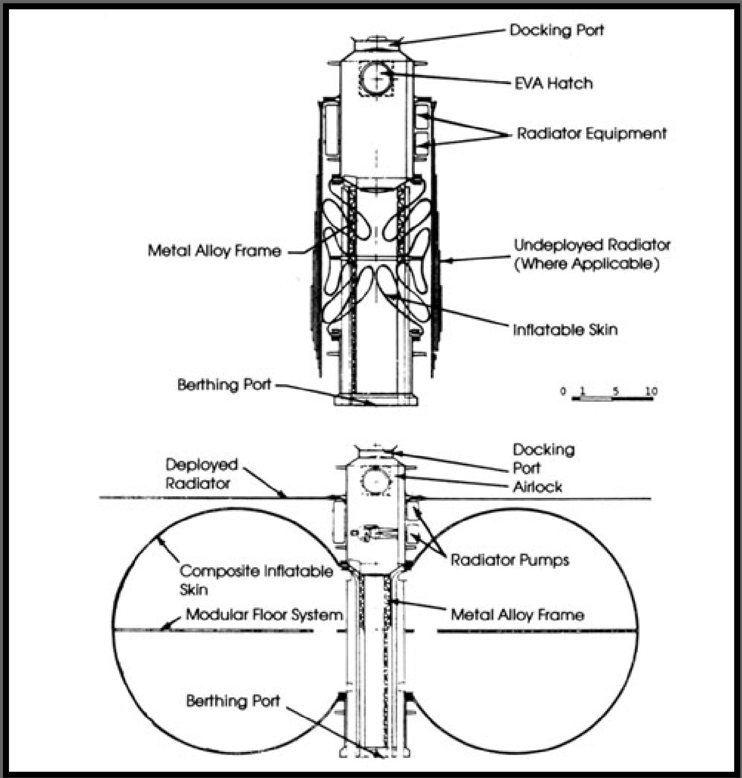
EXPANDABLE MODULES

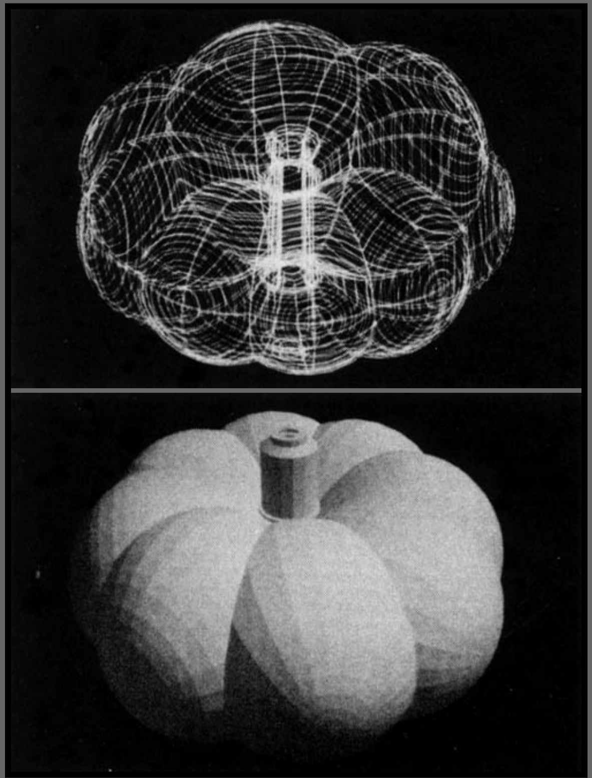
Hybrid modules offer combined advantages of inflatable and conventional elements:

- 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.



Hybrid Structures – SICSA SpaceHab Concept

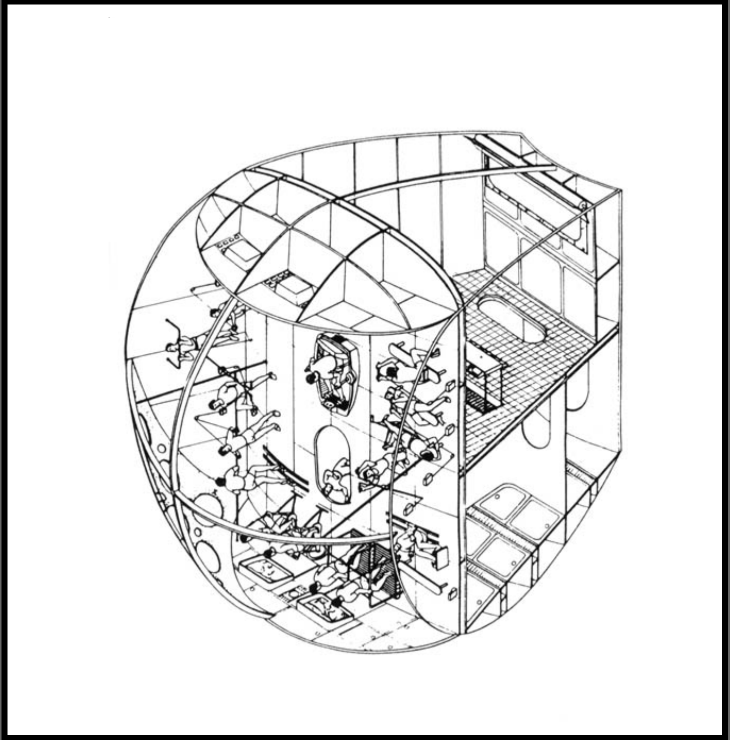


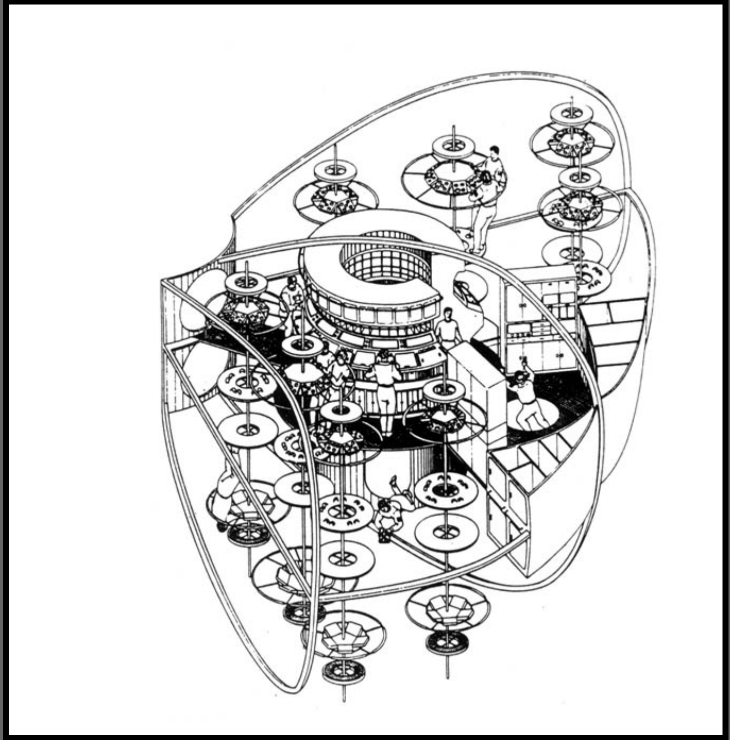


Hybrid Structures – SICSA SpaceHab Concept

HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

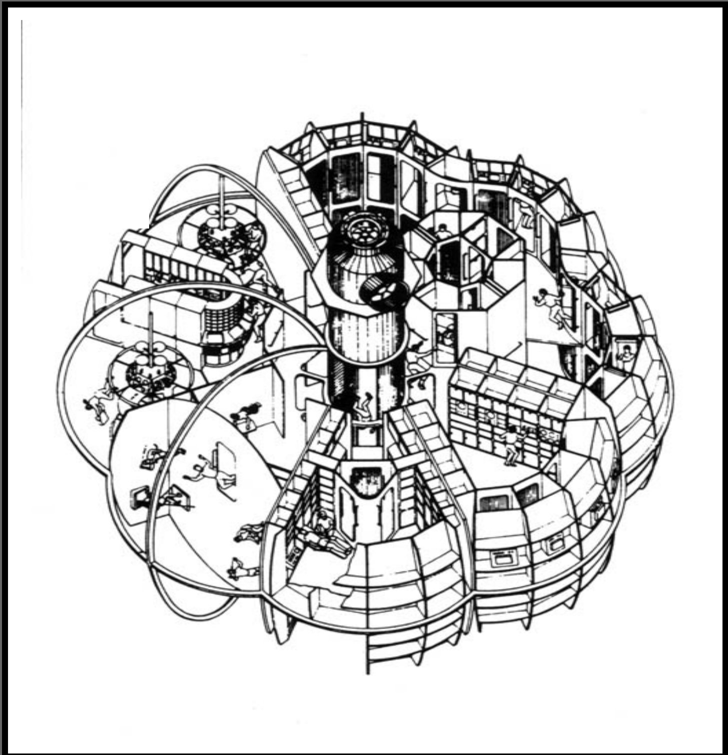


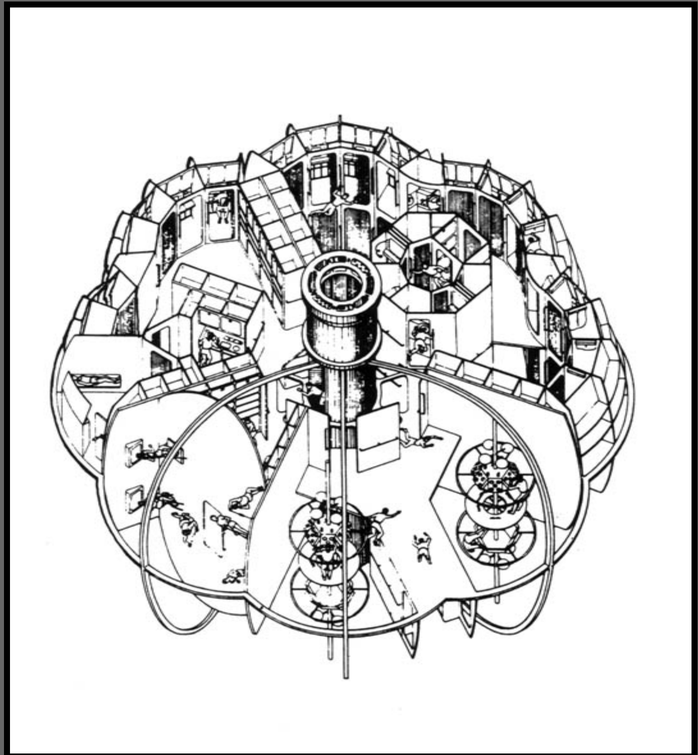


Hybrid Structures – SICSA SpaceHab Concept

HABITAT TYPES AND FEATURES

EXPANDABLE MODULES





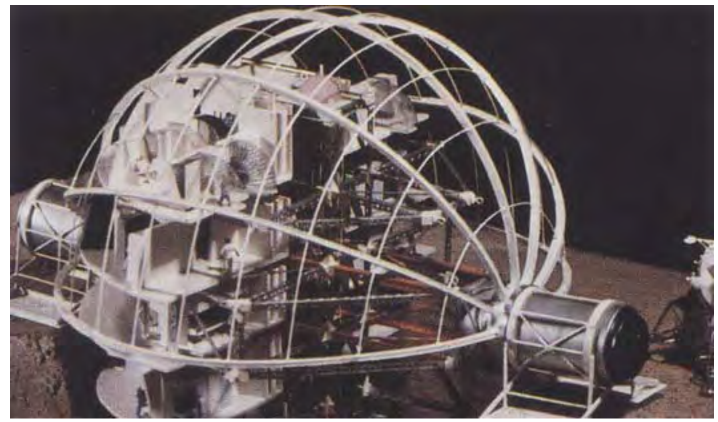
Hybrid Structures – SICSA SpaceHab Concept

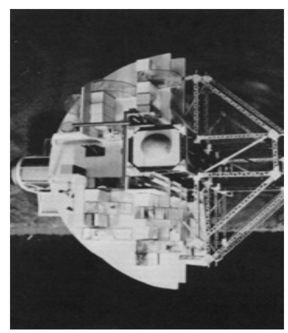
HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

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

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

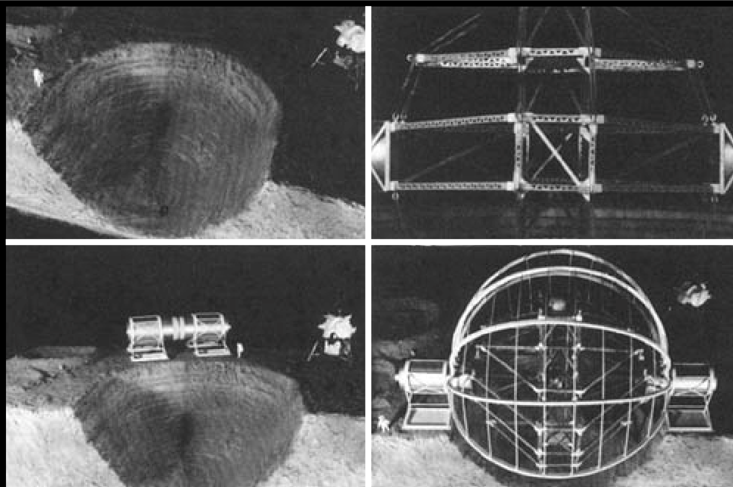




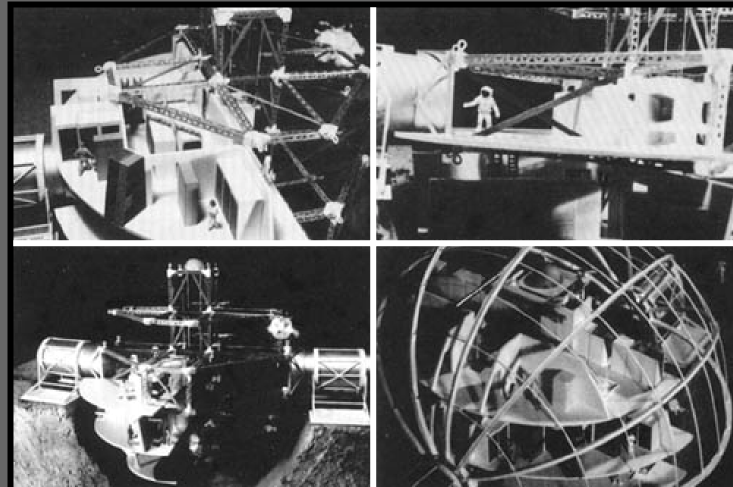
The concept incorporates 2 access/egress airlocks at opposite ends of an inflatable sphere. An internal metal structure would be assembled following envelope pressurization.

Hard and Soft Elements

Hybrid Structures – 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.

Hybrid Structures – SICSA LunarHab Concept

HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

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.

Hybrid Structures – SICSA MarsLab Concept

HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

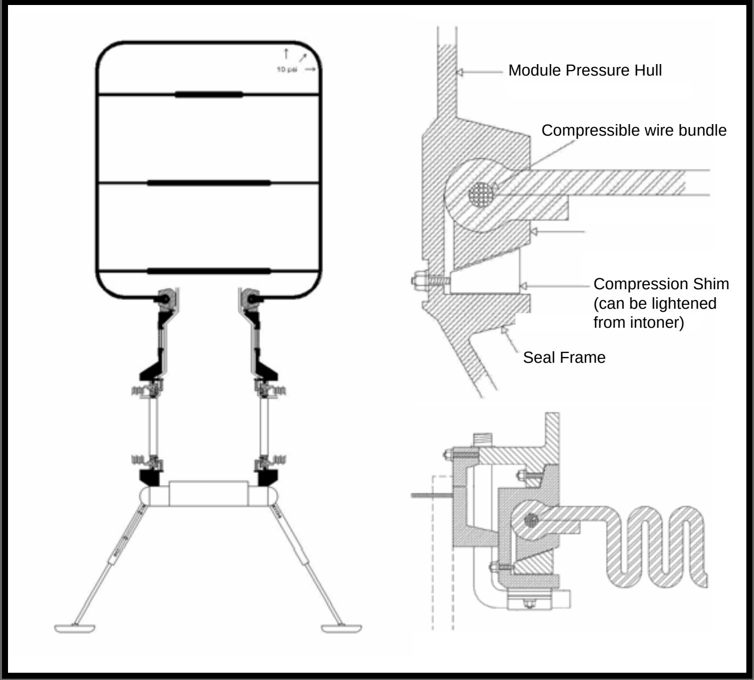
Hybrid Structures – SICSA MarsLab Concept

HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

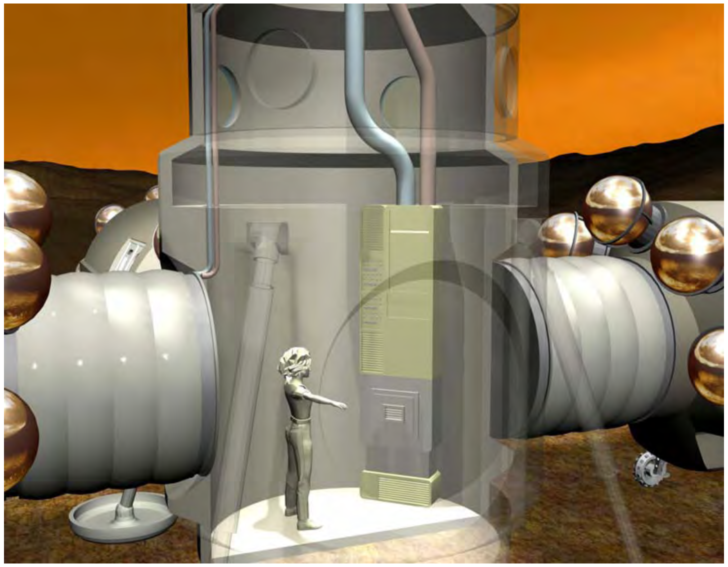
The Lunar/Mars Hab incorporates SICSA's pop-up internal inflatable system and external hard-soft interfaces that were developed and tested by the Goodyear Aerospace Corporation (GAC):

- 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.

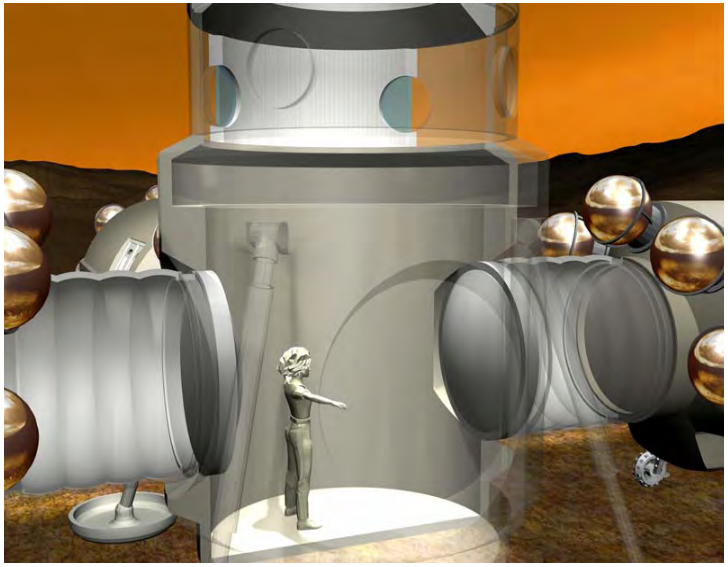


Hybrid Structures – SICSA Lunar/ Mars Hab

HABITAT TYPES AND FEATURES



Hard Section & Utilities



Hard Section & Tunnels

Hybrid Structures – SICSA Lunar/ Mars Hab

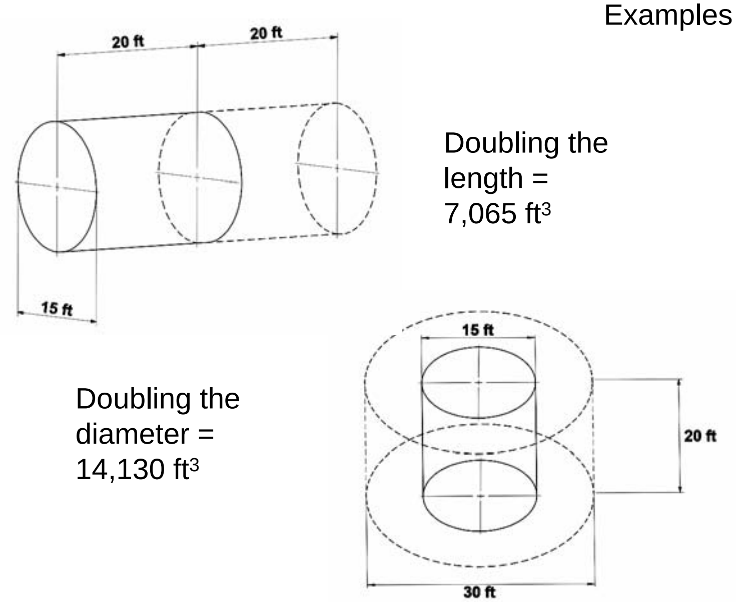
HABITAT TYPES AND FEATURES

EXPANDABLE MODULES

Maximum diameters vs. length dimensions of a habitat module have very different influences upon available interior volume and floor space.

- Since areas and volumes increase as a function of r^2, they grow much more rapidly in relation to radius than to length.
  - Conventional modules with fixed dimensions are limited in size by the dimensions of the launch vehicle cargo bay or payload shroud (along with mass limitations and CG requirements for launch and landing).
  - Telescoping modules are limited to expansion along the longitudinal axis, where ultimate floor areas and volumes for 2 segment modules will be somewhat less than twice their undeployed sizes.
  - Inflatable modules can expand both in length and diameter, affording large combined advantages.

Examples



Assuming a 15ft diameter x 20 ft long cylindrical vessel (3,534 ft^3)

Volumetric Considerations

Habitat modules can be internally configured in two general ways:

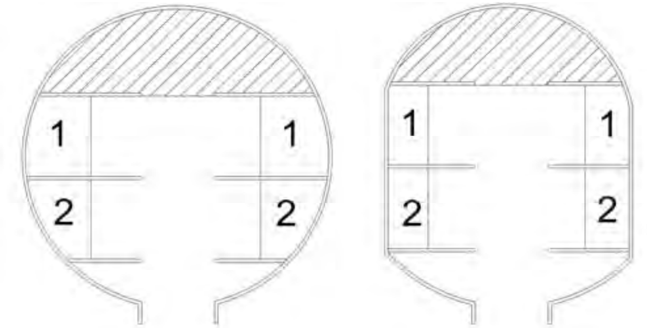
- A "bologna slice" layout stacks the floors within a spherical (A) or predominately cylindrical (B) volume:

  -Spherical schemes offer less efficient volume utilization and equipment standardization between levels (compromised head space at the upper level, and variant wall curvatures at middle levels for racks).

- A "banana split" approach (C) divides a cylindrical module parallel to the long axis, creating roughly rectangular floors:

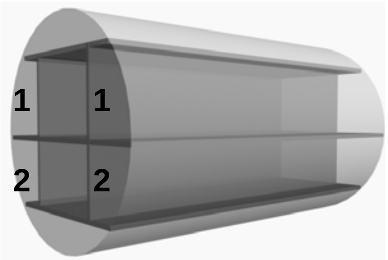
  -Multi-floor schemes have compromised upper level head space and variant wall profiles, but rectangular floors afford versatile and efficient layouts.

Layout Considerations



A. Spherical Module **B. Cylindrical Module**

Bologna-Slice Layouts



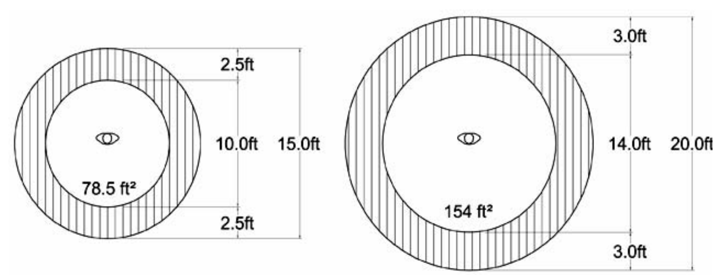
C. Banana Split Layout

Layout Options

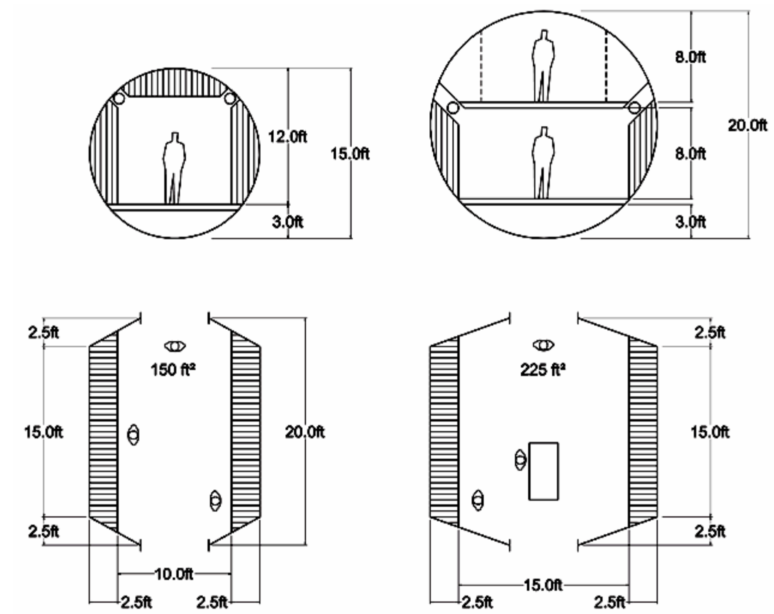
Geometric & Layout Considerations

In sizing modules, floor areas are typically more important than total volumes:

- Diameter and length dimensions must be correlated with influences upon useful interior space for people and equipment :
  - An increase in diameter from 15ft. to 20ft. will provide very little additional floor area in a 2-level scheme, even though the volume is doubled.



Bologna-slice Examples



Banana Split Examples

Volume vs. Useful Space

Bologna slice layouts are most appropriate for habitat modules with relatively large diameters :

- Smaller dimensions will severely limit sight lines, and create claustrophobic conditions.
- Perimeter racks and other vertical circulation between floors will further diminish useable space.

Usable floor area increases rapidly as a function of module diameter (radius^2):

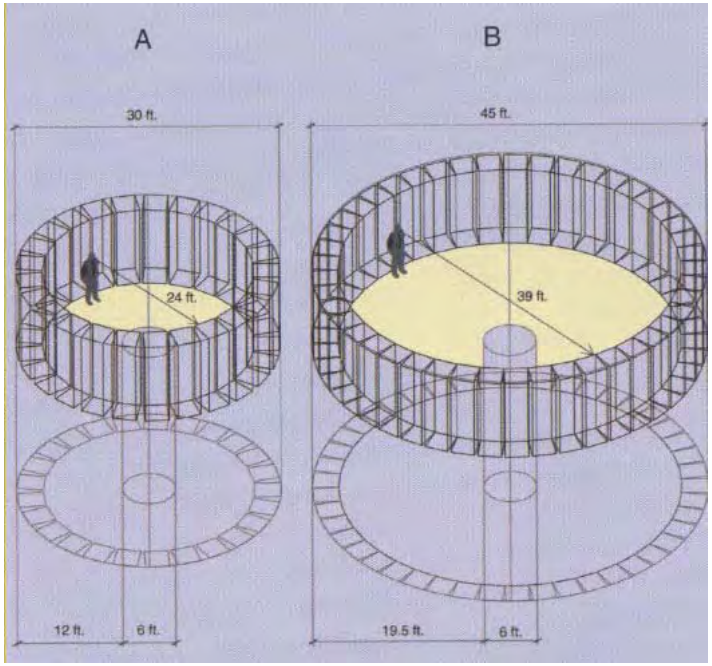
•*Total area per floor:* (A) 705 sq. ft. (B) 1585 sq. ft.

•*Total open floor area: A*) 450 sq. ft. (B) 1195 sq. ft.

•*Useful floor area*: (A) 420 sq. ft. (B) 1165 sq. ft.

•*Maximum sight distance vista*: (A) 24 ft. (B) 39 ft.

Application Considerations



Bologna Slice Layout

Interior Configurations

The banana split option is most applicable for typical horizontal modules:

- The longitudinal floor orientation optimizes sight lines.
- Rectangular floors offer versatility to accommodate efficient functional arrangements using typical racks.

Floor areas increase in a linear relationship between diameter and length:

•*Average area per floor:* (A) 545 sq. ft. (B) 1730 sq. ft.

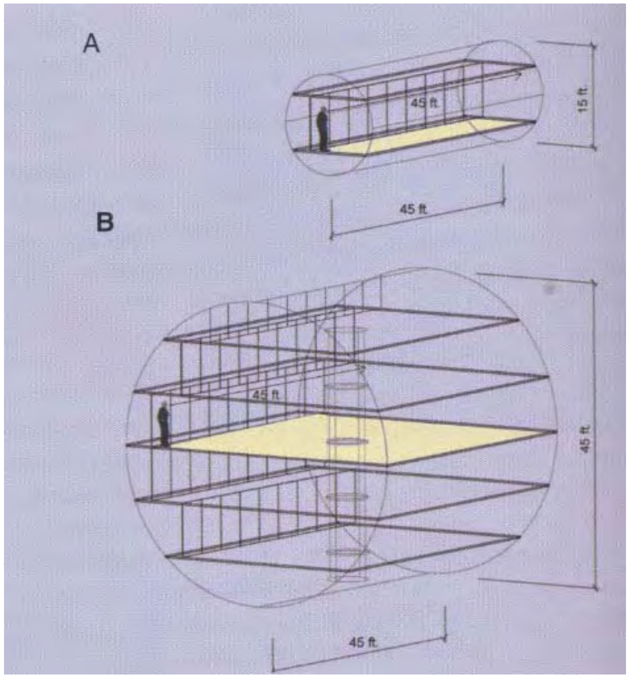
•*Average open area:* (A) 286 sq. ft. (B) 1395 sq. ft.

•*Average usable area:* (A) 286 sq. ft. (B) 1275 sq. ft.

•*Usable/ total floor area ratio:* (A) 0.5 (B) 0.74

•*Maximum sight distance vista:* (A) 45 ft. (B) 45 ft.

Application Considerations



Banana Split Layout

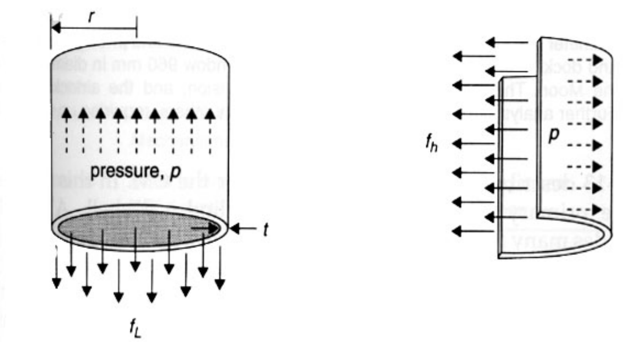
Interior Configurations

HABITAT TYPES AND FEATURES

DESIGN INFLUENCES

All habitable modules are, by definition, pressurized structures which must contain internal atmospheric pressure. (More on this subject is discussed in Part I, Section B, Space Structures and Support Systems, and Part II, Section H, Human Adaptation and Safety in Space) :

- Like all pressure vessels, the most efficient forms are familiar balloon and torroidal shapes :
  - Cylindrical module end caps typically deviate from dome shapes, and instead use conical “frustrums” which can also accommodate longitudinal launch/ deceleration thrust loads.
  - End cap protrusions must be accounted for in determining a module’s maximum length relative to the launch payload capacity length (as well as any external insulation/ shielding or attachment fixtures which add to the diameter envelope).
  - The maximum internal pressure for crew modules is usually set at 0.1096 Mpa (slightly greater than 1 atmosphere).
  - Pressure envelope safety factors are typically set at 2.0 (ultimate stress) and 1.5 (yield stress).

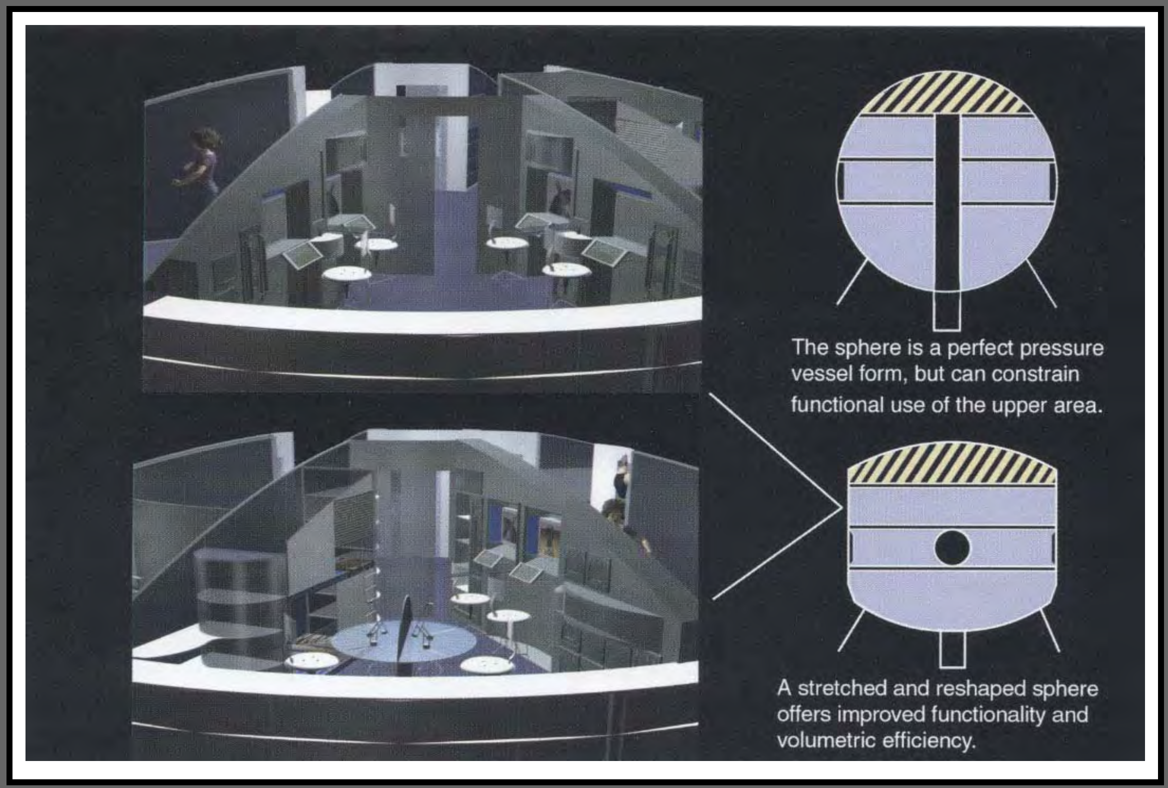


Projected area, $A_p = \pi r^2$
Area of vessel wall, $A_w = 2\pi rt$
Longitudinal stress, $f_L = \frac{pA_p}{A_w} = \frac{pr}{2t}$

$A_p = 2r$ (for unit length)
$A_w = 2t$ (for unit length)
Hoop stress, $f_h = \frac{pA_p}{A_w} = \frac{pr}{t}$

Pressurization Stresses in Cylinders

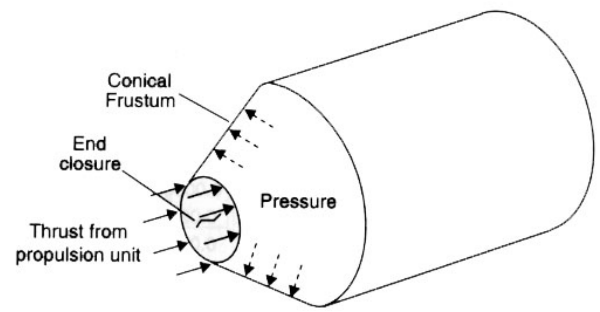
Pressure Influences on Geometry



Geometric Pressure/ Function Correlations

A module's conical frustrum typically serves as a connecting interface docking or berthing point with a spacecraft, another crew module, or an airlock:

- This end cap must be designed to accommodate external thrust/ deceleration forces as well as internal pressures:
  - If a Shuttle module is to be retrieved and landed, load factors for a "normal landing" will apply.
  - If the module will not be retrieved, "abort landing" load factors are applied in the event that something goes wrong during launch.
  - All Shuttle payloads must also be designed for "emergency landing" loads in case something goes wrong that threatens the crew (to ensure that the payload will not rupture or collapse).



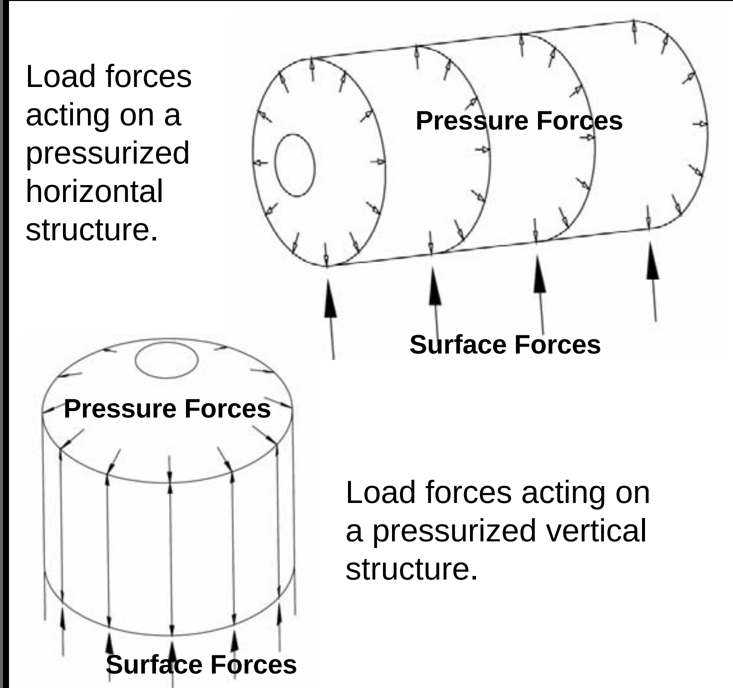
Flight Event	Load Factors n_x	n_y	n_z	Differential Pressure (MPa)
Launch	−0.2, −3.2	±1.4	±2.5	0.00965, −0.00345
Normal landing	1.8, −2.0	±1.5	1.0, −4.2	0.0200, −0.00345
Abort landing	1.5, −1.7	±1.0	0.3, −3.6	0.0200, −0.00345
Emergency landing	4.5, −1.5	±1.5	2.0, −4.5	0.0200, −0.00345

Design Load Factors

Module Envelope Loads

Modules that will be landed on a lunar/ planetary surface must be selected and designed to safely withstand impact forces:

- Although the amount of landing force stresses will depend upon the surface contact velocity and mass of the particular module and its payload, some types of modules pose greater mass/ structure challenges than others :
  - Longer, narrower cylinders that must be landed horizontally will experience load forces in their weakest structural orientation. (This is exactly like a thin aluminum beverage container that is easy to crush when the force is applied to the curved surface).
  - Larger diameter cylinders that will be landed and utilized in a vertical orientation will have a substantial force resistance advantage. (They will act like columns to resist vertical loads).
  - Modules that can be landed pressurized will be stiffened somewhat by internal atmospheres. (Inflatable and telescoping modules lack this advantage).

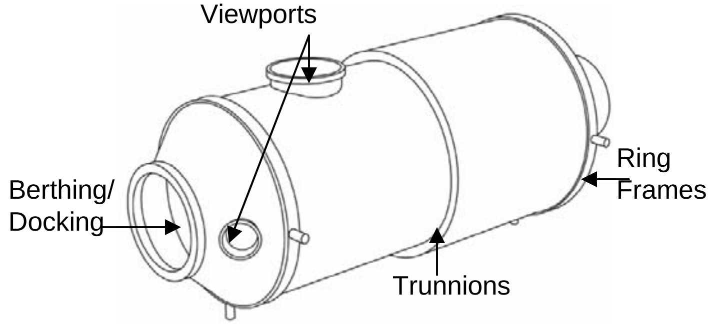


Stresses Influenced by Orientation

Landing Load Influences on Geometry

- **Primary Structures :**
  - Cylindrical shell and end caps to accommodate pressure, propulsive and docking loads.
  - Trunnion support frames to distribute/ transfer loads between the module and the transporter.
  - Integrated framing structures for windows and other pressure shell penetrations.
  - Attachment structures for berthing/ docking fixtures and airlocks.
- **Secondary and Tertiary Structures :**
  - Utility standoffs and equipment interfaces.
  - Attachment devices for internal equipment.
  - Mounts for trusses, solar arrays and other structural mechanisms.

Key Structural Elements



The structural mass of any module will be influenced by its size; the number and types of berthing/ docking, hatch and window assemblies and other special features. As a general rule of thumb, it can be estimated that :

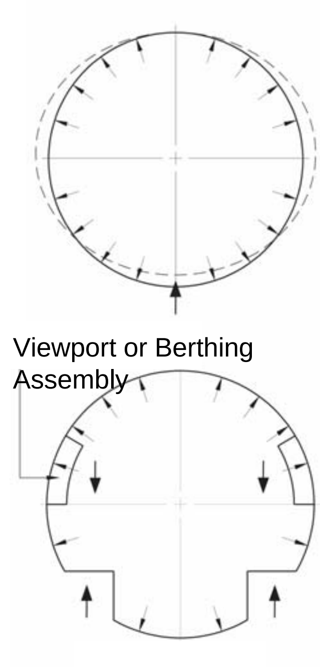
- Primary & secondary structures = 80% dry mass
- Hatches, windows & other items = 10% dry mass
- Thermal protection/ shielding = 10% dry mass

Rough Dry Mass Structural Estimates

Structural Elements & Mass

SICSA has proposed a modified horizontal landing module geometry that redistributes impact load forces to the side wall structure areas, and also reinforces the lower structure for additional stiffness and strength:

- Angle-shaped reinforcement is provided at opposite sides of the undercarriage to distribute loads between two longitudinal beams.
- The beams transfer loads in a more vertical direction, which in some instances can use viewports, berthing and other structures mounted into the walls for an advantage.
- The undercarriage structure can support landing struts and wheel assemblies that might be incorporated to dampen landing loads and accommodate surface mobility for relocations.



Centralized forces acting on a horizontal cylinder will distort the circular cross section, stressing areas of greatest bending.

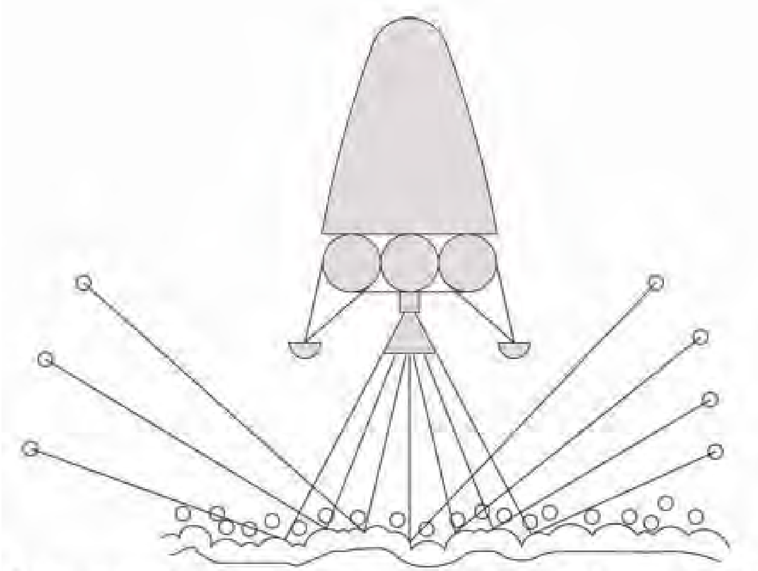
A modified approach can distribute loads and incorporate landing/ mobility assemblies.

Load Distribution and Stiffening

Modified Landing Module Geometry

Module and lander system selection/ design must also consider means to address potentially dangerous environmental and operational hazards :

- Surface conditions on the Moon and Mars pose special challenges for descent/ ascent operations:
  - Global dust storms and local dust devils on Mars can obscure landing visibility.
  - Electrostatic dust and extreme temperatures can damage ascent flight systems.
  - Landing/ ascent thrusters can hurl surface rocks long distances at dangerous velocities.
  - Little or no atmosphere makes parachutes ineffective.
  - Rocky and hilly surface terrain can damage or overturn landed payloads.



Low-gravity conditions and little/no atmospheric drag will cause rocket plumes to propel surface rocks on long ballistic trjectories.

Special Surface Landing Issues

As discussed in Part III, Section A of this lecture series, SICSA has explored a variety of module-lander combination possibilities and concepts:

- Each module/ payload type presents special issues and requirements :
  - Approaches that place large elements above landers create vertical access/ egress and cargo unloading problems.
  - Approaches that involve deliveries of horizontally-oriented payloads with propulsion either above or below encounter similar CG balancing challenges.
  - Long modules present vertical CG problems on the surface, and horizontal CG problems during the landing process.
  - Surface ejecta is an issue with all approaches, but might be mitigated using tethered landers that hover above while modules are being lowered to the final descent stage.

Propulsive Surface Landings

Module Lander Concepts

SICSA identified and characterized several different schematic and design approaches for lander systems to place modules and other large payload elements on the lunar surface. Important considerations that have driven the selections and assessments of the different lander design options include the following:

1. Launch Manifesting and Orbital Assembly:
   - Compliance within allowable launch mass and volumetric payload faring constraints.
   - Number of automated orbital rendezvous and docking assembly events required to mate landers with payloads.

2. Interfaces for Orbital Transfer and Landing
   - Single interface point at or near overall CG location.
   - Use of a common, universal docking interface.

3. Footprint of Thruster Pattern for Landing:
   - Geometric distribution for balance under nominal conditions.
   - Ability to compensate under engine-out malfunction conditions.

4. Surface Hazard Mitigation:
   - Proximity of thrusters to the surface influencing risks of damage from ballistic ejecta.
   - Potential to provide soft landings without free fall to avoid shock damage to vulnerable structures, equipment and interfaces.

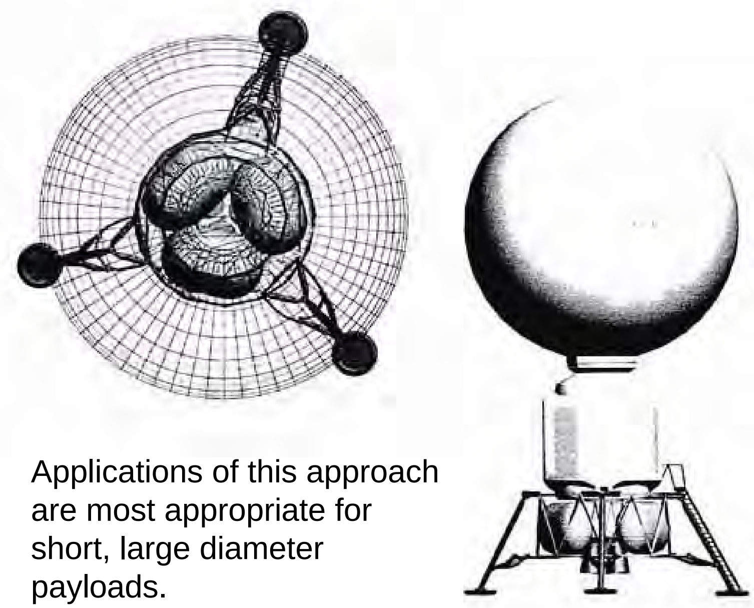
5. Proximity of Payload to Surface:
   - Vertical EVA access/ egress distance for habitable modules.
   - Means to deploy rovers and cargo from unpressurized carriers.

6. Commonality if Elements and Systems:
   - Applicability to diverse pressurized and unpressurized cargo deliveries.
   - Compatibility with surface transportation and deployment scenarios.

7. Influences Upon Mass and Economy:
   - Minimization of descent fuel requirements.
   - Optimization of useful payload volume deliveries to the surface.

Placing a vertically-oriented module (or other payload) above a lander in the conventional fashion affords benefits and liabilities :

- **Advantages:**
  - This approach can be used for habitation modules and unpressurized logistics carriers.
  - The same system might be modified to provide a 2-stage crew descent/ ascent vehicle, using the landing stage as an ascent platform.
  - The scheme offers a symmetrical propulsion footprint for engine-out recoveries.
  - Raising the payload above the lander may provide some surface ejecta protection.
- **Disadvantages** :
  - Raising the module or other payload high above the surface makes access/ egress/ unloading more difficult.
  - The high CG may cause tall/ small-diameter applications to be unstable for landing and surface mobility.



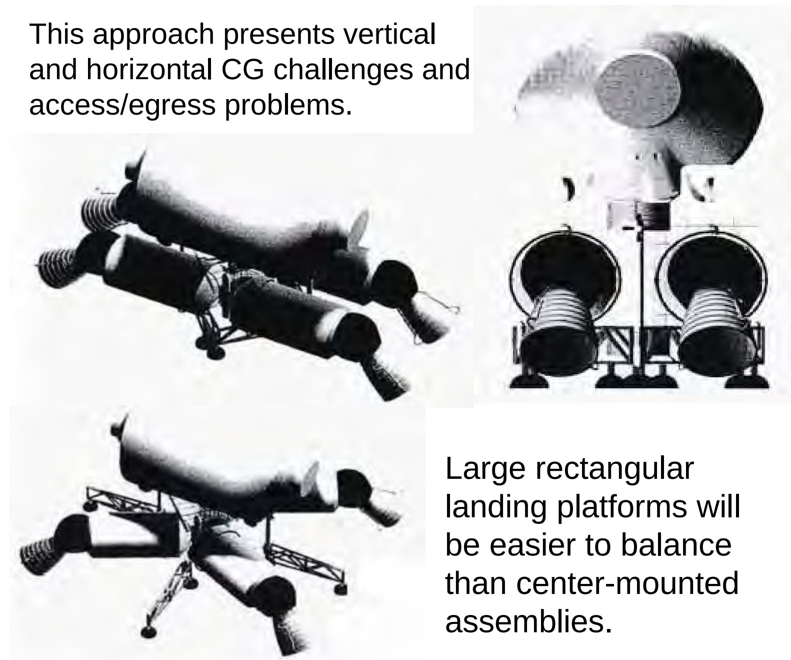
Applications of this approach are most appropriate for short, large diameter payloads.

Lander Below Vertical Module

Lander Option Considerations

Placing a horizontally-oriented module (or other long payload) above a lander presents CG balancing challenges common to all horizontal deployments :

- **Advantages:**
  - A rectangular lander with engines positioned at or near corners can improve landing and surface stability over a more centralized thruster approach.
  - Raising a payload above the lander platform may provide some height and structural shielding to provide surface ejecta protection.
  - A broad landing footprint will enhance surface stability.
- **Disadvantages** :
  - Corner thrusters can make engine-out recoveries particularly difficult with long lander platforms.
  - Raising the payload above the surface will make access/ egress/ cargo unloading more difficult.
  - Removing a large module from the propulsion platform may be difficult and impractical without big cranes which will add transfer mass.



Lander Below Horizontal Module

Fixing a lander above a vertically-oriented module (or other payload) potentially offers some advantages, but also presents some difficult problems:

- **Advantages :**
  - The payload can be centered with its CG aligned along the drop axis.
  - It might be able to place a payload directly on the surface, except for the fact that the lander mass would add large loads and create a very high CG.
- **Disadvantages :**
  - Broad placement of the thrusters and/ or a splayed thrust vector would be required to avoid rocket plume impingement onto the payload.
  - The thruster plumes would not be high enough off the surface to prevent ballistic ejecta from endangering the module.
  - Landing struts would have to be placed on the module/ payload , capable of supporting both the landed element and the lander.

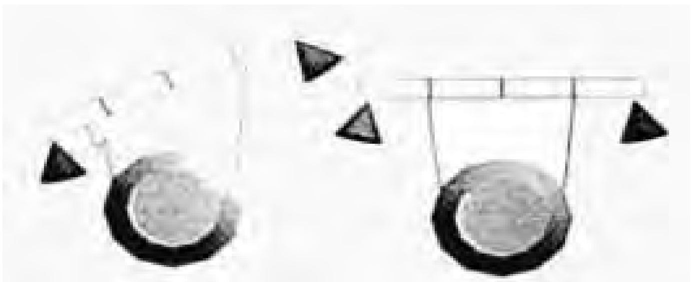
Fixing a lander above will create a very high CG at the surface to create stability and mobility problems.

Lander Above Vertical Module

Lander Option Considerations

A tethered lander approach overcomes many of the disadvantages presented by the fixed overhead concept :

- **Advantages :**
  - The lander can remain high enough above the surface to minimize ejecta damage risks.
  - The module/ payload can be placed directly on the surface while the lander hovers above.
  - Lander tethers can disconnect after the payload is on the surface so that the system can be discarded (and not contribute to the module CG or mass loads).



A targeted landing using surface beacons will be needed to avoid cross-range corrections.

Pendulum Effect Considerations

Tethered Lander Above Module

Lander Option Considerations

SICSA's proposed tethered lander concept is designed to be launched in a conventional rocket fairing with or without its payload attached (depending upon payload and fairing size):

- Applying the same general design, the approach can be adapted for use with horizontal modules, vertical modules or crew descent/ ascent vehicles :
  - For crew ascent/ descent vehicles, the tether system would be attached prior to placement in the launch shroud. (In other applications, the lander and payload might dock together in LEO.)
  - Gimbaled lander engines would pivot down and propulsively slow the entire assembly to a hovering position above the surface.
  - Tethers would deploy to soft-land the payload, and then release it.
  - Relieved of the payload mass, the lander would gain altitude, fly a safe distance from the drop site, and be sacrificed.

Tether System Attached

Tethers Deploying

Engines Deployed

Payload Released

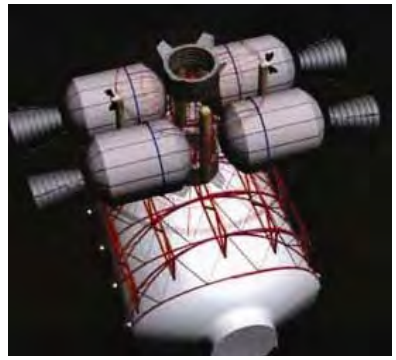
Crew Descent/ Ascent Vehicle landing

SICSA Tethered Lander Concept

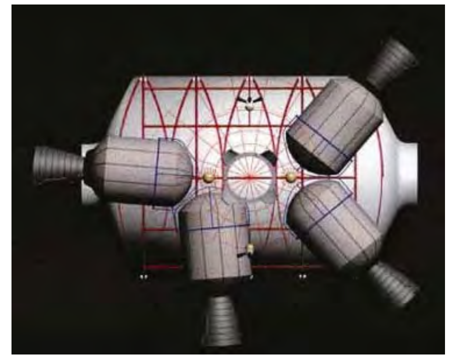
SICSA

Countermeasures are essential to compensate for loss of a thruster during a landing procedure:

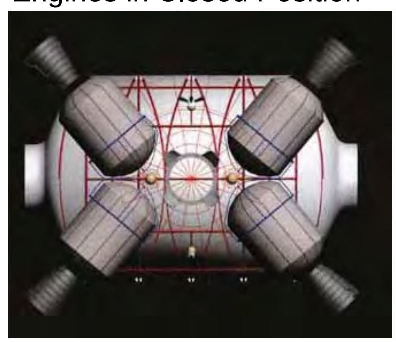
- The tethered system offers an important engine failure contingency advantage :
  - The gimbaled rocket footprint configuration can adapt to provide a better geometry to compensate for loss of any engine.
  - Placement of the engines at corners above the payloads provides a broad footprint to enhance stability under nominal and contingency circumstances.
  - The same general lander design can be applied for vertical and horizontal payloads.
  - Lander positions can be adjusted for varying payload center of gravity locations.



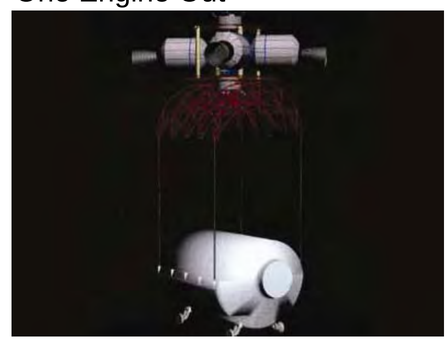
Engines in Closed Position



One Engine Out



Normal Landing Position

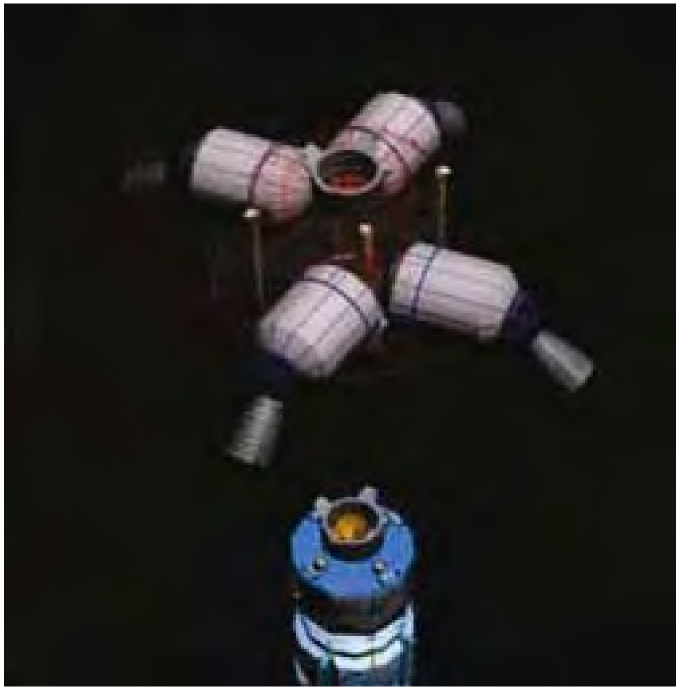


Tethered Deployment

Compensation for Engine failure

SICSA Tethered Lander Concept

Engines in Closed Configuration



Engines in Operational Configuration

SICSA Tethered Lander Concept

Tethered Deployment of Horizontal Module

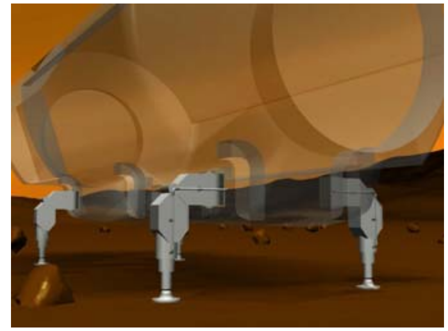
Tethers Released and Lander Sacrificed

SICSA Tethered Lander Concept

Module Strut Deployment


Pre-Lading Configuration


Shock Deployment Initiation


Shock Deployment Complete

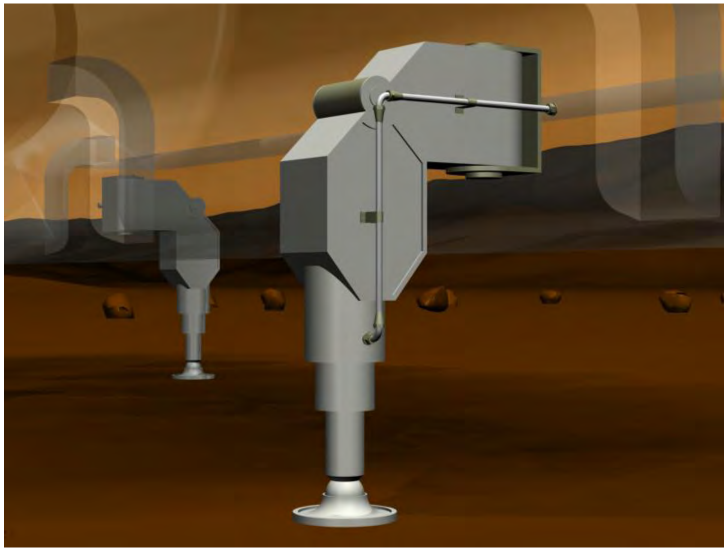
Module Wheel Deployment


Wheels in Stowed Configuration


Wheel Deployment Initiation


Wheel Deployment Complete

SICSA Horizontal Landing Module


Strut Detail


Wheel Detail

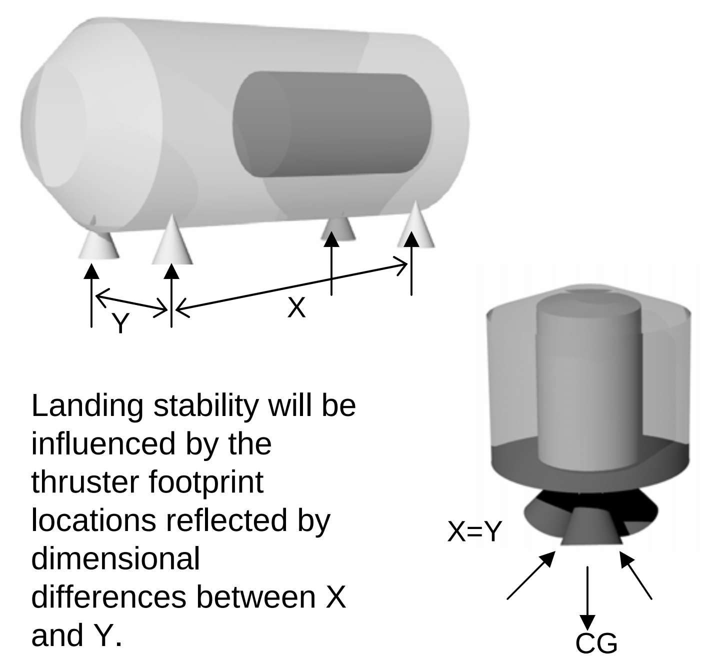
SICSA Horizontal Landing Module

HABITAT TYPES AND FEATURES

SURFACE DELIVERY AND MOBILITY

Module types and landing orientations have important center of gravity design implications which must be accounted for in designing structures and propulsive landing systems.

- Different module types and applications will produce varying loads and distributions which must be accommodated in all system planning :
  - Horizontally-oriented modules will be most challenging because loads will be variably distributed along the axis perpendicular to the final landing vector, potentially creating large imbalances.
  - Vertically-oriented modules will tend to concentrate loads along the landing vector, maintaining the CG in a more central location.
  - Imbalances may be exacerbated during non-vertical entries and cross-range corrections.

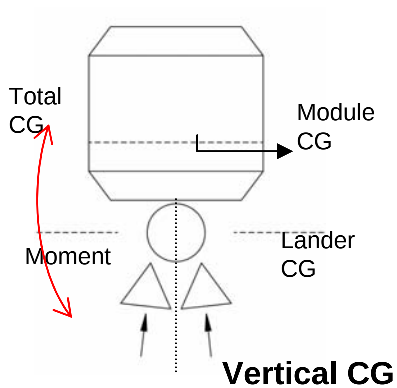


Horizontal vs. Vertical Modules

Landing Load CG's

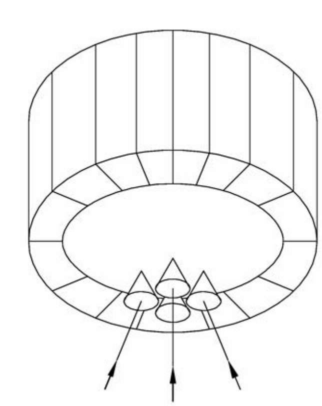
Vertically-oriented modules can be landed with centralized or more broadly distributed thrusters:

- Clustered centralized arrangements present advantages and disadvantages:
  - Advantage : Concentration of gimbaled thrusters about 1 point makes it easier to compensate for an engine loss through closer symmetry.
  - Disadvantage : Concentration of thrusters creates a central fulcrum which is less stable, making vertical CG moment effects difficult to correct.



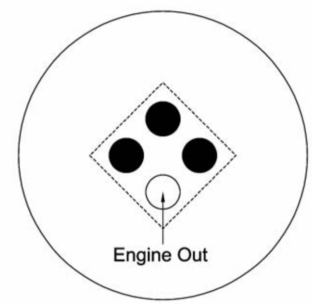
The total CG changes as landing propellant is depleted, requiring the thrust vector to expand.

Vertical CG Shifts



CG balancing is more challenging as the vertical distance between module thrusters decreases.

Under an engine-out condition, only small thruster vector adjustments are needed.

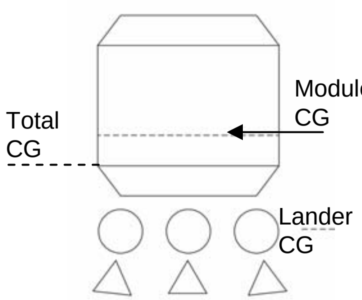


Centralized thruster Pattern

Vertically-Oriented Landings

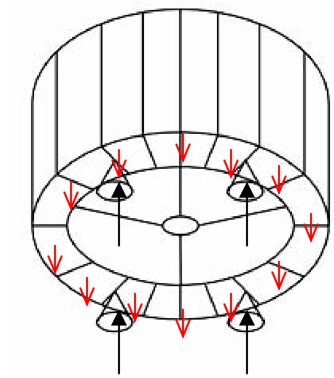
Vertically-oriented landings can utilize a distributed thruster approach which is more stable under nominal conditions, but makes it more difficult to compensate for an engine failure:

- Thrusters are assumed to be attached to a landing system :
  - Advantage : The thrusters act like legs on a table, providing a broad footprint with force vectors nearly aligned with the landing vector.
  - Disadvantage : An engine-out creates a large footprint asymmetry that must be compensated by differential thrust or vector changes.



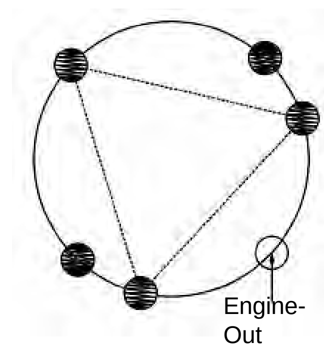
Changes in propellant mass are less critical because the total system is more stable.

Stability Under Nominal Conditions



Thrust forces are directed close to the landing vector for high efficiency.

Broader separation of thrusters cause engine-outs to require larger thrust vector corrections.

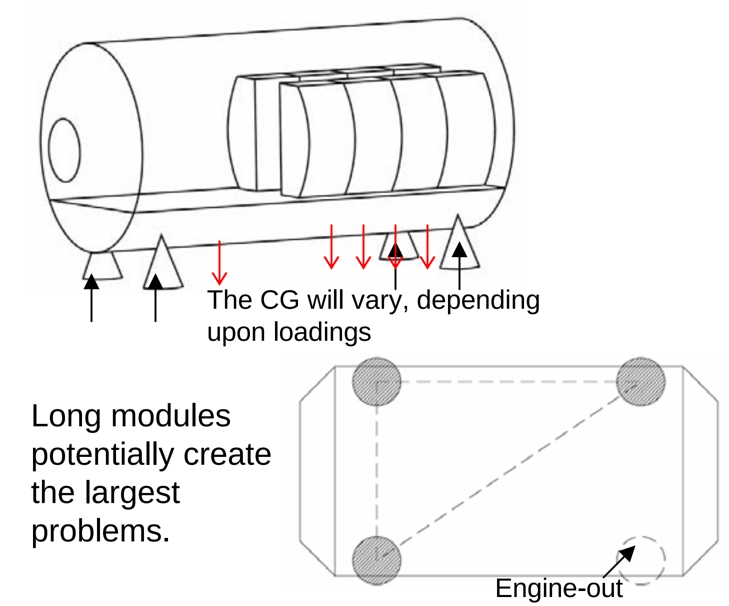


Distributed Thruster Pattern

Vertically-Oriented Landings

Horizontally-oriented modules are inherently unbalanced elements since it is unlikely that internal equipment, cargo, fluids and structures (such as airlocks) will be organized solely for landing optimization

- The extent of these imbalances will be influenced by a variety of factors :
  - The relative length vs. width of the modules will determine deviations from bi-axial symmetries of the thruster footprints (long narrow modules will present worst cases).
  - Deviations from bi-axial symmetry will exacerbate engine-out gimbal compensations.
  - Landing the modules with fluids vs. “dry” will determine mass balances and possible “sloshing” effects that will impede stability.
  - Habitat modules are likely to concentrate heavier utility-dependent equipment in one sector which may not be centrally located.



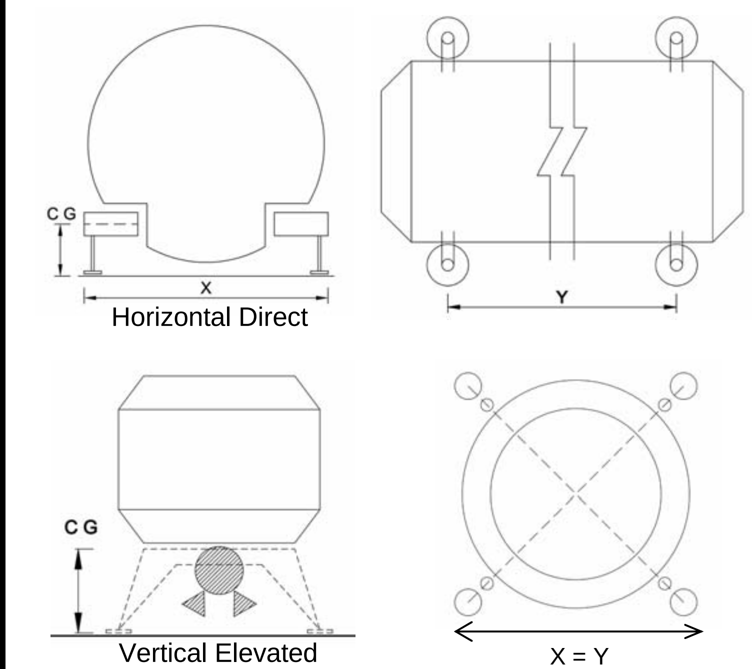
Imbalances and b-axial asymmetries present special challenges.

Distributed Thruster Pattern

Horizontally-Oriented Landings

Module types and designs must be correlated with methods in which they will be landed, the stability afforded by their footprint geometries, and the location of total module/ landing system CGs above the surface.

- Landing system options that place the modules high above the surface vs. directly on the surface influence optimal module geometries:
  - The "horizontal direct" approach can facilitate surface stability for landing and relocation by lowering the CG near the surface , minimizing chances of tipping over on hilly/ rough terrain.
  - The "vertical elevated" approach raises the CG (and crew access/egress height), but can be relatively stable provided that the footprint is broad and symmetrical.



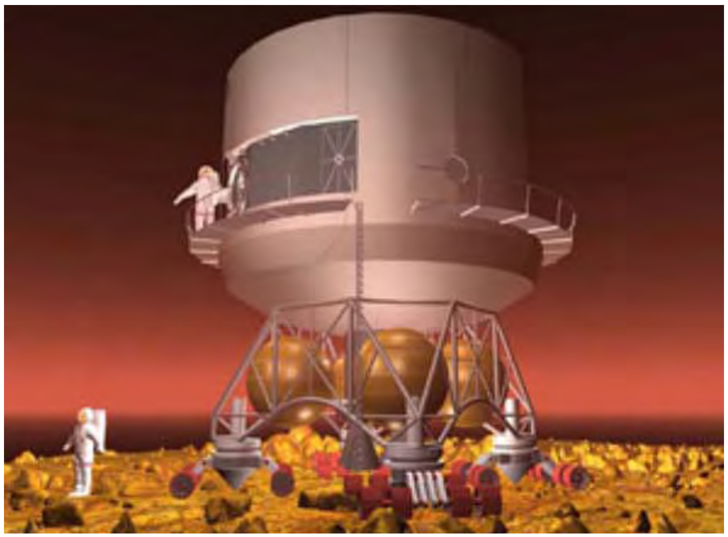
Stability on the surface is influenced by footprints and CG height

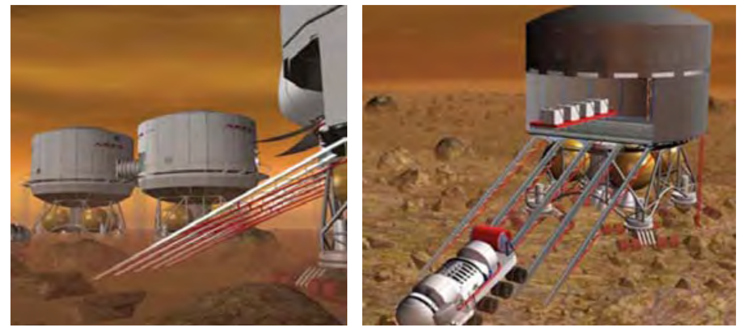
Landing Load Examples

Surface Stability & Mobility

HABITAT TYPES AND FEATURES

SURFACE DELIVERY AND MOBILITY



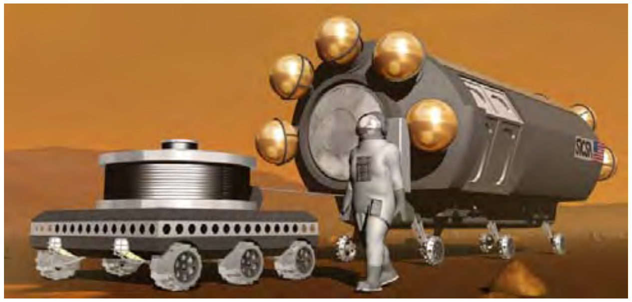


Traditional approaches that place propulsion systems below modules create high access/ egress points for EVA-suited crews, pressurized rover dockings and cargo unloading from logistics modules.

Module Access/ Egress Considerations

SICSA Inflatable Hybrid Module

SICSA Telescoping Surface Module



SICSA Conventional Surface Module

Vertical Elevated & Horizontal Direct Concepts

HABITAT TYPES AND FEATURES

SURFACE DELIVERY AND MOBILITY

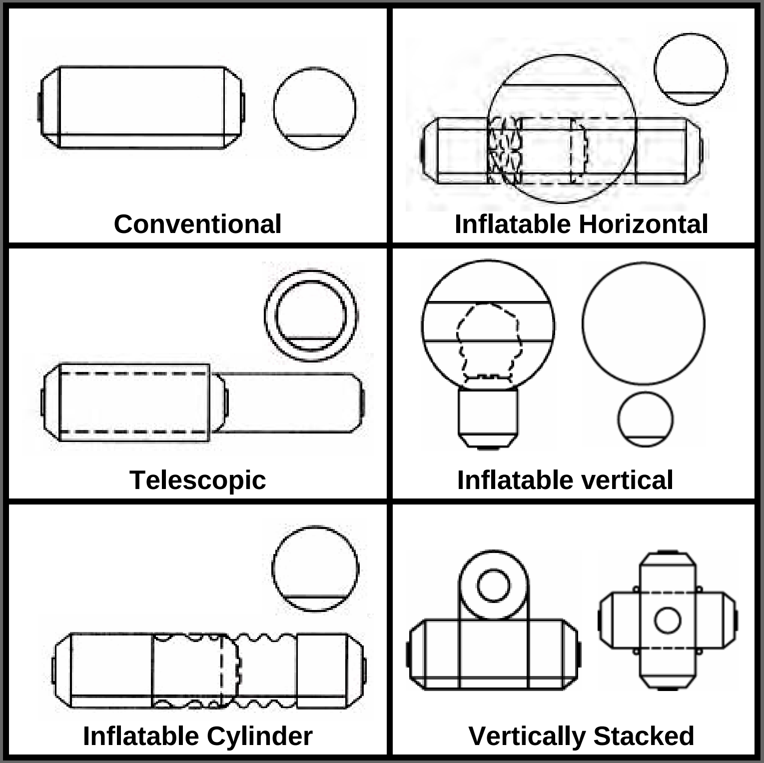
Based upon comparative assessments, SICSA recommends that use of tethered landers located above horizontally oriented payloads are preferred over other options, offering the following benefits:

- They offer versatility, enabling the same basic system to be used for either vertical or horizontal payloads, including habitable inflatable and conventional modules, logistics carriers, and crew descent/ ascent/ Earth return vehicles.
- They enable soft landings of vulnerable and costly elements, avoiding free fall damage to fragile pressure hulls and equipment/ interfaces that will be critical for life safety and operational reliability.
- They can afford a symmetrical thruster footprint for landing stability, and can readily accommodate pattern configurations for 1 or even 2 engine-out failures.
- They can minimize or avoid ejecta ballistic hazards to payloads and nearby facilities by placing thrusters higher above the surface. In doing so, they can enable distances between site facilities to be considerably reduced in comparison with other options, minimizing surface transport requirements and transfer/ EVA times.
- They can place habitats and logistics carriers directly on the surface, facilitating EVA ingress/ egress and rover/ cargo deployments.
- By eliminating the need to land with payloads, they can minimize the size and mass of elements that must be relocated from surface landing areas, to facilitate transport and positioning.
- They can be used in combination with wheeled modules that do not require lifting and positioning onto maneuverable carriers that would involve special cranes or other complex devices and operations for mounting/ de-mounting.

Tethered vs. Conventional Landers

SICSA conducted a comparative review of 6 different module concepts that might be applied if launch and landing payload size is limited to a 3.75m diameter x 12m long capacity. (This restraint eliminated bologna-slice conventional hard modules from consideration).

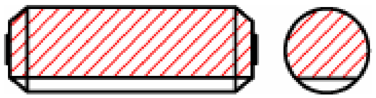
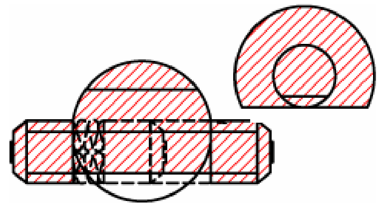
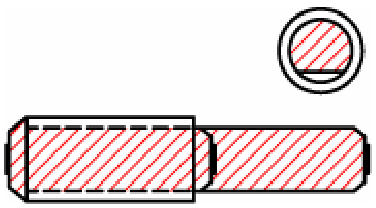
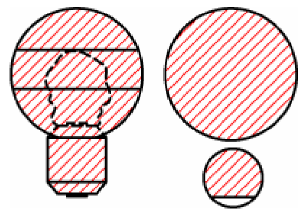
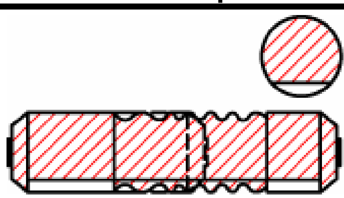
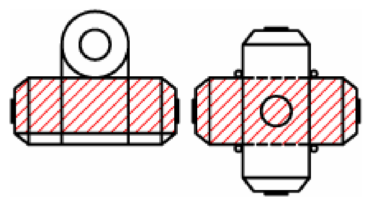
- The construction approaches were assessed according to 5 different feature categories :
  - **Volumetric features** : Capacities and efficiencies to accommodate crews and equipment.
  - **Pressurization factors** : The number and types of atmospheric seals that can present potential leak/ maintenance problems.
  - **Surface transportation and deployment** : Issues associated with relocations and preparations for occupancy.
  - **Surface configuration and growth** : Versatility to adapt to varying site layouts and staging options.
  - **Outside viewing** : Flexibility to accommodate windows without compromising structural integrity and internal functional use.



Module Concepts Considered

HABITAT TYPES AND FEATURES

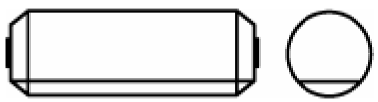
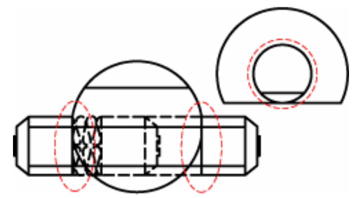
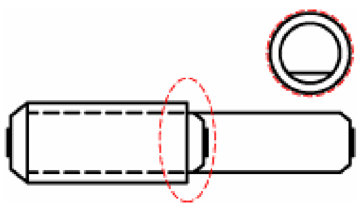
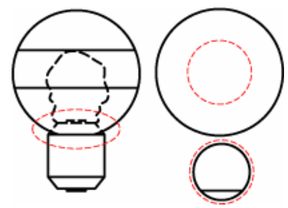
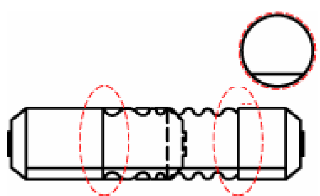
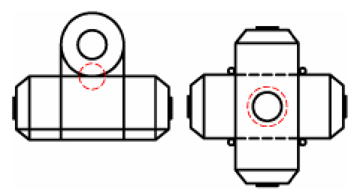
FEATURE COMPARISONS

 **Conventional**	All equipment can be integrated prior to launch. No expansion is possible.	 **Inflatable Horizontal**	Area of the inflatable section expands rapidly with increased diameter (a function of r^2).
 **Telescopic**	Floor area can expand at approx 1:1 ratio, but telescoping section has smaller diameter.	 **Inflatable vertical**	Area of the inflatable section expands rapidly with increased diameter (a function of r^2).
 **Inflatable Cylinder**	Floor area expands as a direct function of inflatable section length.	 **Vertically Stacked**	Expansion is only possible by adding modules. Vertical circulation will reduce useful space.

Volumetric Characteristics

HABITAT TYPES AND FEATURES

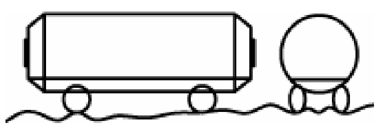
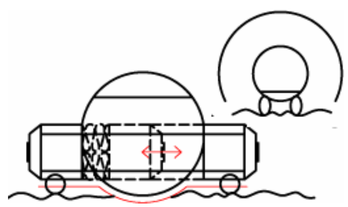
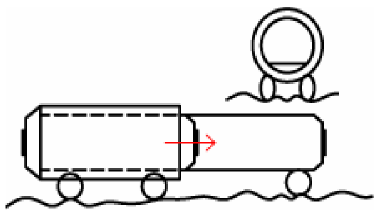
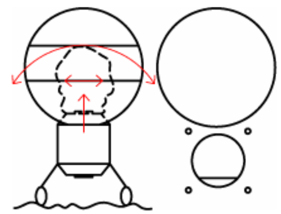
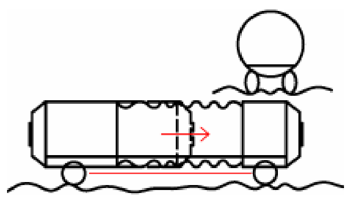
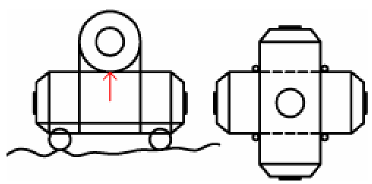
FEATURE COMPARISONS

 **Conventional**	Uses standard module construction and seals with no complications.	 **Inflatable Horizontal**	Requires two hard/ soft seal attachments, presenting possible leak and maintenance problems.
 **Telescopic**	Requires a hard seal at the mating juncture between the two module sections.	 **Inflatable vertical**	Requires only 1 hard/ soft seal attachment to minimize leak and maintenance problems.
 **Inflatable Cylinder**	Requires two hard/ soft seal attachments, presenting possible leak and maintenance problems.	 **Vertically Stacked**	Pressure-tight interfaces at top and bottom of modules present extra complications.

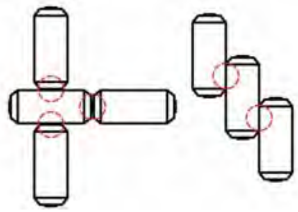
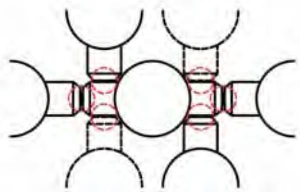
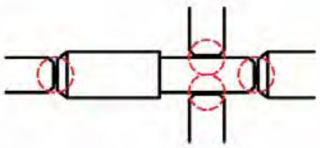
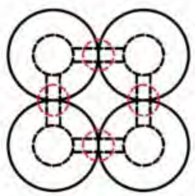
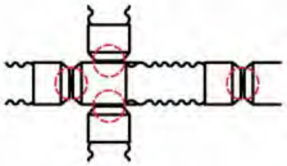
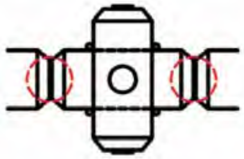
Pressurization Characteristics

HABITAT TYPES AND FEATURES

FEATURE COMPARISONS

 Conventional	Long carrier or wheel base may present difficulties on hilly/ rocky surfaces.	 Inflatable Horizontal	Wheel or carrier base can be short, but a support structure will be needed to keep the module rigid. The bottom of the inflatable must be above the surface.
 Telescopic	Long carrier or wheel base may present difficulties and deployment extension problems.	 Inflatable vertical	Once on the surface, the compact footprint may be maneuverable, but unstable on a rocky/ hilly terrain.
 Inflatable Cylinder	Wheel or carrier base can be short, but a support structure will be needed to keep the module rigid for landing/ deployment.	 Vertically Stacked	Mobility for individual modules is the same as conventional, but raising, positioning and securing them in place may be very difficult.

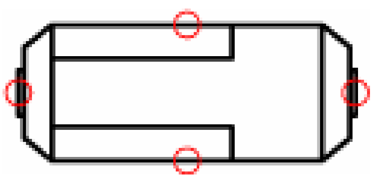
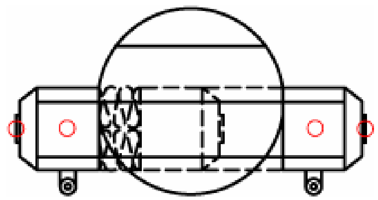
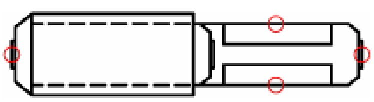
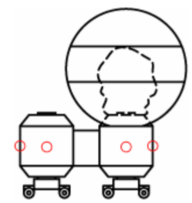
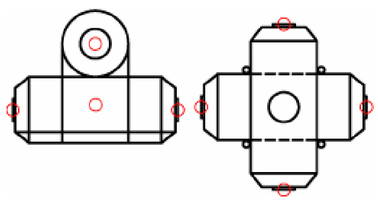
Surface Transportation & Deployment Characteristics

 **Conventional**	Attachment points can be varied according to requirements.	 **Inflatable Horizontal**	Connections are limited to hard shell sections, interfering with use of these areas for equipment and functions.
 **Telescopic**	End connections are standard. Axial connections can occur only at telescoping sections, further reducing the diameters in these areas.	 **Inflatable vertical**	Connections are limited to hard shell sections, and will require long transfer tunnels (or hard modules) between these areas.
 **Inflatable Cylinder**	Connections are limited to hard shell sections, interfering with use of these areas for equipment and functions.	 **Vertically Stacked**	Only the bottom modules can extend the scheme horizontally, and practical vertical growth is problematic.

Surface Configuration & Growth Characteristics

HABITAT TYPES AND FEATURES

FEATURE COMPARISONS

 Conventional	Very limited volume and wall space will prevent windows in areas needed for equipment functions. Viewing can occur at end caps.	 Inflatable Horizontal	Window options are only in hard sections which are likely to be needed for equipment functions.
 Telescopic	Windows can only occur in the end caps and telescoping section, but essential use of this area for equipment will limit this opportunity.	 Inflatable vertical	Window options are only in hard sections and on wall areas that don't have berthed elements. Axial ports can provide 360 degree viewing.
 Inflatable Cylinder	Window options are only in hard sections which are likely to be needed for equipment functions.	 Vertically Stacked	Very limited volume needed for equipment will severely limit windows, since vertical circulation will use up functional space.

Outside Viewing Characteristics

SUMMARY MODULE FEATURE COMPARISONS		VOLUMETRIC FEATURES	PRESSURIZATION FEATURES	SURFACE TRANSPORTATION DEPLOYMENT	SURFACE CONFIGURATION/ GROWTH	OUTSIDE VIEWING POSSIBILITIES
HARD MODULES	CONVENTIONAL TYPE MODULES	⊙	●	●	●	⊙
	VERTICALLY STACKED MODULES	○	○	○	○	○
	TELESCOPING HARD MODULES	⊙	⊙	⊙	⊙	⊙
INFLATABLE MODULES	INFLATABLE CYLINDRICAL MODULES	⊙	○	⊙	⊙	⊙
	INFLATABLE HORIZONTAL MODULES	●	○	⊙	⊙	⊙
	INFLATABLE VERTICAL MODULES	●	⊙	⊙	●	●

1. Volumetric Features:
   - ● Provides large useful living and work spaces.
   - ⊙ Provides reasonable living and work spaces.
   - ○ Provides particularly constrained living and work spaces.
2. Pressurization Features:
   - ● Has typical surface element berthing and EVA penetrations.
   - ⊙ Has 1 circumferential seal and typical interfaces.
   - ○ Has 2 circumferential seals or many interface penetrations.
3. Surface Trans/Deployment:
   - ● Readily transportable with pre-integrated equipment.
   - ⊙ Presents special requirements for relocation and/or set-up.
   - ○ Presents severe problems for relocation and/or set-up.
4. Surface Configuration/Growth:
   - ● Offers flexibility to meet variable sites and needs.
   - ⊙ Enables some adaptability to meet site and mission needs.
   - ○ Configuration and growth options are very limited.
5. Outside Viewing Possibilities:
   - ● Viewports are possible in ends and sides.
   - ⊙ Viewports are principally limited to ends.
   - ○ Side and end viewing is limited by obstacles or space.

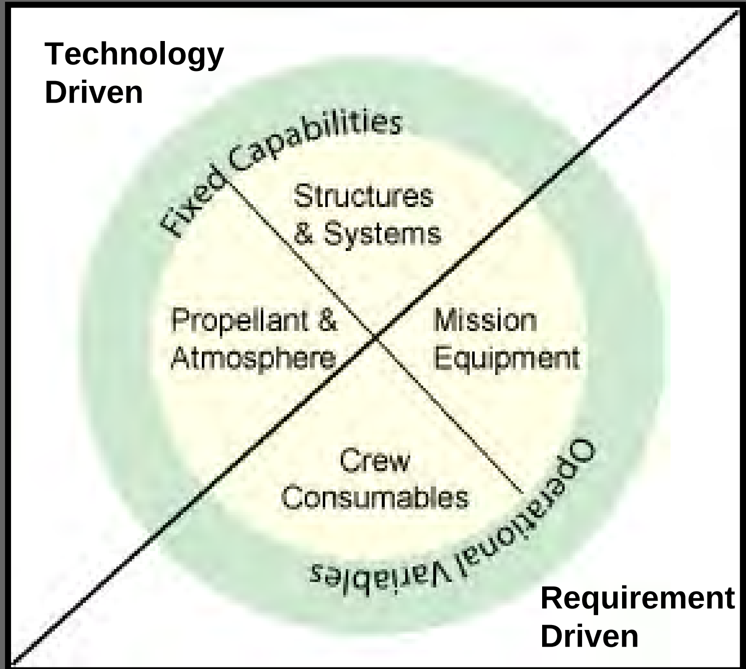
Summary Observations

HABITAT TYPES AND FEATURES

FEATURE COMPARISONS

While some module construction types offer clear advantages over others, option selection must be based upon special technology and mission-driven tradeoffs:

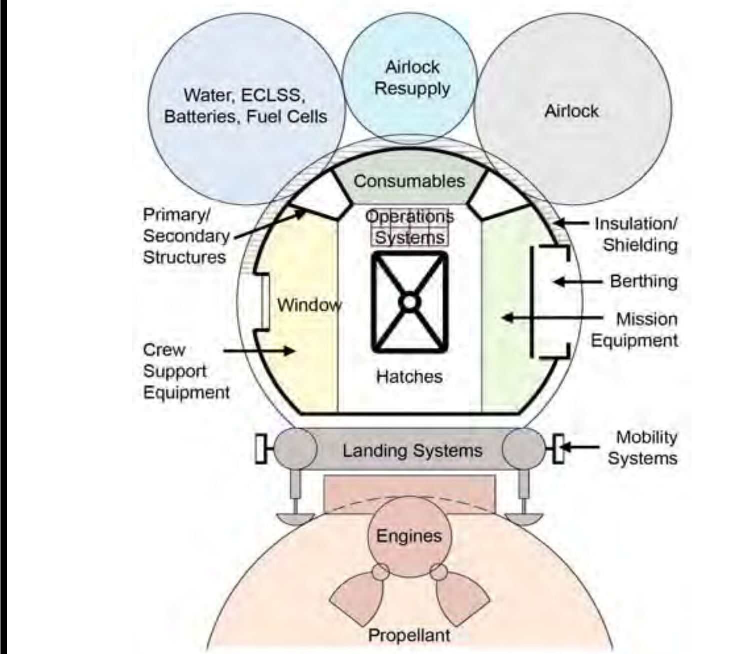
- Technology-driven considerations include:
  - Launch, transfer, landing and surface mobility capabilities.
  - Propellant and structure mass based upon trajectories, propulsive vs. aerobraking, payload ascent/ descent requirements, and engine thrust efficiencies.
  - Applications for automation/ robotic systems to reduce crew size, EVAs and other requirements.
- Mission-driven considerations include:
  - Evolutionary requirements that will size and characterize crew functions and support needs.
  - Mission length, influencing facilities and consumables which correlate with crew size.
  - Numbers and types of EVA operations impacting atmosphere consumption, suit storage and equipment.
  - Contingency strategies such as emergency egress, safe havens and accommodations for mission extensions/ rescues.



Correlative Tradeoffs

Mass constraints will drive every aspect of module design at the expense of allowable human and mission support accommodations :

- Propellant requirements will present enormous mass demands for space exploration missions beyond LEO:
  - It is reasonable to expect that fuel will constitute 3-4 times the mass budget allowed for all payloads transferred to lunar or Mars orbits, although cargo can benefit from one-way, slower, more efficient trajectories.
  - Aerobraking (not possible to the Moon) can substantially reduce propellant needs, but may impose a structural mass penalty of about 15%.
  - Propellant to land a module may constitute a penalty equal to or greater than the delivered payload mass.
  - Surface ascent vehicles may have an additional mass penalty comparable to the landing requirement, but this might eventually be compensated in part if propellant can be obtained at the surface.

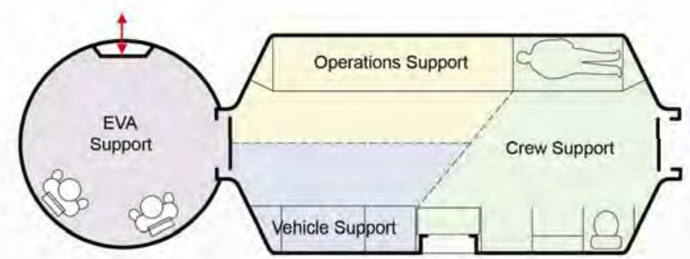


Competing Requirements

Designing Within Mass Budgets

Habitat planning and crew design must balance a variety of competing needs within severe volume constraints :

- Crew support areas are needed to provide:
  - Living accommodations, including food storage/ preparation, toilets/ hygiene, sleeping/ privacy, exercise/ recreation and medical treatment.
  - Outside viewing for proximity operations, science and leisure.
- Operations support facilities are necessary to offer:
  - Equipment, workstations and supplies for mission-driven activities including science and technology.
  - Power, thermal control, data management and other systems.
- Vehicle support is essential for:
  - ECLSS, waste management, power generation/ storage, data management, command control and other functions.
- EVA capabilities may be essential, including:
  - Airlocks, suits and tools for orbit or surface.
  - Airlock and suit resupply consumables.



- Crew vs. operations support for area/ volume
- Equipment racks vs. windows for wall space.
- EVA vs. IVA for atmosphere resupply.
- Vehicle support vs. operations for electrical power.
- Everything vs. everything for storage volume.

Competing Requirements

Balancing Facility Demands

More detailed information about many topics discussed in this section along with references and additional information sources is offered in Part I of this lecture series. Additional information regarding SICSA projects that serve as illustrative examples can be obtained on our website : www.sicsa.uh.edu

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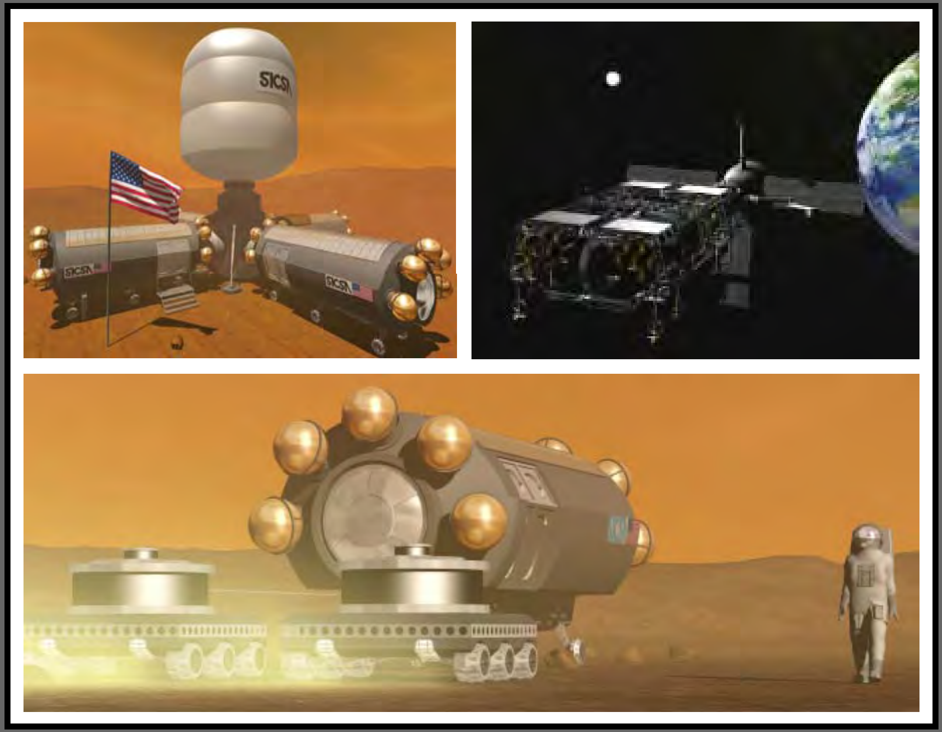


SECTION D: ORBITAL & SURFACE ARCHITECTURES

Each of the different module construction approaches presents particular advantages and limitations that must be considered within the context of special applications and requirements :

- Representative selection considerations will include :
  - Volume and mass constraints imposed by available or planned launch vehicles, orbital transfer and orbital entry systems, and surface landing/ deployment capabilities.
  - Orbital rendezvous/ docking of modules and possible transfer/ landing of elements using automated expeditious means.
  - Volume and equipment integration features of different approaches influencing functional utilization benefits and limitations.
  - Deployment labor, equipment and time requirements to realize operational capabilities.
  - Accommodations for emergency egress, outside viewing, EVA operations and other external connections.
  - Configurability for orbital or surface operations and evolutionary growth.

Issues	Orbital Applications	Surface Applications
Module Configuration	Horizontal and Vertical Organization	Horizontal Organization
Types of Interfaces	Spacecraft Docking (Horizontal & Vertical)	Possible Rover Docking (Horizontal)
Interior orientation	Optional Local Vertical	Fixed Gravity Local Vertical
Gravity Level	Weightless or Artificial Gravity	Partial Gravity (Planetary)
Outside Viewing	Proximity and Earth-oriented	Fixed-direction Surface (Horizontal)
Transport Issues	Spacecraft Access/ Docking	Surface Landing And Mobility
Loads and Stresses	Spacecraft Docking	Surface Landing and Transport
Debris Shielding	Hypervelocity Space Debris	Landing Rocket Surface Ejecta

Key Issues

Special Application Influences

The architectural configuration of any modular space station or planetary base must comply with many different types of constraints, requirements and Features of Merit (FOMs):

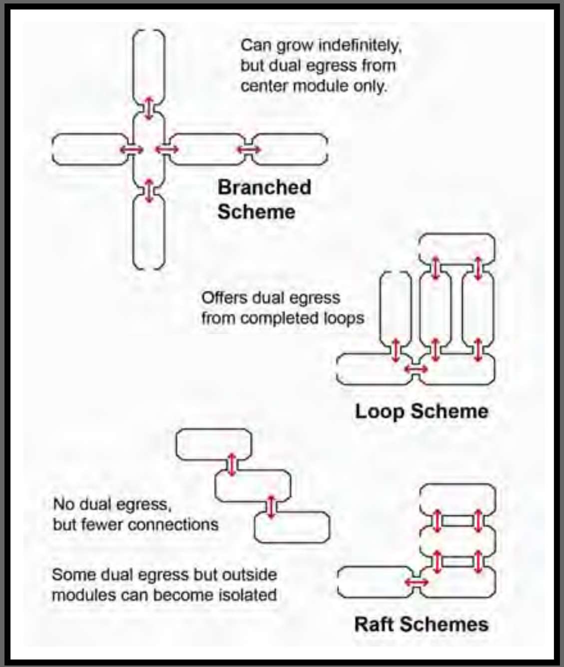
- Although particular condition and planning responses for orbital vs. surface habitats differ, they share important issues that must be addressed :
  - Crew operational and safety conditions will be influenced by ways that internal functions are linked together, provisions for outside viewing, and IVA-EVA interfaces under nominal and emergency circumstances.
  - Module delivery, positioning and assembly will depend upon CG features of the elements, how they are arranged and connected, and access to available support systems.
  - Power and thermal factors will be influenced by the location and orientation of the habitats relative to the Sun.

Issues	Orbital Habitats	Surface Habitats
Center of Gravity	Limits imposed by launch vehicle (Shuttle)	Limits imposed by landing/ surface mobility
Functional Arrangements	Internal up-down orientation & layout	Internal circulation and IVA-EVA connections
Outside Viewing	Flight orientation and structural obstacles	Surface orientation and structural obstacles
Crew Safety	Emergency egress and safe havens	Emergency egress and safe havens
Types of Connections	Vehicle docking and module berthing interfaces	Berthing interfaces and transfer tunnels
Assembly Requirements	EVA vs. automated procedures	Surface mobility and construction systems
Access Corridors	Vehicle rendezvous, docking and departures	Surface conditions and mobility systems
Solar Power	Station orbit and orientation	Site location and seasonal influences

Common Orbital & Surface Issues

Since modules used in orbit or on the surface will have similar construction and functional features, the requirements and options for configuring them together often involve the same general patterns:

- Common proposals are based upon variations of three geometries :
  - Branched configurations enable facilities to be added indefinitely along a horizontal (and/or vertical) plane, but lack assured dual egress features to enable crews to escape from an unsafe module for safe refuge in another in the event of fire or any other emergency.
  - Loop (or "racetrack") schemes provide dual egress after the loop is completed , but can be more complicated and difficult to assemble.
  - Raft patterns can connect modules together at 1 or 2 points for dual egress and can grow laterally and longitudinally, but lack of redundant access paths through center modules can isolate those on the outside.

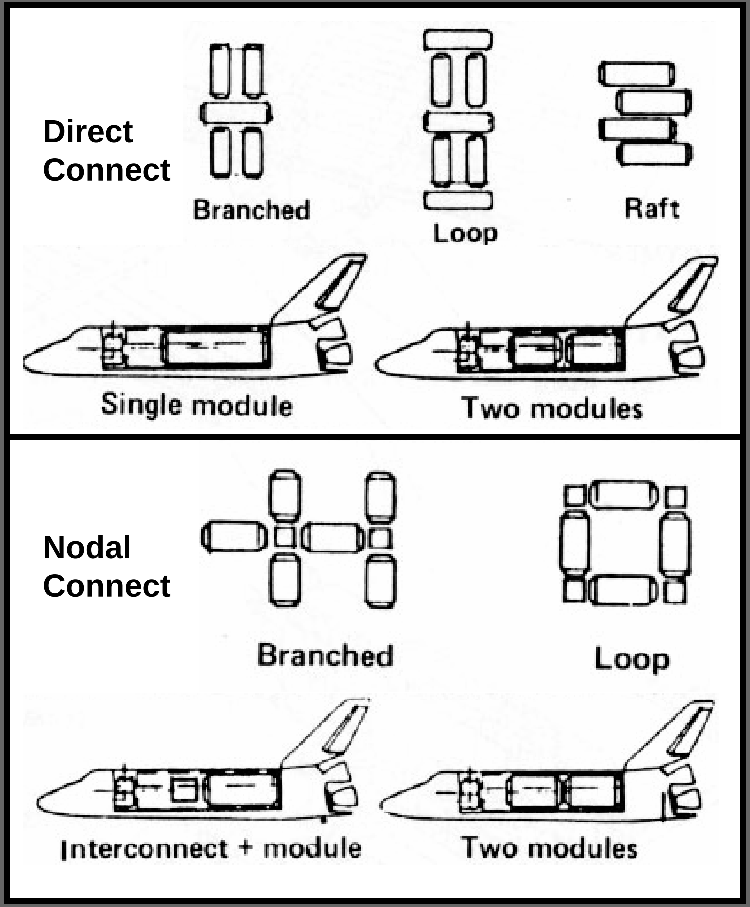


Configuration patterns & Features

Modules can be either joined together directly or using connecting nodes:

- Direct connections are the simplest, but not necessarily the easiest or most efficient:
  - Berthing penetrations through module side walls reduce a module's potential rack space, and hatches can interfere with circulation paths.
  - Some branched, and all loop schemes require as many as 4 side berthing ports in certain modules.
- Nodal connections maximize useful space within the primary modules, but represent additional elements to be delivered and assembled:
  - They enable primary modules to be of a common type in regard to berthing interfaces.
  - They must provide utility pass-throughs and interfaces between modules they connect.

SPACE STATIONS
AND PLATFORMS

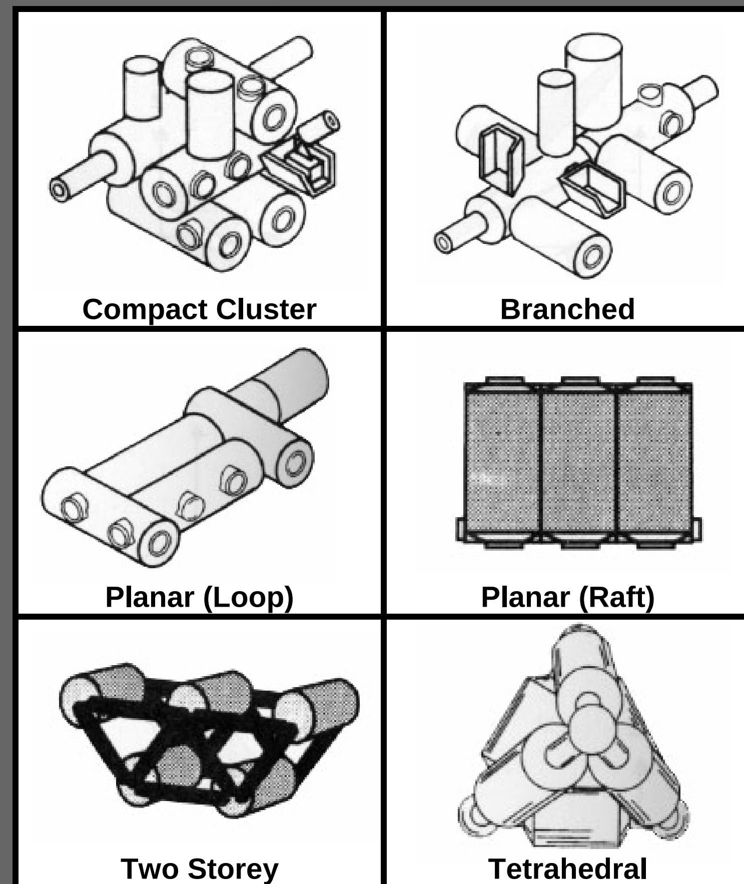


Module Interconnect Patterns

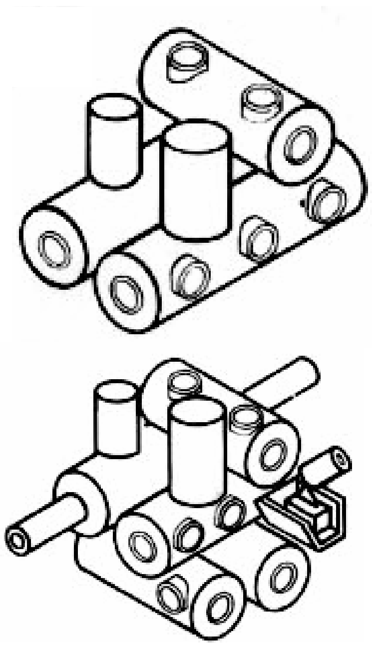
A variety of configuration architectures have been proposed for orbital flight applications, including variations on planar schemes and other geometries.

- Each pattern, along with the intended uses, presents special characteristics and considerations:
  - Compact clusters might sometimes reduce flight-destabilizing mass gravity gradients, but present telerobotic assembly problems.
  - Branched and planar approaches present tradeoffs between traffic flow and volumetric efficiency vs. dual egress for safety.
  - Side-to-side raft berthing variations of branched and planar patterns (analogous to single and multi-level buildings on Earth) present simple interface connections at the expense of volume utilization efficiencies and assured emergency egress due to side module isolation.
  - Tetrahedral schemes might offer gravity gradient stability, but non-orthogonal traffic patterns may create internal up-down, left-right orientation confusion, and incremental growth is eliminated.

HUMAN SPACEFLIGHT



Configuration Proposals



Pros:

- Two or more egress paths.
- Inertial symmetry permits all orientations.

Cons:

- Difficult to assemble.
- Growth is quite limited.

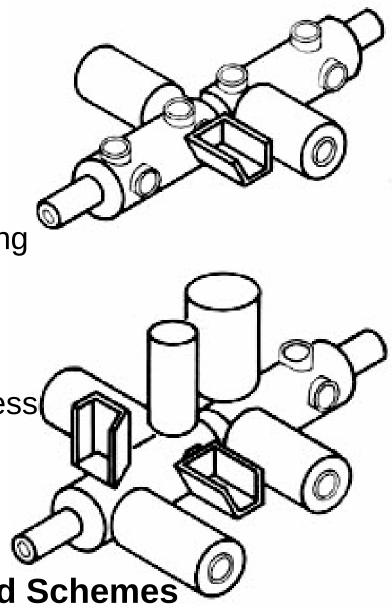
Cluster Schemes

Pros:

- Can grow indefinitely.
- Flexible for instrument pointing and attachment.

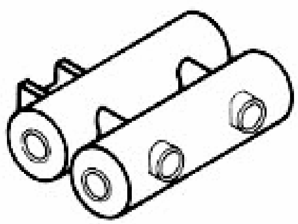
Cons:

- Lack of dual egress
- Large inertial differences.



Branched Schemes

Configuration Comparisons

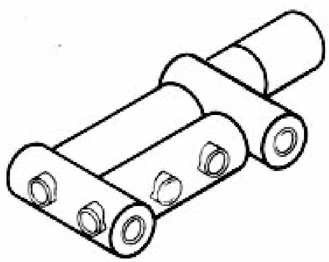


Pros:

- Two or more egress paths.
- Can be assembled by Shuttle/RMS.

Cons:

- Large inertial differences.
- Limited orbit orientation options.



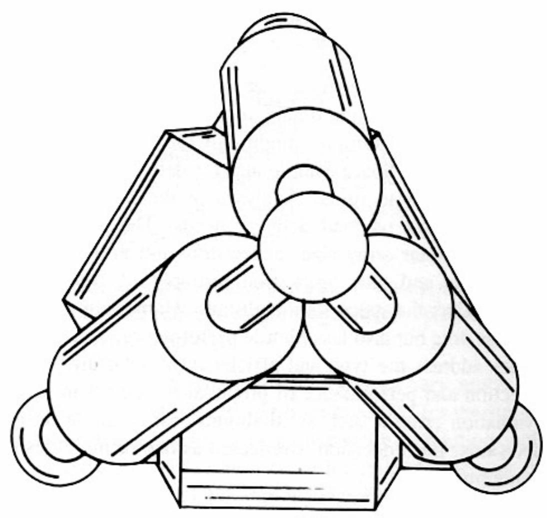
Planar Schemes

Pros:

- Low gravity gradient influences.
- Rigid/ stiff structure.

Cons:

- Internal orientation confusion.
- Restricted growth.



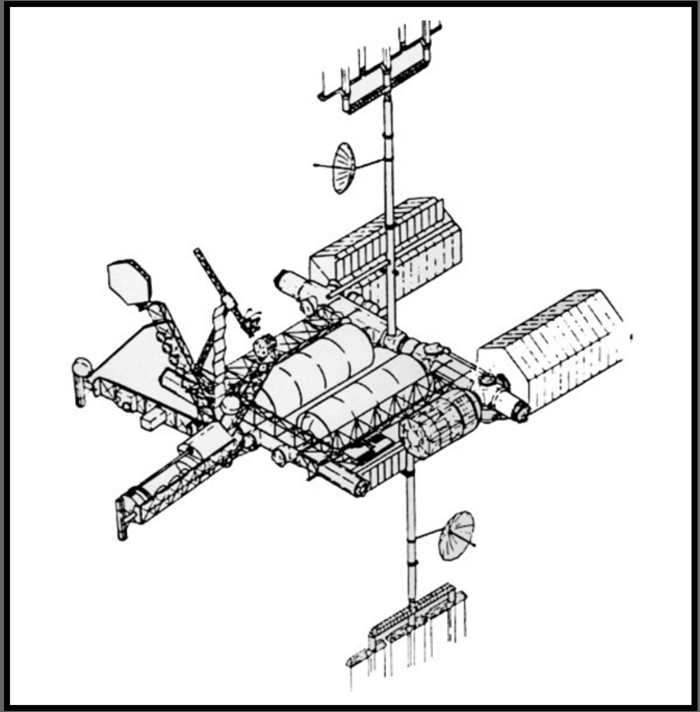
Tetrahedral Schemes

Configuration Comparisons

SPACE STATIONS AND PLATFORMS

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 configuration possibilities.



Attachment Structures

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

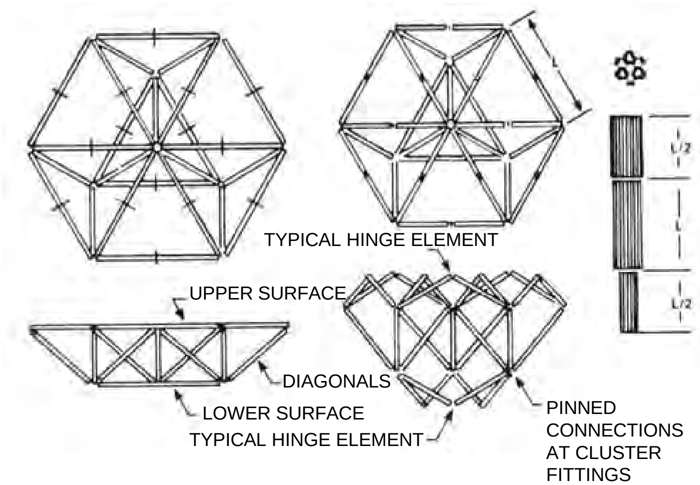
- Some systems are comprised of individual solid or tubular members and connector sockets that are assembled in "tinker toy" fashion by space-suited astronauts, or attached using teleoperated devices.
- Some are pre-assembled with hinged joints, compactly folded during launch and automatically expanded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

Attachment Structures

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.

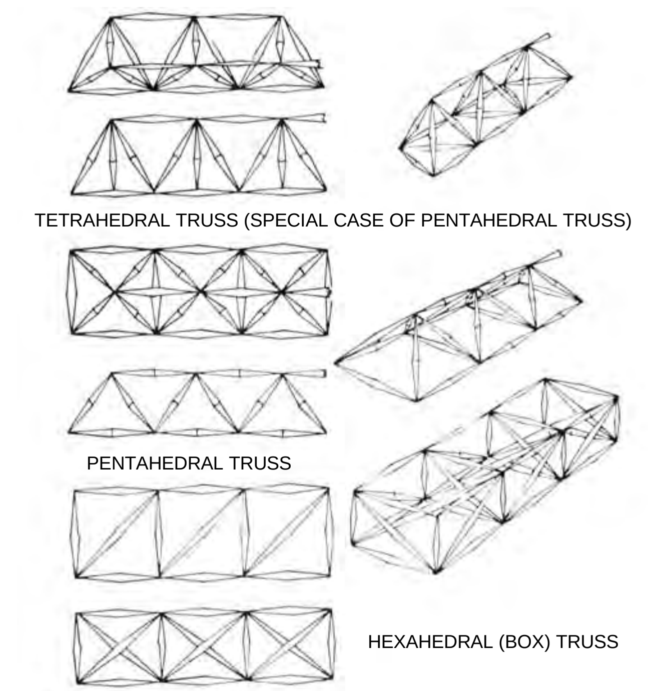
“Tetrahedral” Trusses

Attachment Structures

SPACE STATIONS AND PLATFORMS

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).

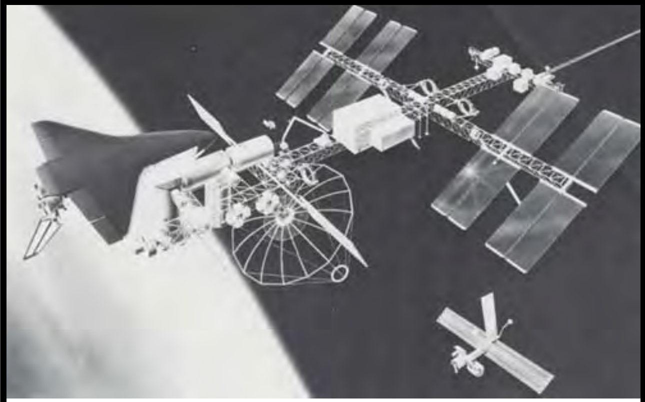


Common Truss Geometries

Attachment Structures

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.

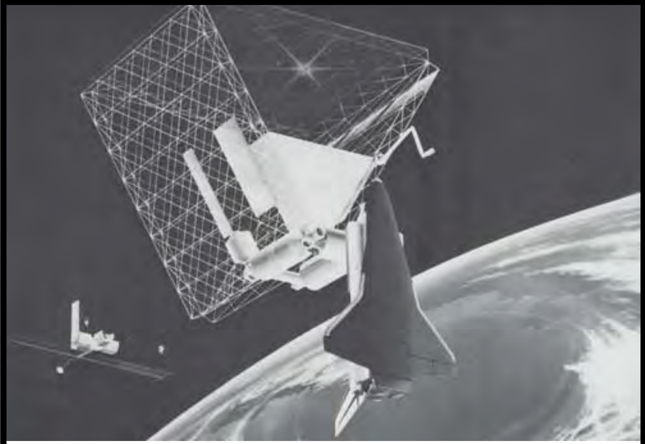


The Power Tower featured a long box truss backbone structure that could accept a variety of functional attachments, including modules, storage facilities and solar arrays.

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.



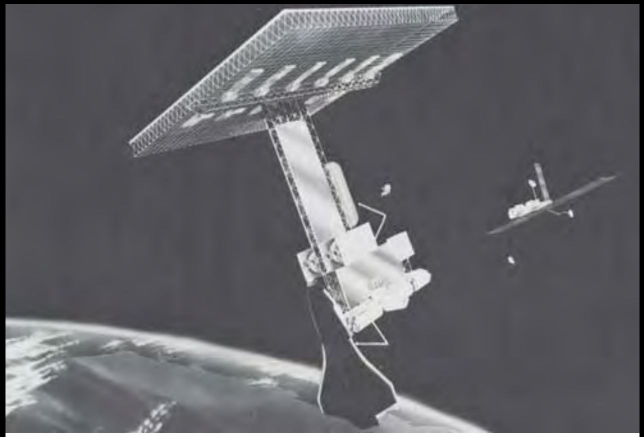
The Delta configuration was devised to provide stiffness to avoid dynamic controllability problems associated with the long, flexible Power Tower truss.

NASA Delta Space Station Concept

Infrastructure Configurations

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.

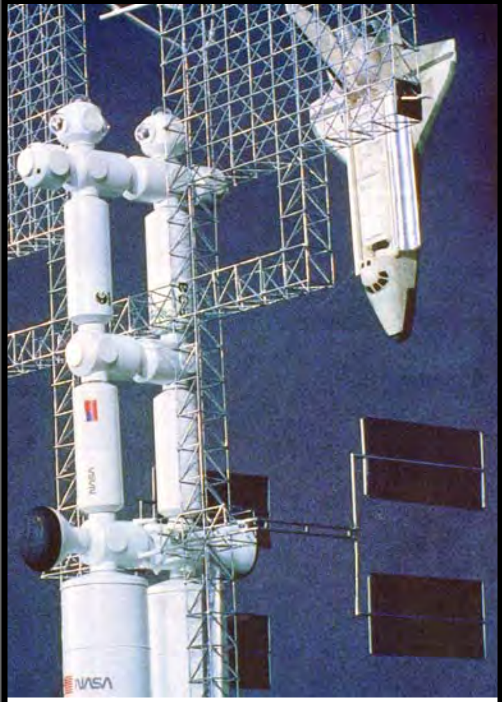


The design which was conceptualized at the NASA Johnson Space Center in the early 1980s was determined not to provide adequate power generation efficiency.

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.

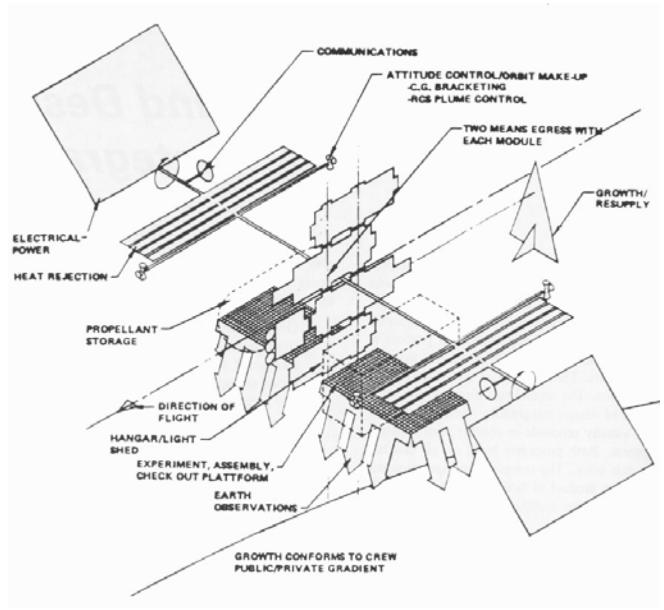


SICSA Space Post Concept

Infrastructure Configurations

A space station's orbital flight modes, orientation and module/ structure configuration have fundamental influences upon a variety of important planning and design issues, including :

- Solar tracking to provide power for systems and operations.
- Radiator positioning and orientation for heat rejection and possible space debris protection.
- Balancing of gravity gradient and aerodynamic torques to stabilize the station in orbit.
- Drag minimization and compensation to maintain propellant-efficient orbital life.
- Outside viewing for proximity monitoring, crew psychological benefits and sciences.
- Rendezvous and docking corridors for assembly operations and crew/ logistics transfers.
- Reducing hazard risks posed by space debris in LEO through configuration design and pointing.

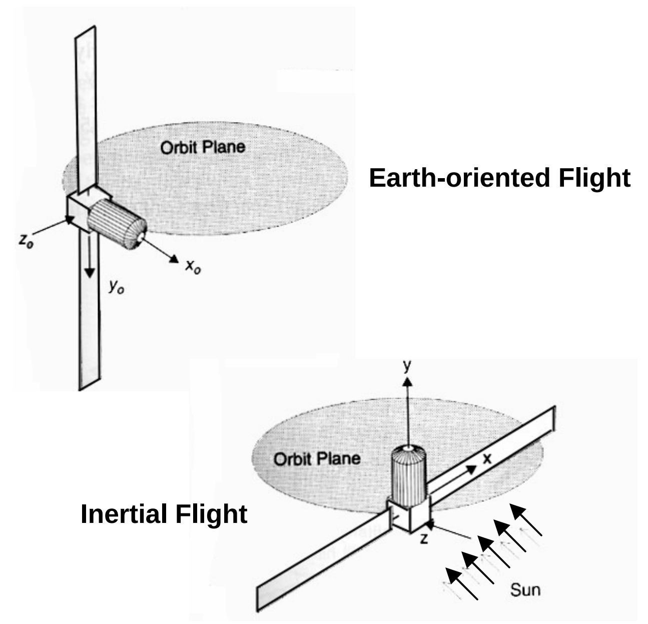


Representative Considerations

Flight Mode, Orientation & Configuration

Solar tracking for photovoltaic power is governed by a LEO space station's orientation to its orbital plane:

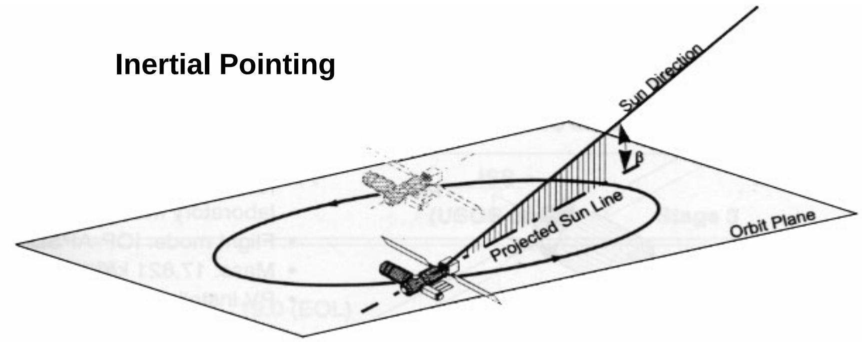
- Earth-oriented flight aligns masses along a local vertical gravity gradient torque angle that is balanced by aerodynamic forces to stabilize the vehicle:
  - The solar array must have two rotary joints, one to track around the Earth ("a tracking"), and another to adapt for the Sun's changing seasonal incidence due to the inclination of the elliptical plane ("B tracking").
- Inertial-oriented flight maintains a constant orientation to the Sun in its orbital plane:
  - Because of fixed pointing, no solar tracking is required.
  - Fixed solar pointing provides constant thermal control and lighting conditions.



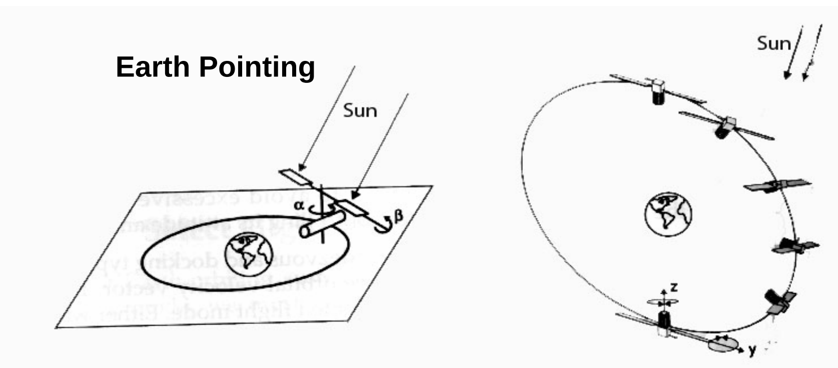
Earth and Inertial Flight Operations

Solar Tracking

- Favorable for astronomy (required for permanent observation)
- Simpler collectors and radiators (best performance even without tracking)
- Constant lighting conditions (EVA)
- Constant thermal control conditions.
- × Gravity gradient is always a perturbation.
- × Difficult to keep the best mass distribution during assembly and space-element growth.



- Favorable for Earth observation and telecommunication.
- Allows using gravity gradient to stabilize attitude
- More flexibilty for microgravity experiments.
- Earth is a reference to orient the crew (EVA)
- Easier rendezvous and docking
- More flexible mass distribution for assembly and space-element growth.
- × Variable lighting conditions (EVA)
- × Needs solar array and radiator tracking for best performance.

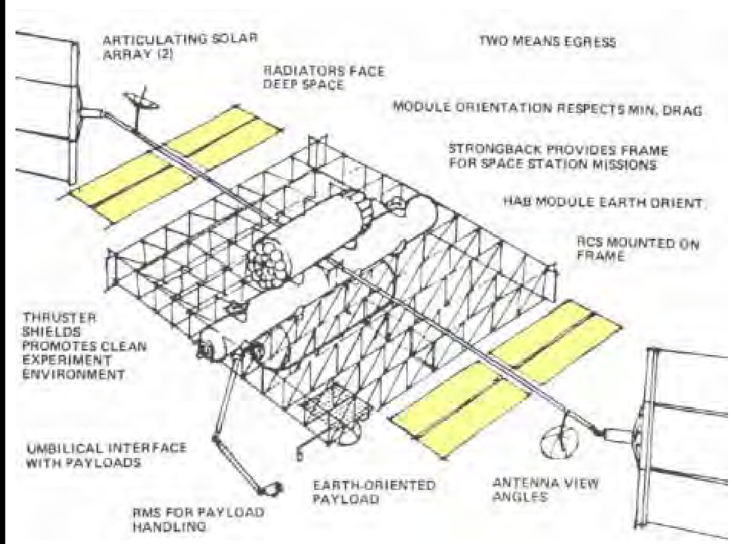


Solar Tracking

SPACE STATIONS AND PLATFORMS

Radiator locations and designs are important configuration and orientation considerations:

- The objective is to reject heat produced by spacecraft equipment, people and solar thermal loads into deep space.:
  - Placements and designs must attempt to avoid solar radiation incidence on the panels , both through the vehicle flight orientation to the Sun and through rotational gimbaling.
  - Wherever possible, the panels' rotation axis should align them with edges in the flight vector to avoid drag (in LEO).
  - Module body-mounted radiators offer alternatives to "feather" types, and can serve a separate function as debris shields.
  - Body-mounted systems can only be used in an inertial vehicle orientation that can enable them to have a fixed and opposing orientation vector to the Sun.

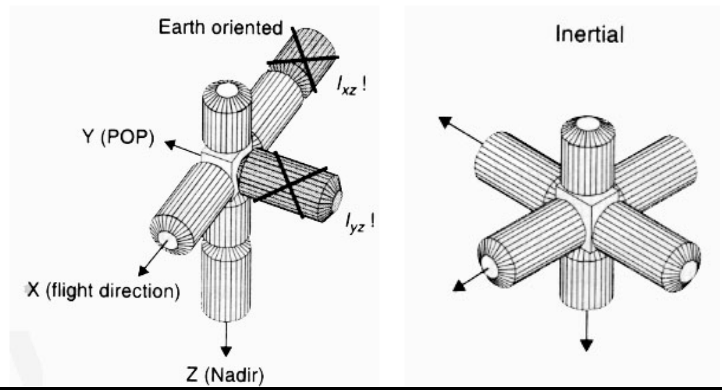


Typical Space Station Elements

Heat Rejection

Gravity gradients induce a gravitational pull (or “bias”) on any part of a Earth/planet-orbiting station that is not at the center of gravity:

- A gravity gradient can stabilize a station in an Earth-oriented flight mode, but will always perturbate the attitude of a vehicle in an inertial mode.
  - For Earth-oriented vehicles, the configuration and mass distribution design places most of the mass in the nadir direction (towards Earth).
  - Gravity gradient-stabilized Earth-oriented structures balance gravitational torque forces and aerodynamic torque forces.
  - Gravitational and aerodynamic balancing requires a high level of symmetry in the flight direction (X).
- Inertially-oriented vehicles typically use control moment gyros (CMGs), momentum wheels or propulsive systems to balance torques :
  - Orienting one principal axis towards Earth and another in the orbital plane can eliminate most or all gravity gradient torque.



To achieve gravity gradient and aerodynamic torque balance.

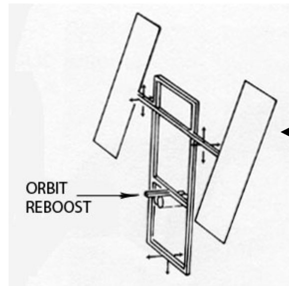
$T_{gg} = T_{aer}$, where:

T_{gg} (gravity gradient torque) =
T_{aer} (aerodynamic torque)

Balancing Torque Forces

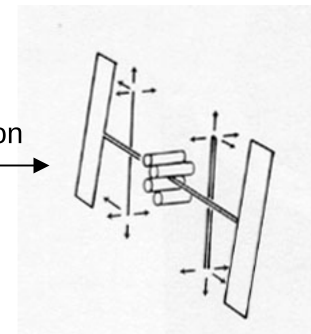
Orbital drag in LEO will reduce the velocity of a spacecraft, causing it to eventually de-orbit unless reboosted. Orbital lifetimes without reboost can range from a few months during periods of high solar activity, to a few years.

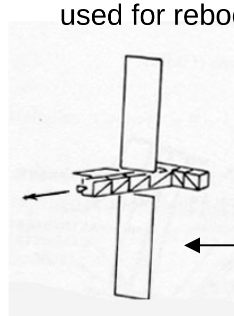
- The amount of drag experienced is influenced by a spacecraft's configuration and orientation :
  - To decrease drag, the vehicle's area in the velocity direction should be as small as possible.
  - Ideally, the longitudinal axes of most of the modules would be parallel to the velocity.
  - If possible, the normal vectors of solar panels and radiators should be perpendicular to the v-bar (but often this can't be accomplished).
- Thrust to offset drag is directed in a posigrade (path of flight) vector :
  - Thruster plumes should be located clear of sensitive external equipment that can become contaminated.



Power tower arrangement with three attitude control locations and separate reboost thruster.

Planar arrangement with attitude control thrusters on masts.
Attitude control thrusters used for reboost.





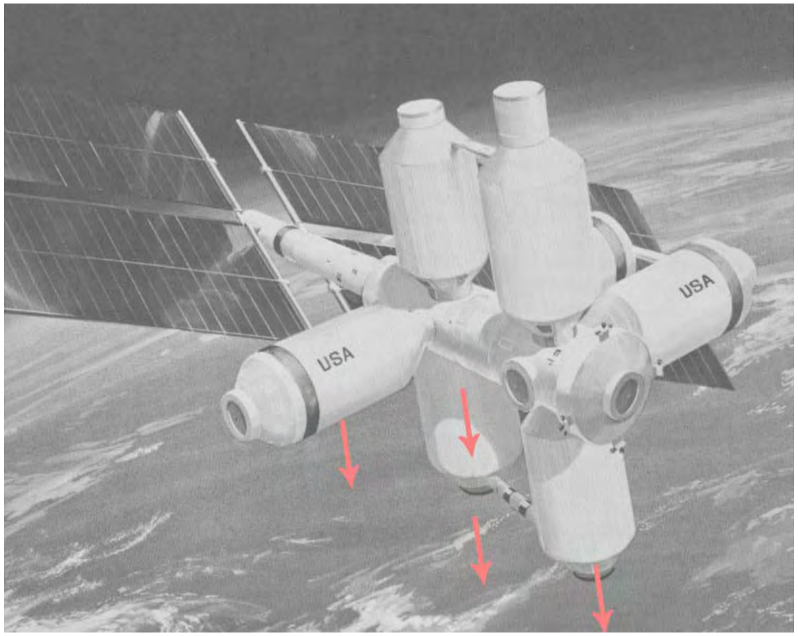
Inertially-stabilized platform concept with thruster for reboost only. Momentum management devices for attitude control. Platform is maneuvered to direct reboost thrust.

Station Reboost Strategies

LEO Orbital Drag

Outside viewing opportunities are important for safe rendezvous/ docking maneuvers, EVA monitoring, crew morale and scientific observations :

- Space station configuration, orbital orientation, and module design have a variety of combined influences:
  - Configuration geometry determines where windows can be located to avoid viewing obstructions posed by other modules and structures.
  - Flight orientation relative to geometry determines where windows can point (e.g, towards Earth and rendezvous/ docking corridors).
  - Module type and internal design determines where windows can be incorporated into a module’s pressure shell, where they can avoid interferences with other elements and functions, and how viewers and viewing vectors are oriented relative to the internal local vertical.

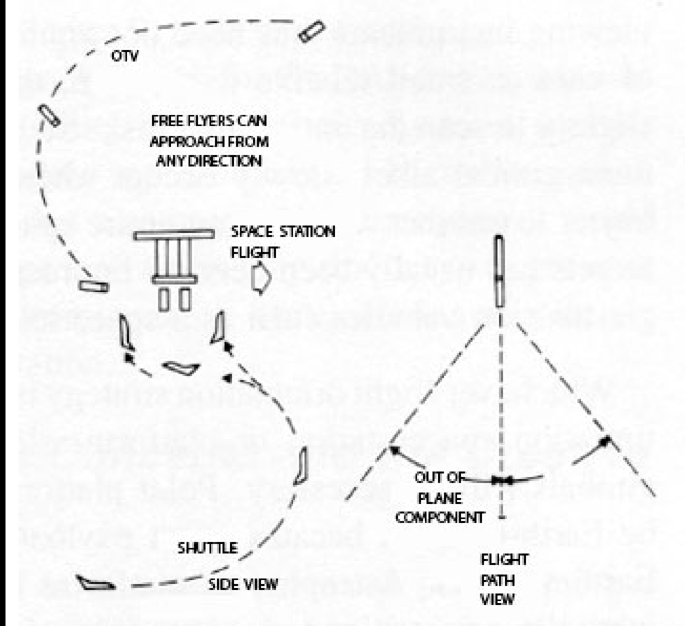


Earth-Viewing Opportunities

Outside Viewing

Approaches for rendezvous and docking require corridor pathways that are clear of obstructions:

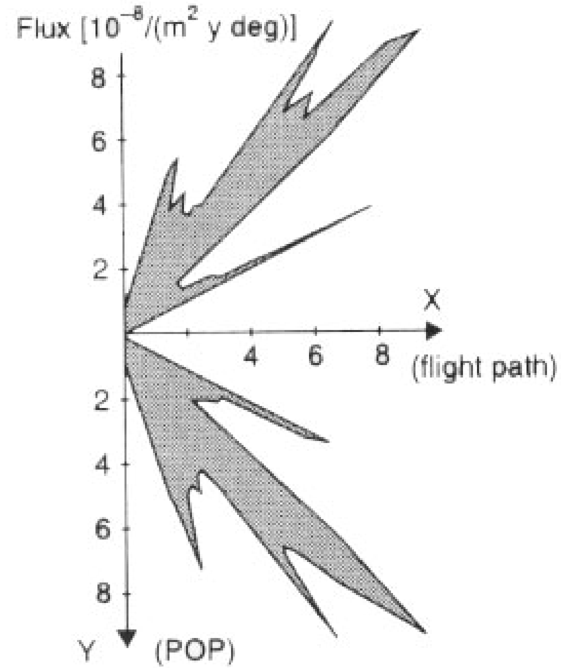
- Corridors are typically oriented along either the radius vector (r-bar) or velocity vector (v-bar):
  - Both directions are reference axes in the Earth-oriented flight mode.
  - Station assembly staging and configurations must take flight corridors, rendezvous/ docking vehicle attachment points and EVA/ RMS procedures into account to avoid interferences and obstructions.
  - Particular concern must be to avoid conflicts with solar arrays, radiators, truss sections and other elements that can pose hazards to the rendezvous vehicle and station.
  - Internal viewing of the access corridor can facilitate safe operations.



Flight and Viewing Paths

While meteoroids can strike a LEO spacecraft from any direction with about the same probability, nearly all local space debris approaches in a plane tangential to the trajectory :

- LEO debris risk hazards vary with orientation:
  - The lowest flux exposure will be for longitudinal module arrangements oriented perpendicular to the orbital plane.
  - The highest flux risk will be for modules lined up in a radial direction with their cylinder axis pointed towards Earth (gravity gradient).
  - Mutual shielding to reduce strike risks can be accomplished by aligning cylinders in the flight direction with axes perpendicular to the orbital plane.
  - A planar orbit for a large size station poses a big attitude control problem if it is not in a gravity gradient orientation.

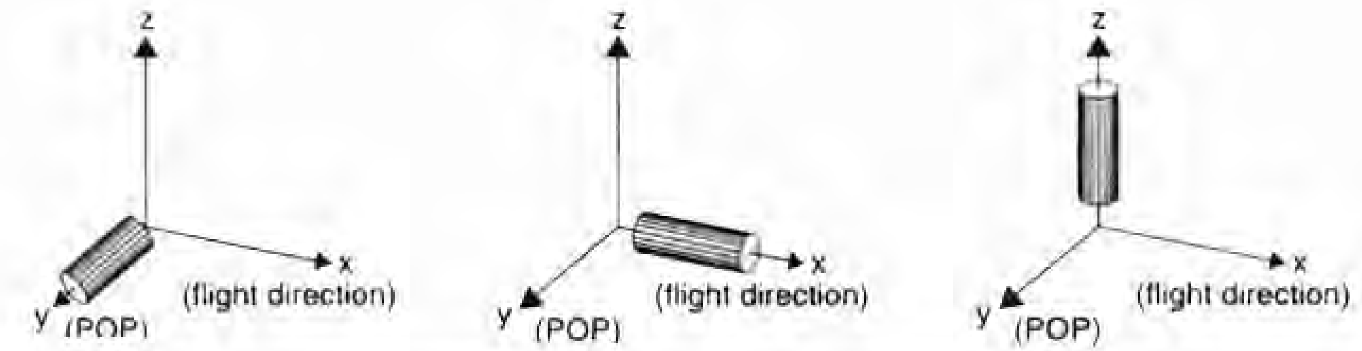


POP = Perpendicular to Orbital Plane

Flux Relative to Orientation

LEO Debris FLux

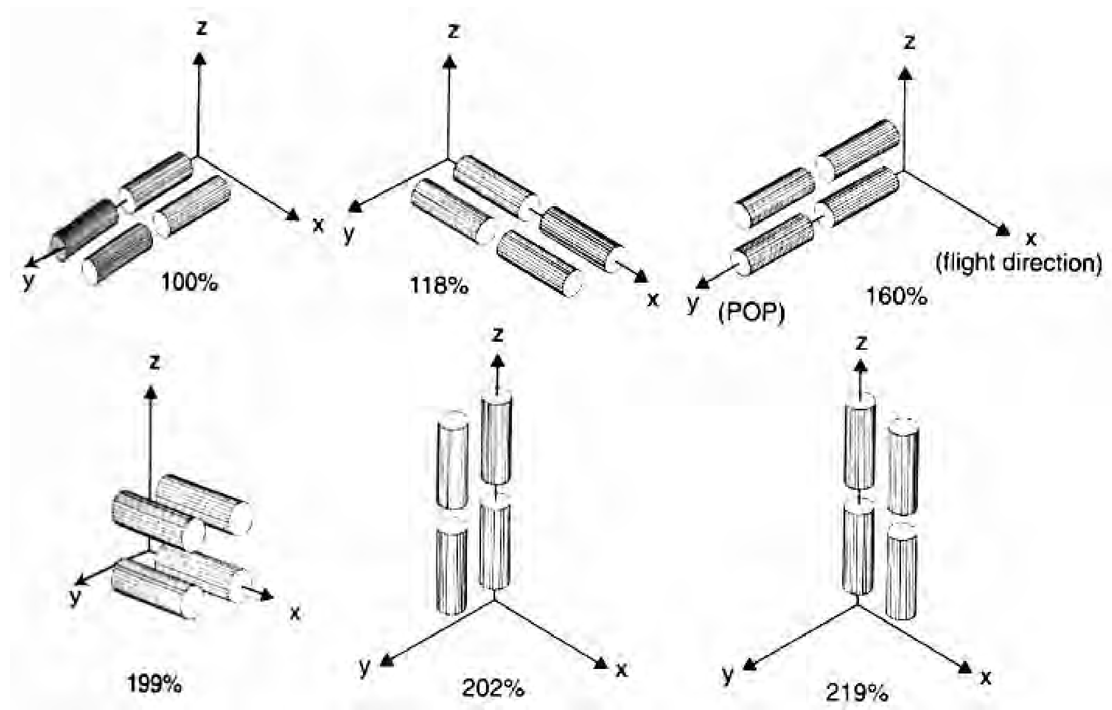
HUMAN SPACEFLIGHT



Debris flux [10^{-4}/ year]	1.55	1.88	2.03
[%]	100	121	131

Debris Flux for Three Orientations of a Pressurized Cylinder [Eichler and Rex, 1990]
Diameter = 4m and length = 12.7m. Information provided for particles larger than 1cm at an orbital altitude of 500 km and an inclination of 28.5 degrees.

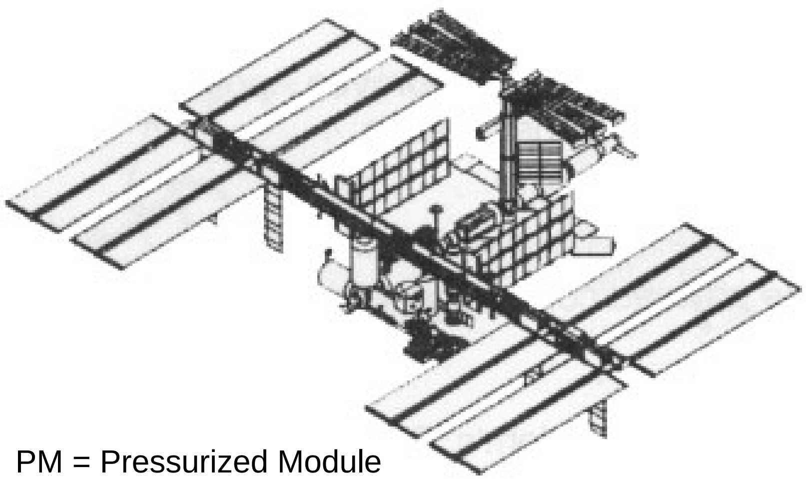
LEO Debris FLux



Relative Debris Flux for a Module Cluster with Different Orientations. [Eichler and Rex, 1990]

4 modules,
Diameter = 4m
Length = 12.7m

LEO Debris FLux



PM = Pressurized Module

- PM-backbone structure ensures early operational capabilities.
- Truss backbone architecture in US Orbital Segment allows higher electrical power and heat rejection performance.
- Operational redundancy between Russian Orbital Segment and US Orbital Segment.
- Many PMs aligned with the flight path direction (microgravity).
- Dual egress and redundant access for some US and Russian modules.

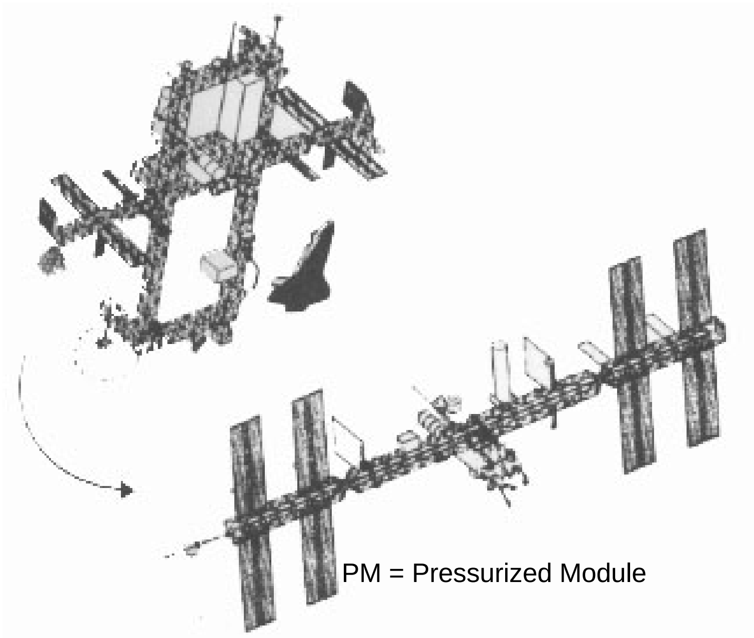
× No gravity gradient stabilization.

× Mass distribution leads to significant pitch deviations from local horizontal.

× Solar array location leads to cyclic aerodynamic torque.

Extended Infrastructures **International Space Station**

Summary Examples



Extended Infrastructures

- Gravity gradient flight mode.
- Active alpha and beta- tracking solar arrays.
- Very good external payload accommodations.
- PMs close to the center of mass.
- Solar array's center of pressure close to the center of mass.
- Good growth potential.
- PMs in race-track pattern (dual egress/ redundant access).

× Very ambitious in terms of hardware and EVA.

× Mass distribution leads to significant pitch deviations from local horizontal.

× Solar array location leads to cyclic aerodynamic torque.

Space Station Freedom 'Revised Baseline' concept is same as 'Dual-keel' , except:

× No gravity gradient flight mode.

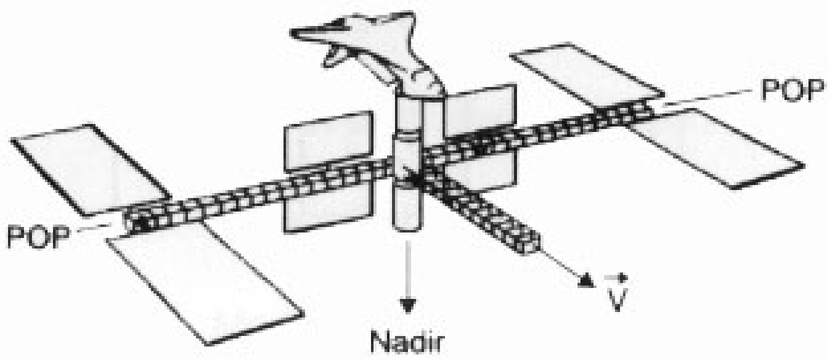
× Less space for external payloads.

× Dual egress/ redundant access for US modules only

Space Station Freedom "Dual-keel" Concept

Summary Examples

HUMAN SPACEFLIGHT



CDG = NASA Concept Development Group
PM = Pressurized Module

- Active solar tracking with de-spun truss tips (alpha-tracking) and solar arrays rotating around the longitudinal axis (beta-tracking).
- Pressurized section in gravity gradient attitude.

× PM arrangement in nadir direction less suited for microgravity.

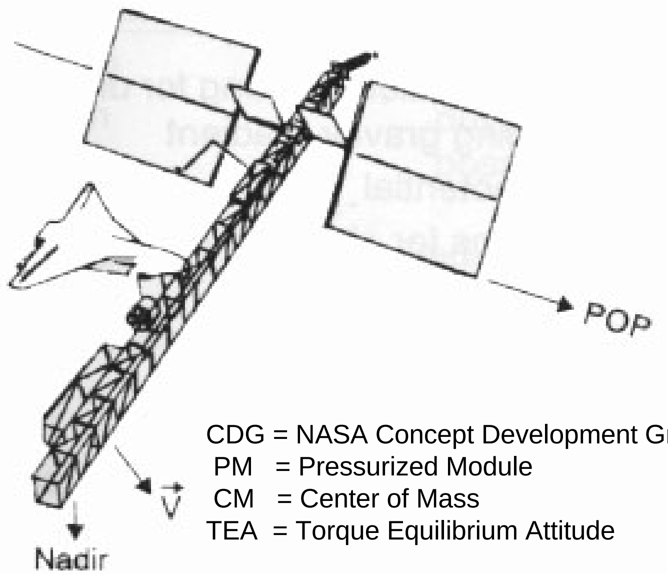
× Limited growth potential.

Extended Infrastructures

CDG-Planar Concept

Summary Examples

HUMAN SPACEFLIGHT



CDG = NASA Concept Development Group
PM = Pressurized Module
CM = Center of Mass
TEA = Torque Equilibrium Attitude

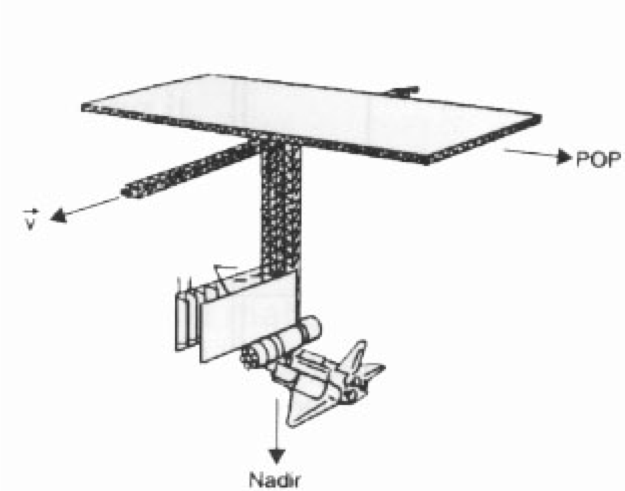
Extended Infrastructures

- Gravity gradient flight mode
- Active solar array tracking.
- PM locations allow for TEA.
- Good growth potential.
- Good accommodations for Earth and space observation payloads.

× PM sections away from center of mass.

× Solar array tracking causes TEA oscillations.

CDG-Power Tower Concept



CDG = NASA Concept Development Group
PM = Pressurized Module
CM = Center of Mass

Extended Infrastructures

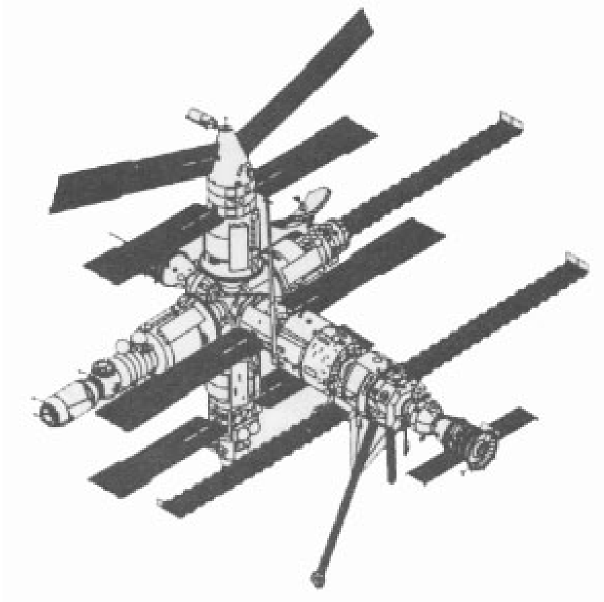
- Gravity gradient-stabilized flight mode
- Fixed solar array without aerodynamic incidence area.

× Lack of tracking leads to oversized collector area (factor 2.5 as compared to an alpha/ beta-tracked array).

× PM cluster away from CM.

× Limited field of view into space.

GDG – Big "T" Concept



- Highly flexible in configuration.
- Compact configuration allows for different flight modes, including gravity gradient.
- Good growth potential.

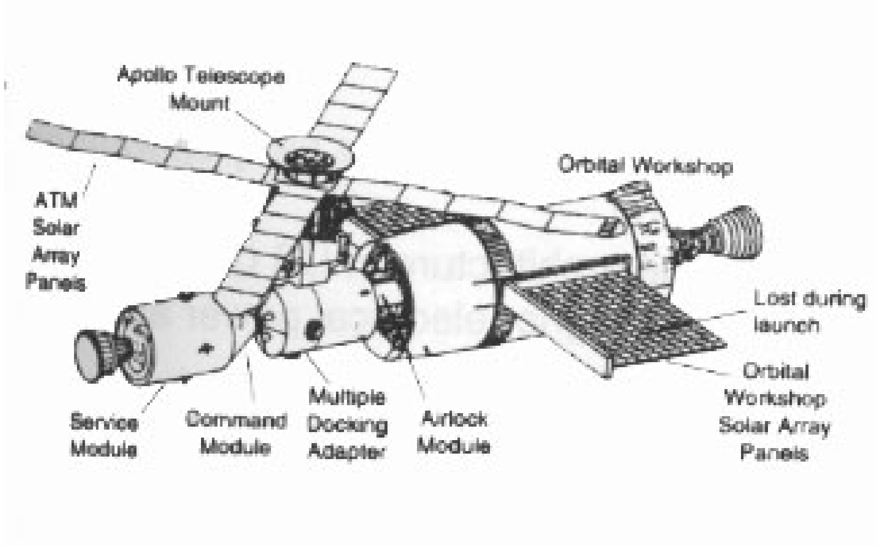
× Strong limitations for electric power (body-mounted collectors).

× Restricted space for external payloads.

Compact Infrastructures

Russian Mir Space Station

Summary Examples



- Single launch system.
- Large pressurized volume.
- Significant reuse of flight-proven Apollo hardware; low-cost and low-risk design.

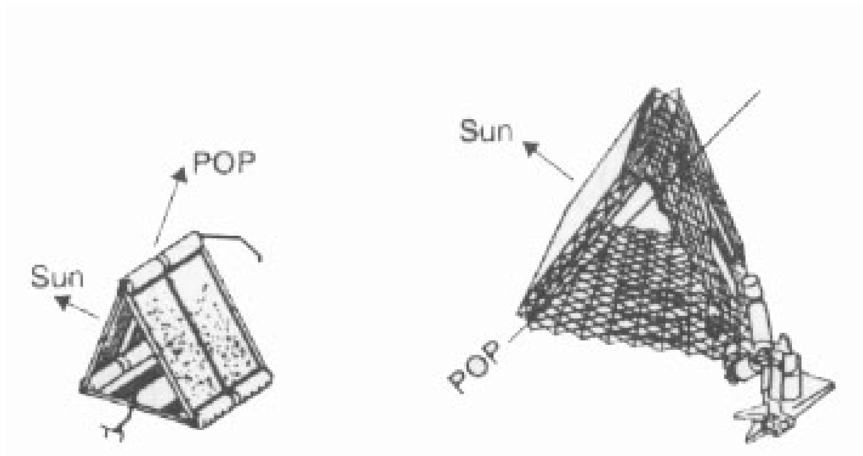
× No reboost capability.

× Limited (<1 year) operational lifetime.

× Single payload complement (launched with Skylab).

Tetrahedral Infrastructure **Skylab**

HUMAN
SPACEFLIGHT



CDG = NASA Concept Development Group
PM = Pressurized Module

- High structural stiffness.
- Early symmetric configuration suited for inertial flight mode and fixed solar array.
- Natural “hangar” for construction, servicing, etc. inside the delta.

× PMs in the edges (away from center of mass).

× Limited growth potential.

× Scaling problems lead to module cluster with resulting attitude stability penalties.

Tetrahedral Infrastructure | **CDG – Delta Concept**

Summary Examples

Module Configuration	Provide dual egress if possible, with at least 2 docking ports. Optimize internal traffic flow and functionality efficiencies. Design and orient to minimize aerodynamic drag and debris incidence.
Flight Corridors	Place corridors in radial or orbit-tangential directions. Avoid structural interferences and hazards. Provide good viewing angles for internal monitoring. Avoid flight orientations that deviate from nominal.

Configurations

Station Infrastructure	Provide stiffness to minimize dynamic vibrations. Configure for easy assembly using telerobotic systems.
Solar Arrays	Provide for necessary tracking (a and B vectors). Keep the center of pressure close to the station's center of mass. Avoid shading of arrays by structures (distant in POP direction).
Radiator Panels	Avoid solar radiation incidence and minimize drag effects. Avoid blocking flight corridors, sensors and internal viewing.

Structures

Summary Considerations

A guiding priority for habitat planning and design is to deliver and deploy the greatest amount of useful real estate assets possible to the destination of use in the most practical and efficient manner, considering factors as :

- Interior living and work volumes :
  - Maximizing the total space available for transport of equipment and supplies to the destination site.
  - Optimizing the amount and layout of space available for living and work activities after the module is delivered and deployed.
  - Planning interior circulation within and between modules for efficiency and safety.
- Utilities and equipment :
  - Accommodation, manifesting and delivery of as much equipment as possible within transportation mass and volume constraints.
  - Enabling rapid relocation, integration and change-outs of utility-dependant systems during and following initial operational setup procedures.

Space/ Launch Efficiency :
Available functional space excluding areas dedicated to interior traffic/ airlocks.

Emergency Egress :
Module design/ configuration influences upon worst-case crew escape contingencies.

Module Commonality :
Correlations between module type, configuration and berthing locations determining standardization.

Evolutionary Growth :
Module/ configuration influences upon site preparation requirements and expansion options.

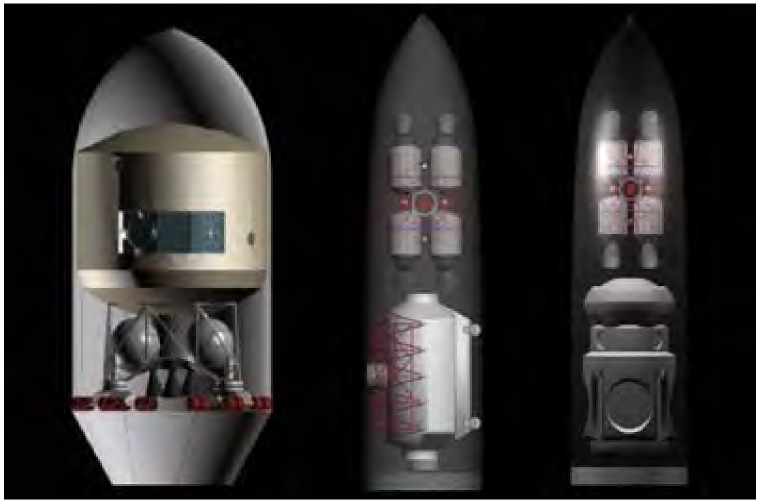
Surface Positioning :
Module/ configuration influences upon assembly requirements at the site.

Key Planning/ Design Considerations

Real Estate Issues

Surface module design options are driven by mass and payload shroud capacities of available launchers:

- If Heavy Lift Vehicles (HLVs) are available with capabilities to launch payloads approaching 100MT and 7 meter diameter, the module of choice is likely to be a bologna-slice cylinder with a landing system attached below :
  - This approach combines CG balancing and stability advantages for landing, good internal volume features, and abilities to pre-integrate utility and equipment systems.
- Approaches that utilize Medium Lift Vehicles (MLVs) with capacities ranging from about 15MT to somewhat less than 100MT are most likely to use a combination of horizontal conventional and vertical inflatable modules :
  - The combination combines advantages of pre-integrated utility/ equipment systems afforded by conventional modules, and large internal volumes enabled by inflatables.



HLV Payload MLV Payloads

Launch-Driven Options

HLV vs. MLV Options

It should be no surprise to observe a high degree of similarity between lunar/ Mars surface modules depicted by different sources since general form is dictated by broadly recognized requirements :

- Within these general design principles and constraints, a variety of special features will differ in response to varying mission and technology-driven strategies, including :
  - Where crews can access a module from the surface (possibly influenced by lander/ propulsion design).
  - How crews and cargo will move between the surface and lowest interior level.
  - Positioning and design of EVA airlocks relative to the surface and traffic connections between adjacent modules.
  - Configuration-based locations of berthing connections and outside viewing ports.
  - The type of “tunnel” to be used between berthing ports for crew/cargo transfer between modules.

HLV Reference Module Concept

HLV-Class Modules

The reference patterns shown provide separate module surface access/egress locations at center locations and berthing tunnel connections between modules at the habitation level.

- A triangular pattern scheme affords certain advantages and disadvantages.

  Pros : A relatively compact configuration footprint at the entry airlock level can minimize the area for site surface preparation if required.

  Loop egress is achieved with three modules.

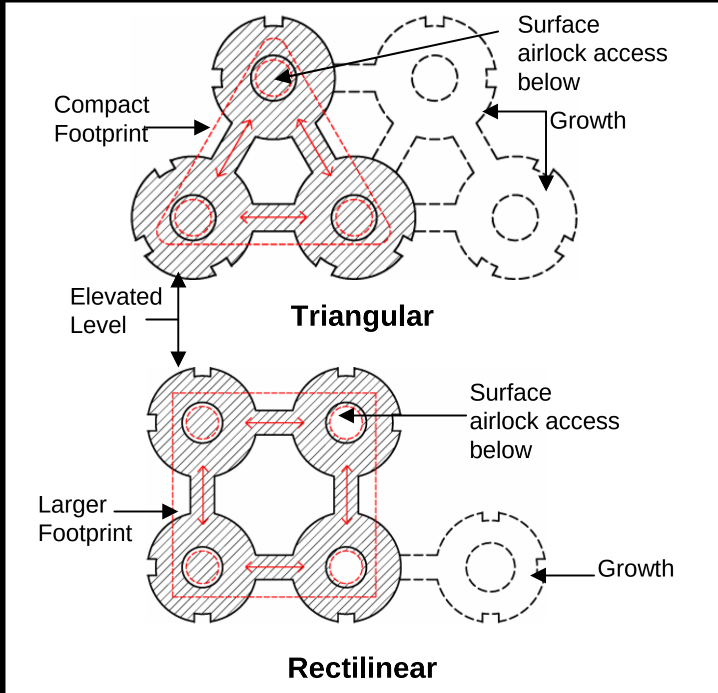
  Con : May be more difficult to position/ assemble.

- A rectilinear scheme also offers advantages/ disadvantages :

  Pro : Greater spacing between berthing locations affords more useful wall/ equipment space.

  Cons : Larger footprint for good site selection and/ or surface preparation.

  Four modules are needed for loop egress.



Pattern Examples

HLV- Class Module Configurations

As previously discussed in Section C, conventional modules applied for MLV-class deliveries are likely to be too narrow, unbalanced and unstable for surface landing and mobility with propulsion systems placed below, but might be landed using an overhead tether approach :

- A reference module design for configuration option comparisons is assumed to have features that follow :
  - Suitlocks are proposed in lieu of conventional airlocks to conserve limited interior space.
  - Each module would be provided with 3 sets of wheels to facilitate transfer from the landing area to the destination site via powered rovers.
  - An alternative design option would use separate connecting nodes to achieve module berthing connections, and also to potentially serve as EVA airlocks for surface access/ egress.

MLV Reference Conventional Module

MLV-Class Modules

Module comparisons presented in Section C observe that a combination of conventional horizontal and inflatable vertical types can be advantageous for MLV-class applications:

- Conventional modules can serve stand-alone purposes during early surface missions, and later become elements of multi-module configurations:
  - They utilize simple and proven design approaches which can be made operational quickly and easily.
  - They can carry equipment and cargo to be transferred to inflatable modules .
  - They can serve as useful connecting elements between inflatable modules which require separation for pressure envelope clearance.
- Vertical inflatable modules can provide large interior volumes for extended surface mission needs:
  - They can interface with conventional modules at their hard sections.
  - They can integrate outside viewing ports above berthing connections without sacrificing valuable wall space needed for equipment and operations.

MLV Reference Combination

MLV-Class Modules

The reference patterns shown show two geometric pattern approaches, both providing surface access/ egress through suitlocks in the horizontal modules:

- The triangular scheme offers advantages as well as disadvantages:

  Pros : A very compact footprint around the inflatable module support bases to minimize site surface preparation requirements.

  Loop egress is achieved with 3 inflatable modules.

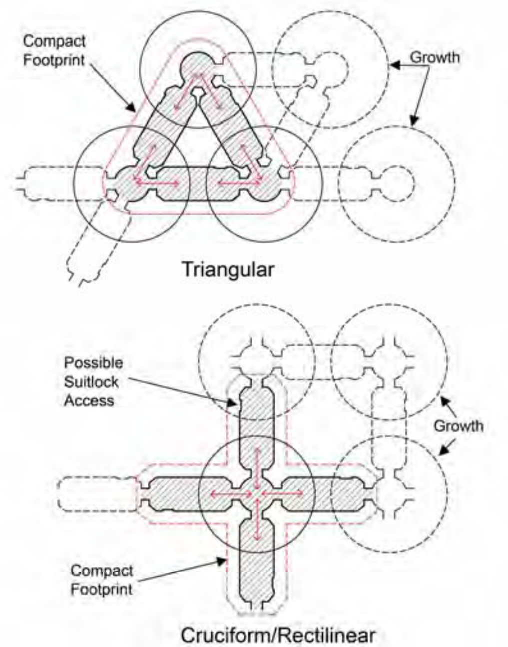
  Con : May be more difficult to assemble.

- The cruciform scheme also offers advantages and disadvantages:

  Pros : The deployment footprint around the horizontal module is quite small, limiting site preparation.

  The scheme can begin as a cruciform and evolve into a closed-loop plan.

  Con : Dual egress is not achieved until 4 modules are in place.

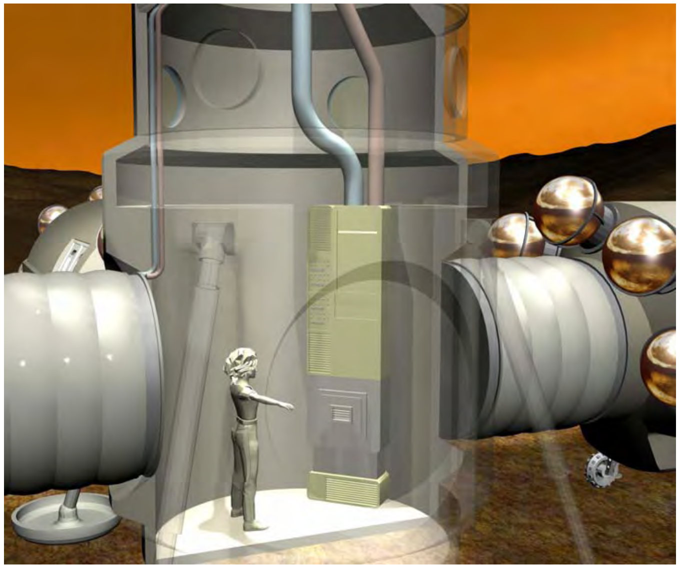


Pattern Examples

MLV-Class Module Configurations

Uneven surface conditions and difficulties in achieving precise axial berthing port alignments are likely to require use of flexible connecting tunnels between modules :

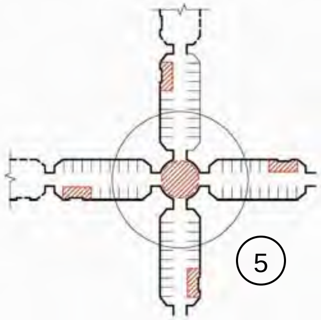
- These conditions will apply for connections between conventional modules and also between conventional modules and hard sections of inflatables :
  - The tunnels must provide utility pass-throughs between connected elements.
  - Connections must also enable transfers of cargo as well as people, requiring that floors be installed to prevent damage to tunnel pressure walls.
  - Although rectangular hatches would be ideal to enable people to pass through upright under partial-g conditions, the tunnels will require circular cross-sections for pressurization, making circular hatches more practical.



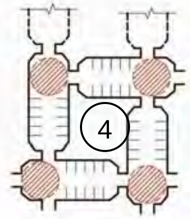
Hard Section and Utilities

Given that HLV-class module configurations and all triangular module patterns present limited variations, SICSA compared four different possibilities for MLV-class modules :

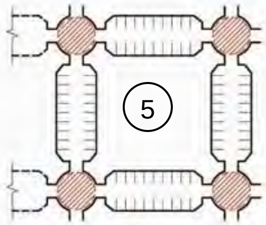
- Scheme A incorporates a combination of horizontal conventional and vertical inflatable modules to realize special advantages of each type:
  - EVA access/egress would be provided by suitlocks in each horizontal module.
  - The cruciform plan could later be expanded into a closed-loop racetrack.
- Scheme B utilizes only horizontal modules in a racetrack pattern:
  - Each module is assumed to contain an airlock which also serves as a berthing/ interface passageway.
- Scheme C utilizes a combination of horizontal conventional modules and corner berthing/ airlock nodes:
  - Suitlocks could be used, but are not presented to conserve functional module space.
- Scheme D presents a raft pattern with 2 types of horizontal modules plus separate berthing/ airlock nodes:
  - The configuration assumes that 2 EVA access/ egress airlocks will be provided.



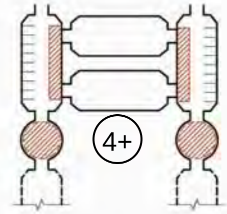
Scheme A: Cruciform with inflatable+ conventional modules



Scheme B: Overlap with conventional modules



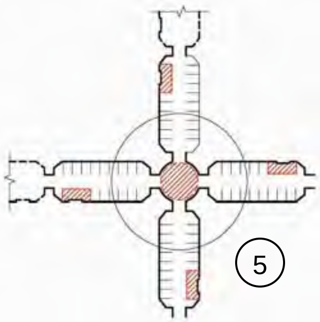
Scheme C: Conventional modules with corner airlock nodes



Scheme D: Raft with conventional modules + airlock nodes

Scheme Examples

Configuration Comparisons



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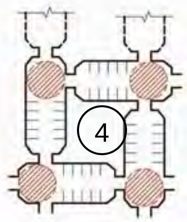
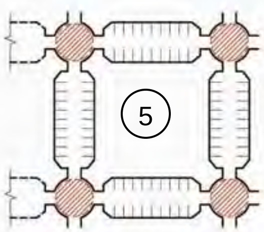
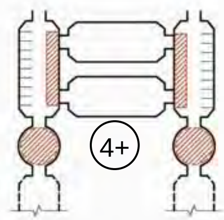


Scheme B: Overlap with conventional modules



Scheme C: Conventional modules with corner airlock nodes



Scheme D: Raft with conventional modules + airlock nodes

Non-functional space

Number of launches required to achieve configuration

Scheme A:

- Suitlocks minimize non-functional space associated with conventional airlocks.
- Inflatable module greatly increases crew living/ work volume over all other schemes.

Scheme B:

- Internal airlocks in all modules produce a high non-functional/ useful volume ratio.

Scheme C:

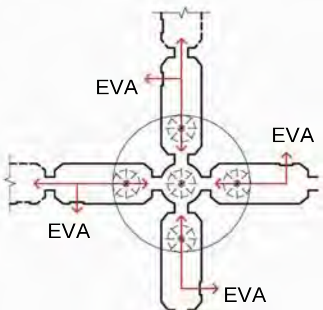
- External airlocks enable full utilization of modules but impose additional launch requirements.

Scheme D:

- Special circulation modules plus external airlocks impose substantial launch requirements.

Space/Launch Efficiency

Configuration Comparisons



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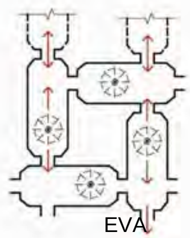
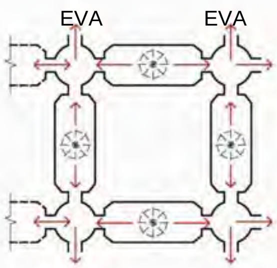
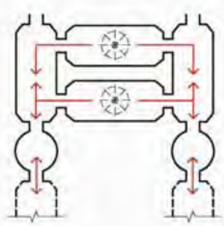


Scheme B: Overlap with conventional modules



Scheme C : Conventional modules with corner airlock nodes



Scheme D: Raft with conventional modules + airlock nodes

Emergency Evacuation

To Connecting Module

To EVA

Scheme A:

- Direct connections, all modules.
- EVA-suitlocks in conventional modules.
- Worst case- central atrium emergency.

Scheme B:

- Connections/ EVA egress through internal airlocks.
- Worst case- airlock failure prior to complete racetrack, isolating modules.

Scheme C:

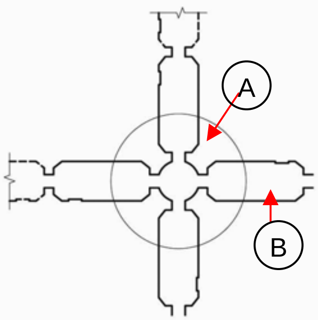
- Connections/ EVA egress through external airlocks.
- Worst case-airlock failure prior to complete racetrack, isolating modules.

Scheme D:

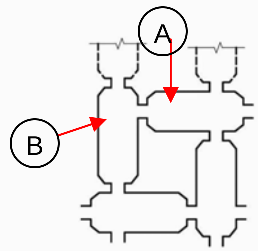
- Connections through special modules.
- EVA egress through separate nodes.
- Worst case- airlock failure prior to complete racetrack, isolating modules.

Emergency Egress

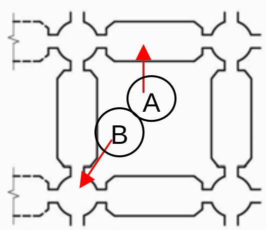
Configuration Comparisons



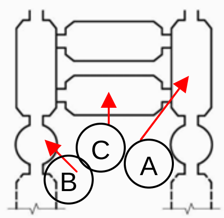
Scheme A: Cruciform with inflatable+ conventional modules



Scheme B: Overlap with conventional modules



Scheme C: Conventional modules with corner airlock nodes



Scheme D: Raft with conventional modules + airlock nodes

Separate Module Types

Scheme A:

- Applies 2 module types, each with important functional support benefits (inflatable volume & conventional module pre-integration).

Scheme B:

- Uses a single standard module but with constricted volume capacity.
- For double connection interfaces the module must be modified for a 2nd berthing port.

Scheme C:

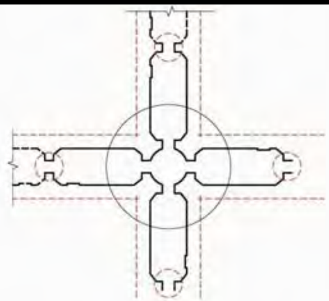
- Uses a single standard module + separate airlock element.

Scheme D:

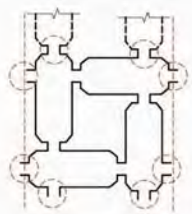
- Uses 2 types of modules + a separate airlock element.

Module Commonality

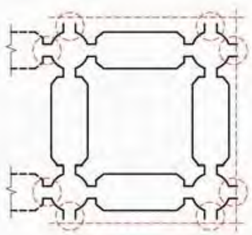
Configuration Comparisons



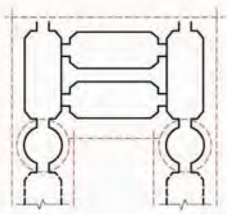
Scheme A: Cruciform with inflatable+ conventional modules



Scheme B: Overlap with conventional modules



Scheme C: Conventional modules with corner airlock nodes



Scheme D: Raft with Conventional modules + Airlock nodes

Possible Growth Interface

Site Preparation/Level Area Boundary

Scheme A:

- Configuration can extend lineally & possibly replicate.
- Smallest boundary for level site requirement.
- Does not impose a requirement for more than 2 modules/ launches prior to operational configuration.

Scheme B:

- Configuration can grow along 2 axes & can replicate a 2nd racetrack group.
- More compact for site preparation than Scheme C.
- Requires 4 modules/ launches to achieve racetrack advantage.

Scheme C:

- Configuration can grow along 2 axes & can replicate a 2nd racetrack group.
- Imposes the largest level site requirement of all schemes.
- Requires 4 modules/ 5 launches to achieve racetrack advantage.

Scheme D:

- Configuration can grow along one side (unless additional airlocks are added) requiring 4+ launches, and can replicate.
- More compact for site preparation than schemes B&C.
- Requires 4 modules + 2 airlocks to achieve racetrack advantage.

Evolutionary Growth

Configuration Comparisons

Scheme A:

- Central inflatable module establishes the site center & is not repositioned.
- Conventional modules with wheels are aligned to interface at a single point.

Scheme B:

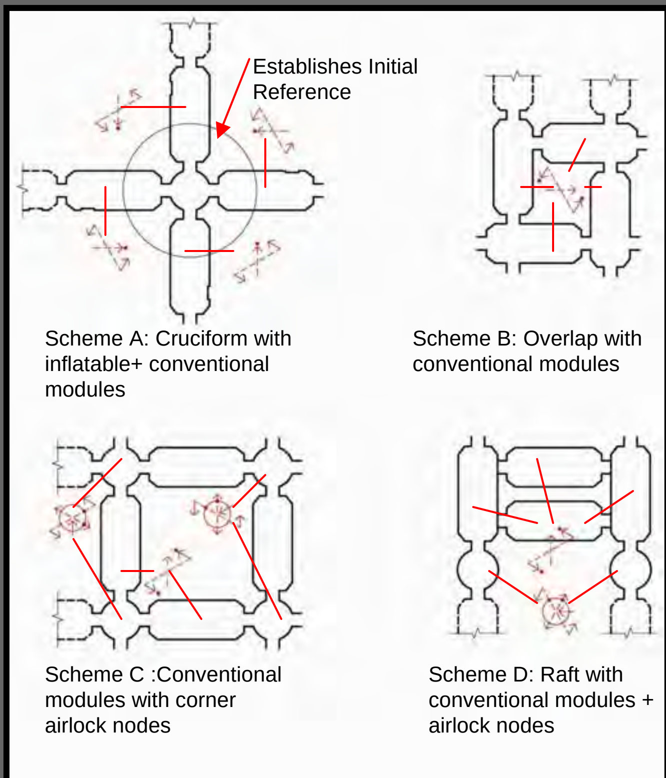
- Conventional modules with wheels must be forward & rotationally aligned for mating at 2 berthing points.
- Placement positioning may be difficult by towing due to interference by obstructing modules.

Scheme C:

- Accurate positioning of conventional modules and nodal airlock elements may be difficult, particularly on rough, uneven sites.
- While conventional modules can have wheels, means for transferring/ aligning nodal airlocks are unknown.

Scheme D:

- Accurate positioning of all 4 conventional modules to accommodate berthing interfaces may be difficult, particularly for rotational alignments of end circulation modules.
- Transport & positioning problems for nodal airlock elements are similar to Scheme C.

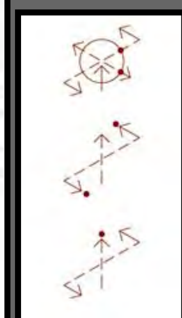


Scheme A: Cruciform with inflatable+ conventional modules

Scheme B: Overlap with conventional modules

Scheme C :Conventional modules with corner airlock nodes

Scheme D: Raft with conventional modules + airlock nodes



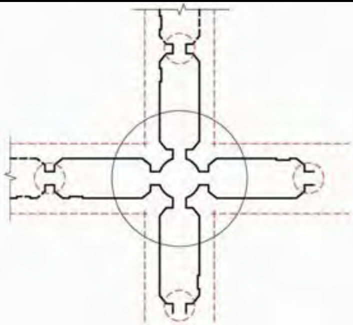
Forward, Rotational & Elevation Alignments with 2 or more interfaces

Forward,Rotaional & Leveling Alignments with 2 or more interfaces

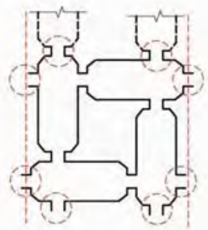
Forward,Rotaional & Leveling Alignments with 1-2 interfaces

Surface Positioning

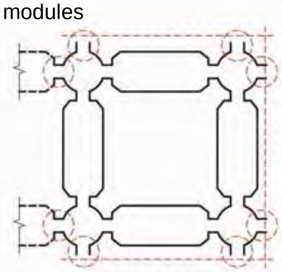
Configuration Comparisons



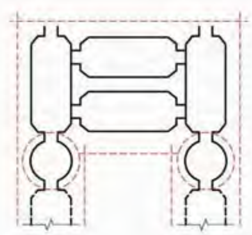
Scheme A: Cruciform with inflatable+ conventional modules



Scheme B: Overlap with conventional modules



Scheme C: Conventional modules with corner airlock nodes



Scheme D: Raft with conventional modules + airlock nodes

	SPACE/LAUNCH EFFICIENCY	EMERGENCY EGRESS	MODULE COMMONALITY	EVOLUTIONARY GROWTH	SURFACE POSITIONING	SUMMARY COMPARISON	RANK ORDER
SCHEME A	GOOD	FAIR	FAIR	GOOD	GOOD	GOOD	1
SCHEME B	POOR	FAIR	GOOD	FAIR	POOR	FAIR	3
SCHEME C	FAIR	FAIR	FAIR	FAIR	POOR	FAIR	2
SCHEME D	POOR	POOR	POOR	FAIR	POOR	POOR	4

Summary Observations

Configuration Comparisons

ORBITAL AND SURFACE ARCHITECTURES

SURFACE FACILITIES

Guided by the configuration option comparisons, SICSA selected a reference design that combines use of conventional and inflatable (hybrid) modules for further investigation :

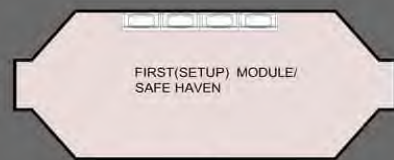
- This approach combines advantages of large interior volumes of inflatables with means to integrate utilities and equipment systems afforded by conventional modules. In addition:
  - It allows conventional modules to be used to transport cargo/ equipment that can't be carried in inflatables.
  - It enables conventional modules to be standardized for use as laboratories, and for use as logistics carriers that can be used for lab/ hab functions when emptied (excellent commonality functions).
  - It can evolve into a racetrack pattern, offering dual egress capabilities.
  - It can accommodate separate attachable airlocks, but potentially will not require them.
  - It presents a small footprint to minimize site selection and preparation problems.

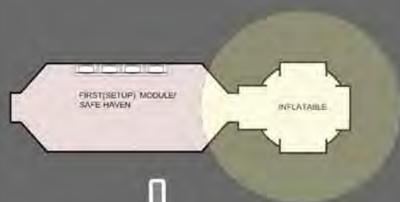
Module Combination Approach

Reference Design

FIRST/SETUP MODULE :

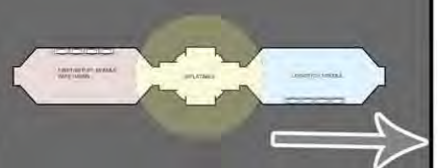
Astronauts will live and work out of this module for the first few days till the habitat is set up. This module will later be used as a safe haven.

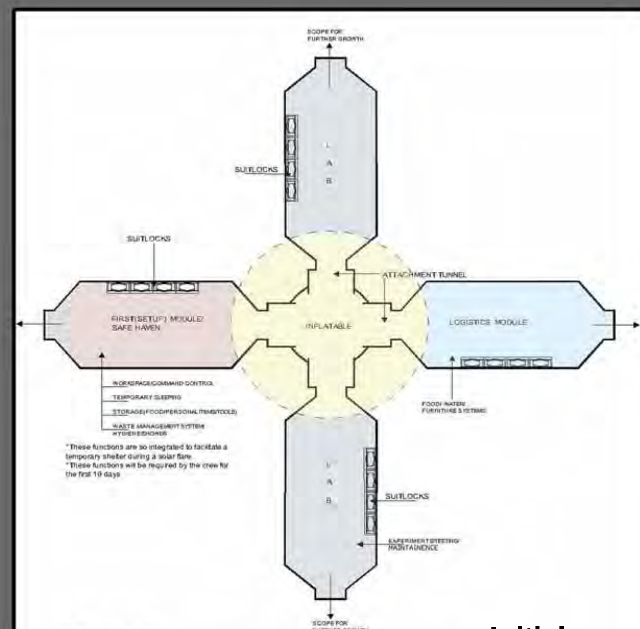




Astronauts will dock the core module with the first one, deploy the inflatable and get the systems in order .

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)

Initial Base Staging

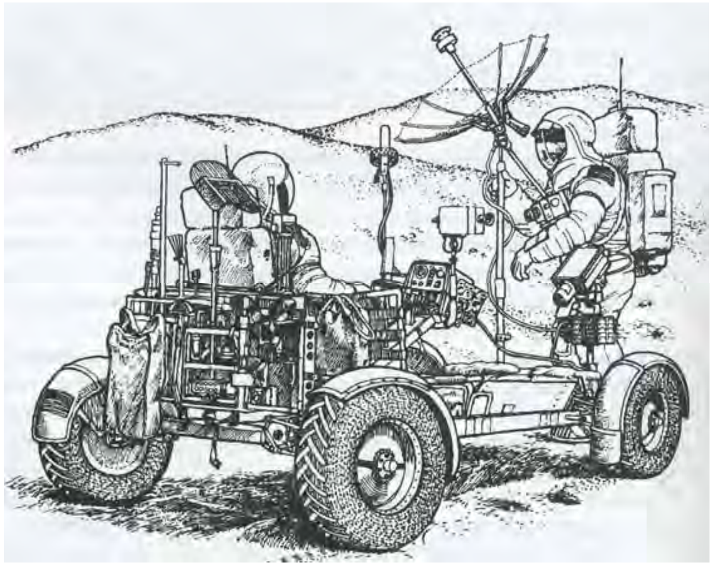
Reference Design

ORBITAL AND SURFACE ARCHITECTURES

SURFACE FACILITIES

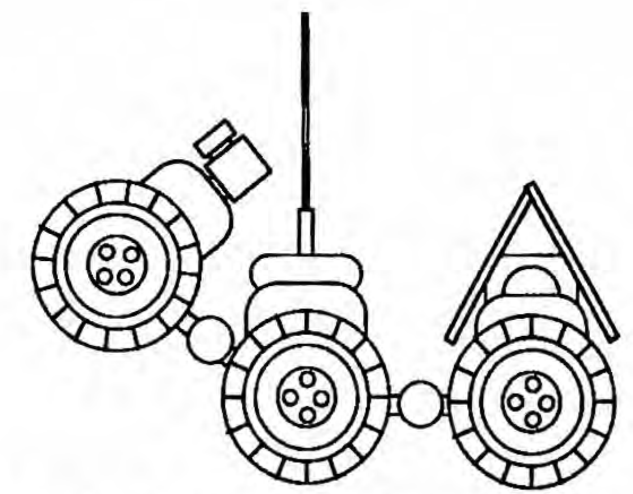
Habitat modules capable of supporting even 4-8 person crews for lunar surface missions lasting weeks, and Mars missions lasting months or even years, will be many times larger and heavier than the tiny Apollo Lunar Module (LM) :

- Means must be planned to transport these modules and other massive items to destination sites from landing/ ascent areas located a safe distance away from ballistic ejecta hazards :
  - The transport design must consider reduced traction of any prime mover used to pull or push payloads under reduced gravity conditions.
  - Rocky/ hilly surfaces that can upset stability and present physical obstructions must be taken into account.
  - Given that the devices can be expected to be large and massive, the methods to launch, land and deploy them at the surface must be addressed.
  - Recognizing the large space transportation costs, they should be versatile to support multipurpose uses.



The lunar rover used for Apollo 15, 16 and 17 missions will be too small for transporting large modules and cargo elements.

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

HUMAN SPACEFLIGHT

Screw Drive Mobility Vehicle
Example: Snowmobile

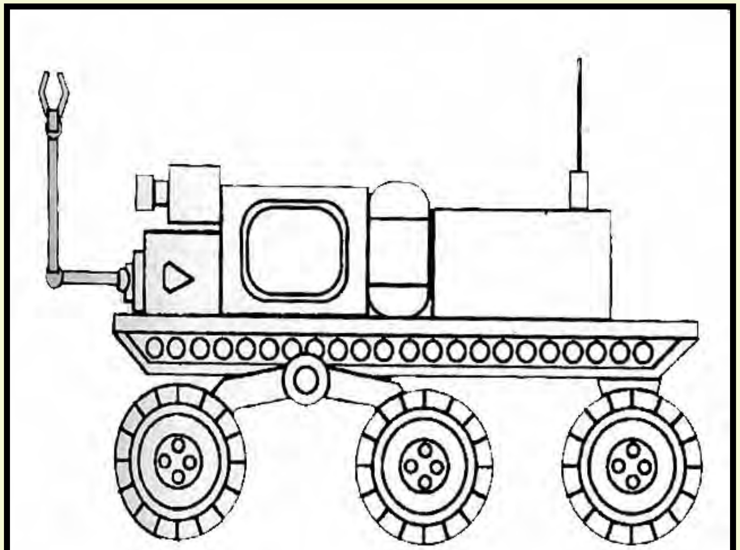
Chassis: 3-5 m long, rigid frame
Mobility System: Counter-rotating helixes
Operation: Human driver
Power: Batteries, fuel cells or RTG
Range: A few kms, depending on energy available
Speed: Moderate, good on soft soil
Energy Efficiency: Moderate on smooth terrain
Towing: Very good on proper surface
Complexity: 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

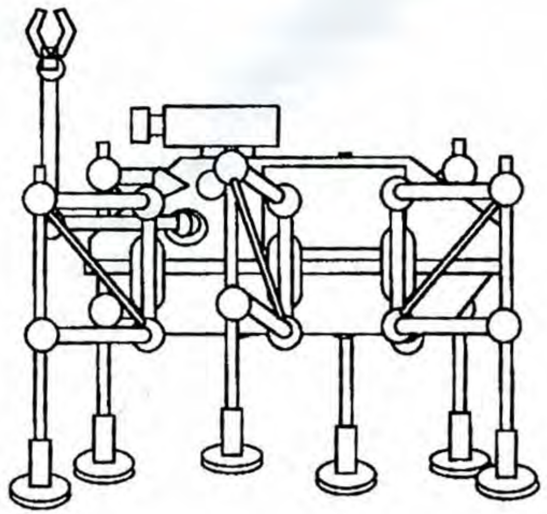
Chassis: 3-5 m long, rigid frame
Mobility System: 4-wheel electric motor drive
Operation: Human driver
Power: Batteries, fuel cells or RTG
Range: A few kms, depending on energy available
Speed: Moderate to high
Energy Efficiency: High on smooth terrain
Towing: Not recommended
Complexity: Moderate
Lifetime: 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

HUMAN SPACEFLIGHT



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

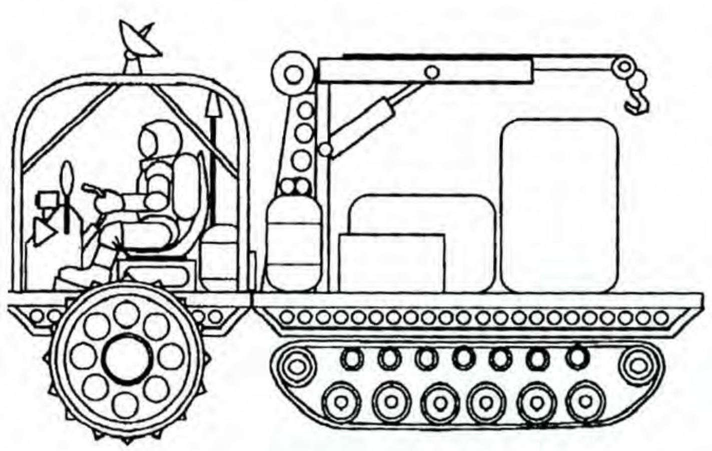
Chassis: 0.1-1 m long, rigid frame
Mobility System: 6 wheels, 4 articulated
Operation: Automated or human driver
Power: Batteries, fuel cells or RTG
Range: Depends on vehicle size, stored energy
Speed: Good to excellent, power limited
Energy Efficiency: Good on smooth terrain
Towing: Not recommended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



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

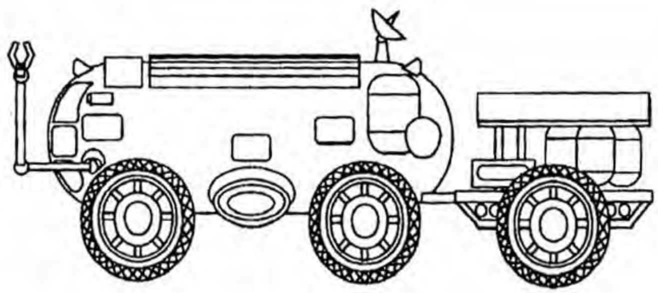
HUMAN SPACEFLIGHT



Flat-Bed, Open-Cab Utility Vehicle

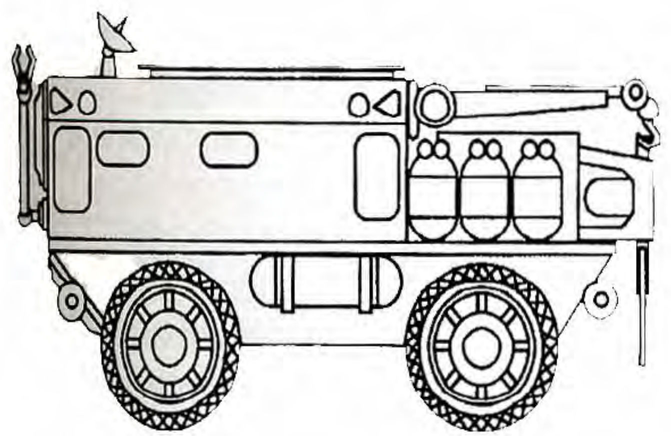
Chassis: 5-10 m long, rigid or pivoted frame
Mobility System: Wheels and/or tracks
Operation: Human driver
Power: Batteries, fuel cells or RTG
Range: Up to 100 km, depends on energy availability
Speed: Moderate to good
Energy Efficiency: Moderate with tracks
Towing: Excellent, especially with tracks
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

HUMAN
SPACEFLIGHT



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



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

Any surface transportation and base deployment strategy must optimize all systems and operations for diverse and difficult conditions :

- Environmental Influences :
  - Systems should be designed to accommodate rough/ hilly terrain features at all candidate sites without requiring a large inventory of equipment types.
  - Extremely cold temperatures will degrade battery power efficiency/ life, and long lunar nights will exacerbate this condition.
  - Reduced gravity will limit wheel traction, and dust will cause friction and degrade mechanical functions.
- Operational Influences :
  - Large parts and accessories will be difficult to change out/ repair under EVA conditions.
  - Systems must be versatile to meet diverse and changing evolutionary mission requirements.
  - Offloading of modules/ cargo from carriers must be made as simple and safe as possible.
  - Launch and delivery of all devices to the site should apply a universal transportation strategy.

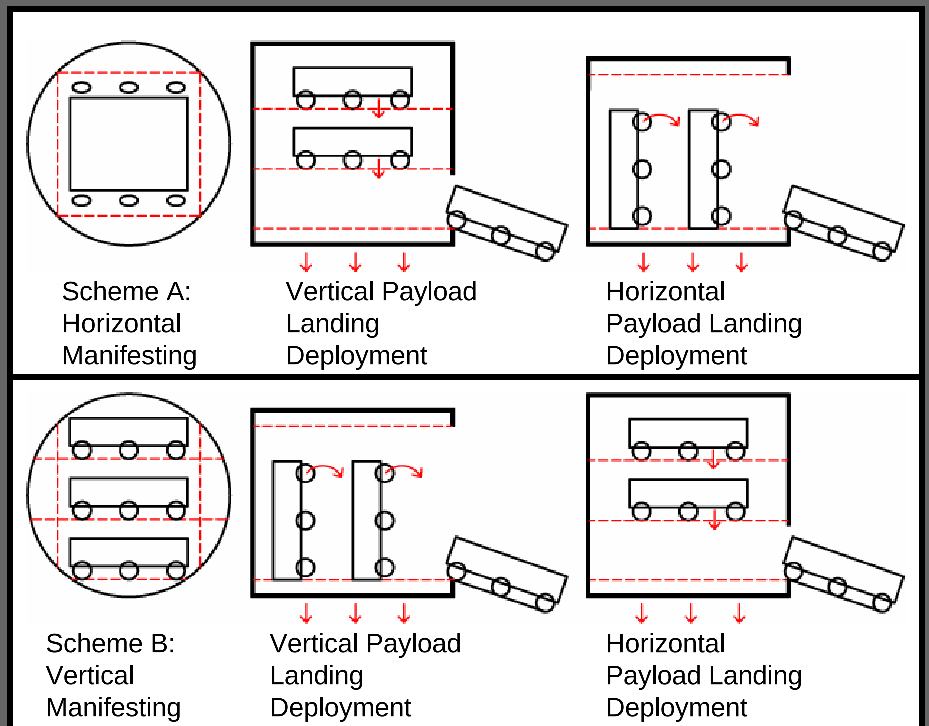
Expandable modules (Vertical and Horizontal)	Fixed Modules (Horizontal Short and Long)
• **Transportability:** - Vertical modules present a tall, narrow geometry that can topple over on rocky, uneven surfaces. - Surface relocation will be more difficult for long telescoping modules following deployment.	• **Transportability:** - Horizontal modules with wheels can be towed in a relatively stable fashion. - Fixed modules, including those with upper inflatable segments can be most easily relocated to near-by sites.
• **Operational Preparation:** - EVA crew must deploy/ pressurize expandable modules prior to use. - Approaches are best suited for crew operations following establishment of a conventional shirtsleeve habitat.	• **Operational Preparation:** - Modules (without inflatable sections) can be pressurized prior to crew arrival. - Approaches can be used either alone or in combination with expandable modules that are added later.
• **Site Development:** - Difficult mobility makes them most suited for location at the final base site. - Limited transfer capacity for hard equipment and consumable stowage will require augmentation.	• **Site Development:** - Can be used to augment equipment capacities of expandable modules. - Subsequent modules can be added as needed to meet evolutionary site development for expanded operations.

Implications of Different Module Types

Mobility Planning Considerations

Rover planning must consider launch manifesting influences on surface landing and deployment :

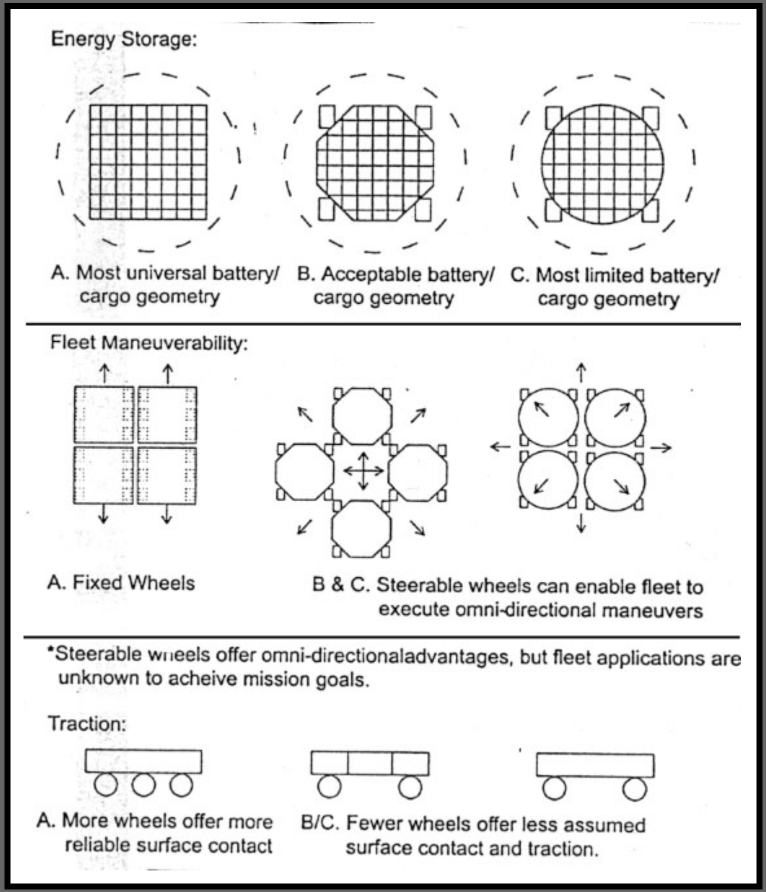
- Scheme A assumes a horizontal bologna-sliced payload orientation :
  - If the payload carrier lands in a vertical orientation, landing loads will act on wheels/ shelves, and means must be provided to lower the stacks.
  - If the payload carrier lands horizontally, loads will act on a platform end, and the rovers must tip down.
- Scheme B assumes a vertical manifest (platforms aligned with the launch axis) :
  - If the carrier lands in the original launch orientation, loads will act upon a platform end and rovers must tip down for offloading.
  - If the carrier lands horizontally, impact loads will act through wheels and the rovers must download from the stacks.



Rover Manifesting for Launch & Deployment

Rover design must consider energy and cargo storage capacity for long traverses, maneuverability on rough/ hilly surfaces, and ability to achieve adequate traction :

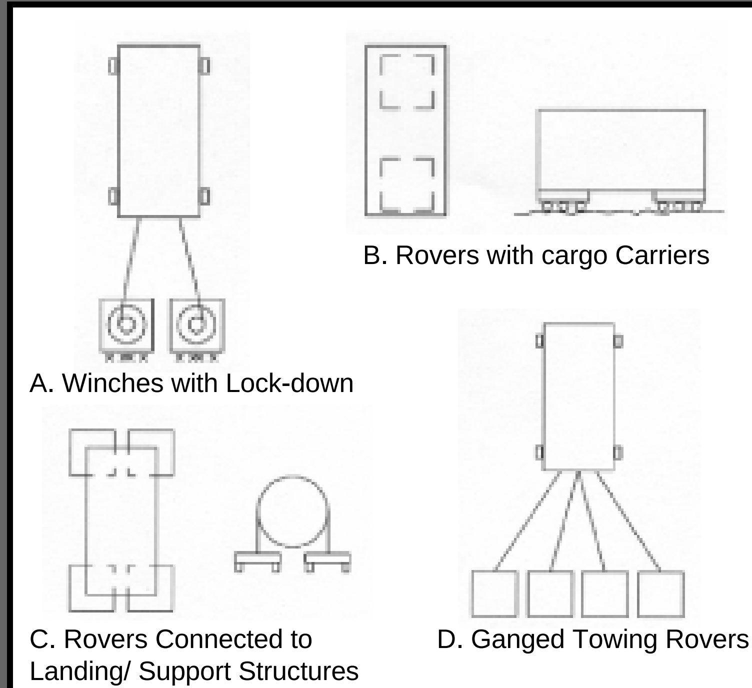
- Platform geometry must be correlated with launch manifesting and influences upon available platform area/ volume for energy storage and payloads:
  - Given that batteries and other payloads are most likely to be rectilinear, a square shape (Scheme A) might be most ideal.
- Individual unit and fleet maneuverability might utilize variable power applied to fixed wheels or steerable wheels (possibly individually powered and controlled) :
  - Steerable wheels may offer maneuvering advantages for some fleet applications.
- Traction will be determined by vehicle loaded mass, contact surfaces and wheel/ track design :
  - More wheels may often provide more contact surface and contact occurrences.



Energy Storage, Maneuverability & Traction

SICSA considered 4 different element approaches for moving and positioning large items such as modules and logistics carriers :

- **Option A – Tow Winches with Lock-down :**
  - Multiple rovers might be outfitted with power winches that pull wheeled cargo items after the rovers “lock-down” with anchoring devices, eliminating a need for wheel traction.
- **Option B – Rovers with Cargo Carriers :**
  - Payloads would be placed on one or more rover beds to optimize traction, but large items would need offloading means, potentially requiring cranes or other massive equipment.
- **Option C – Rovers Attached to Landing/ Support Structures :**
  - Payloads would be supported by individual rover platforms at each corner with real-time operational coordination and maneuvering , an approach that might be perilous on uneven surfaces.
- **Option D – Ganged Towing Rovers :**
  - This approach would depend upon total rover mass and wheels contact to develop sufficient traction, potentially requiring many units.

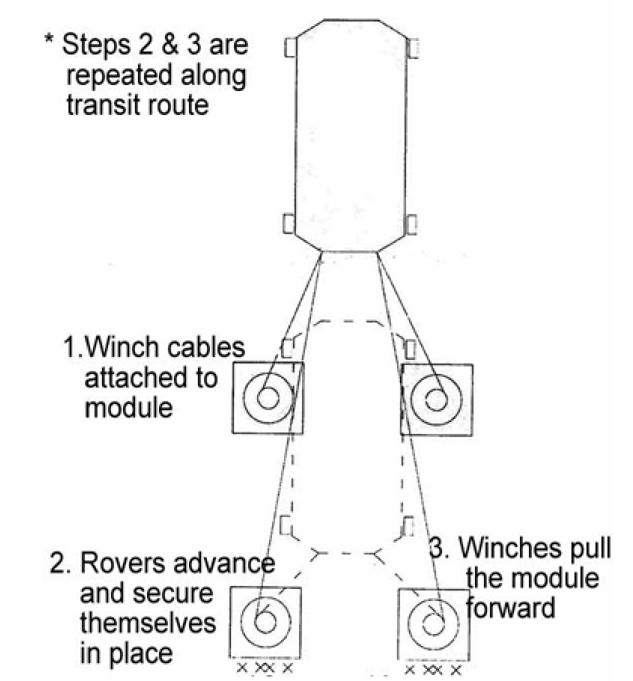


Design and Operational Approaches

Payload Transfers & Positioning

The tow winch scheme was selected as a reference design approach to enable a pair of relatively small rovers to move and position modules and other large elements 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

Reference Transport Concept

The tow winch approach offers a variety of important advantages :

• **Minimization of rover size and numbers :**

- The lock-down feature makes the system much less dependant on rover mass for pulling traction than other wheeled or tracked alternatives, reducing rover transport launch, transfer and landing costs.
- Smaller, lighter rovers will be more power efficient, enabling longer traverses with larger payloads.
- More rover units can be delivered within a given transportation payload budget, enabling functional versatility and redundancy.

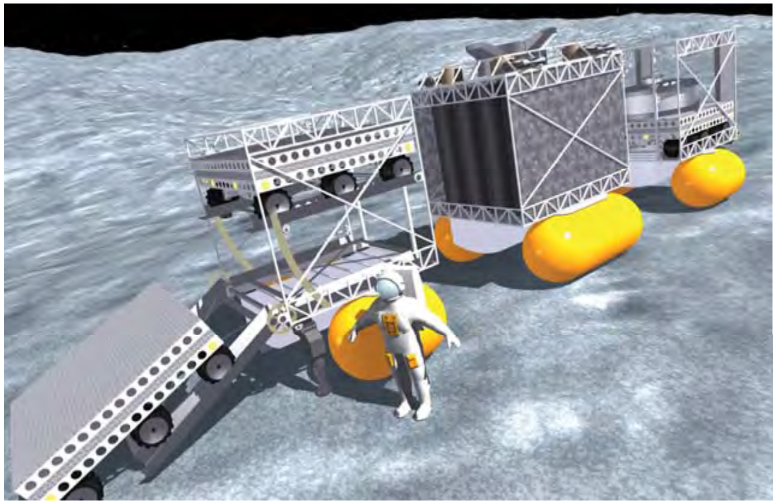
• **Optimization of capabilities :**

- The rover winches can be used to deploy electrical cables between the base and a nuclear power source located a safe distance away.
- A standard rover platform can be outfitted with cranes, drilling rigs and other useful equipment.

Reference Transport Concept

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

A scenario for establishing initial planetary base operating capabilities is outlined in four general stages that follow :

Stage 1 : A pressure system is landed and deployed:

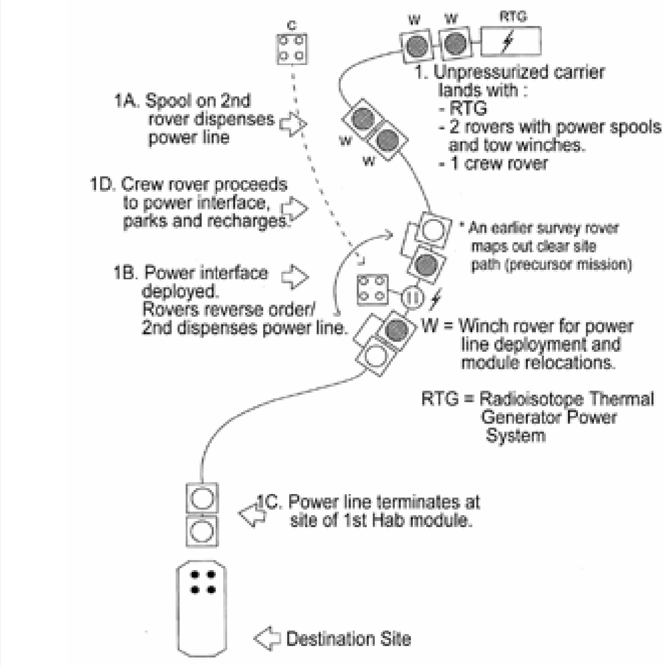
1. An unpressurized logistics carrier lands and delivers a RTG power source, 2 rovers with winches, and a crew rover.

1A : Rovers are automatically deployed and the 2nd winch rover in a 2-rover train dispenses a power until the spool is depleted at a power interface junction.

1B. The winch rovers reverse order, and the full-spool winch dispenses remaining cable to the destination site.

1C. The spent winch rovers park at the destination site with power connections to the RTG.

1D. The crew rover automatically proceeds to the power interface junction, parks and recharges.



Stage 1 : Power is Established

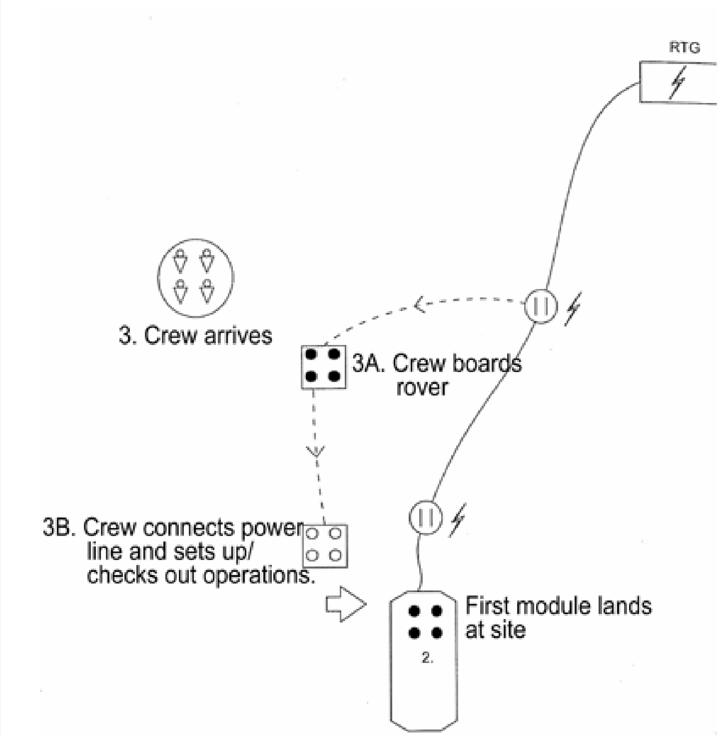
Initial Base Development Scenario

Stage 2 : The first module is landed at the site. The module parks unmanned at the end of the power line leading from the RTG.

Stage 3 : The first 4-person crew arrives at a different landing site at a safe distance from the modules.

3A. The crew rover leaves the power interface charging station and automatically tracks to the crew landing site.

3B. The crew departs on the rover and proceeds to the module site to connect the power cable and set up/ check out operational capabilities.



Stages 2 & 3 : Ist Module Set-up

Initial Base Development Scenario

Stage 4 : A second hab module, which also carries logistics supplies, lands at a new site.

4A. All rovers recharge at the site of the first module.

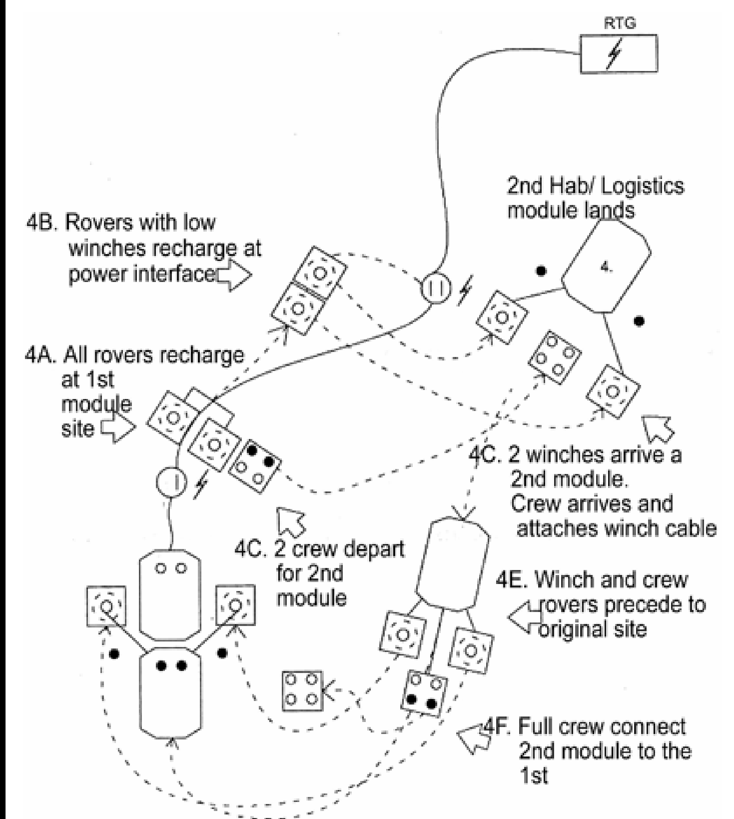
4B. The rovers with tow winches proceed to the power interface and recharge.

4C. Two of the crew members depart on the crew rover to the 2nd module.

4D. The tow winch rovers are automatically dispatched to rendezvous with the crew at the 2nd module and winch cables are attached to the module.

4E. The winch rovers tow the 2nd module to the site of the 1st module, and the crew onboard their rover control operations.

4F. The full crew participates in positioning the 2nd module into a berthing alignment with the 1st, check out interfaces, and complete operational readiness procedures.



Possible Base Set-up Stages

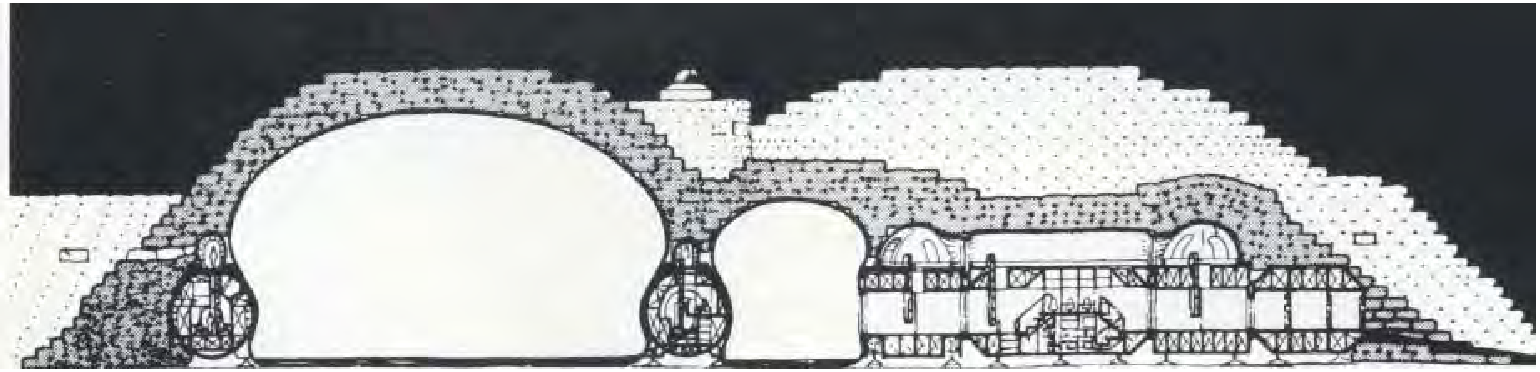
Initial Base Development Scenario

A variety of lunar habitat shielding concepts have been proposed to take advantage of natural geologic features and surface materials for radiation protection:

- Putting modules in underground lava tubes.
- Tunneling into crater walls.
- Covering facilities with 50 centimeters or more of lunar soil (regolith).

Each of these proposed approaches present significant problems:

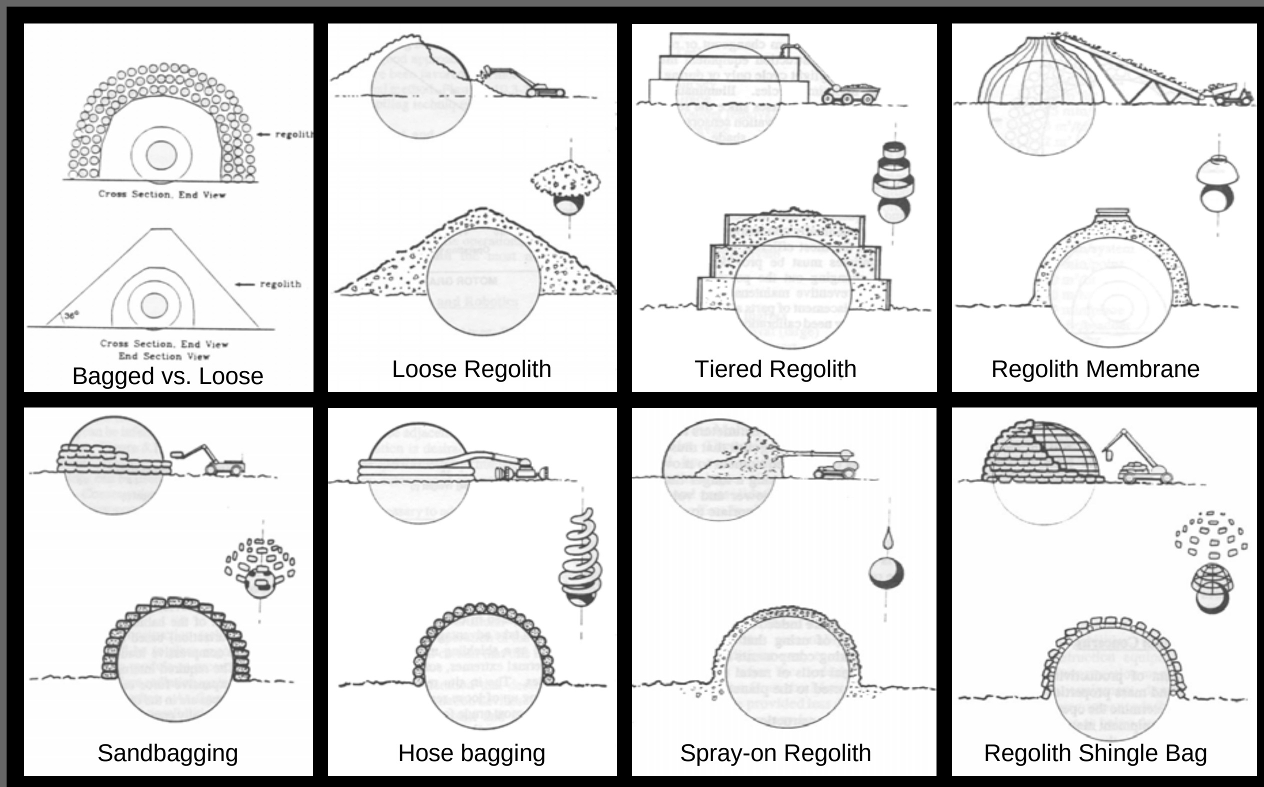
- Use of lava tubes will severely limit site selection and development options.
- Tunneling or material transfer to cover modules will require large, automated equipment, and it will be difficult or impossible to connect other modules later.



Radiation Protection

D-77

NASA



Regolith Shielding Concepts

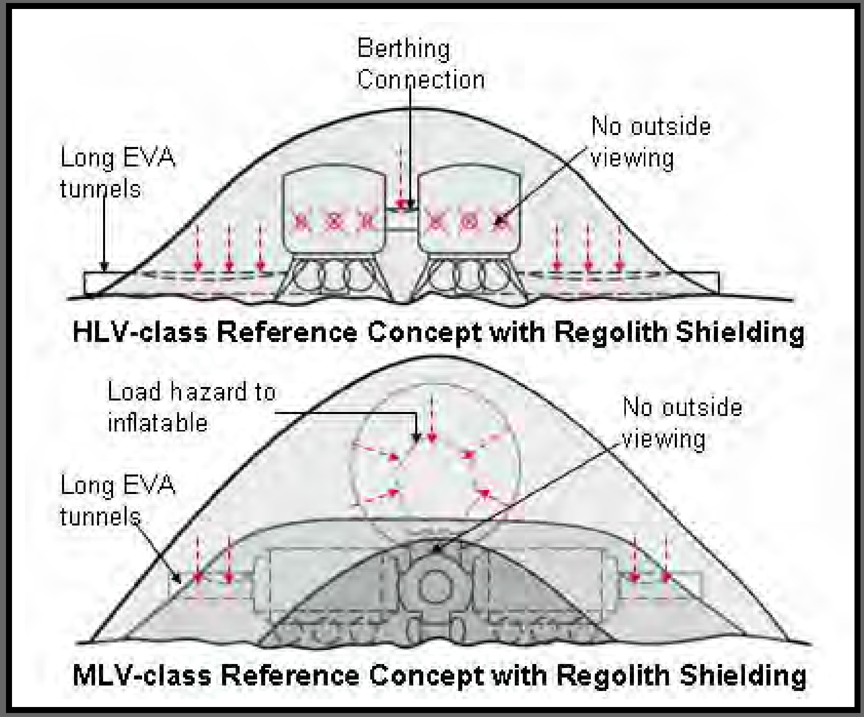
Radiation Protection

ORBITAL AND SURFACE ARCHITECTURES

SURFACE FACILITIES

Use of regolith radiation shielding is not recommended for lunar /Mars surface habitat applications :

- The amount of material that would have to be excavated, moved and emplaced exceeds capabilities of equipment that would be practical to launch, transfer and land.
- After a module is covered, it would be unimaginably difficult to connect another for evolutionary growth.
- Very long EVA tunnels would be required to enable access/ egress at points beyond regolith slope angles.
- Flexible tunnels and other inflatable structures would be collapsed by loads in the event of temporary pressure losses.
- Outside viewing would be prevented due to material obstruction.



Regolith Shielding Problems

More detailed information about many topics discussed in this section, along with reference and additional information sources, is offered in Part I and Part II of this lecture series. Additional information regarding these and other SICSA projects can be obtained on www.sicsa.uh.edu

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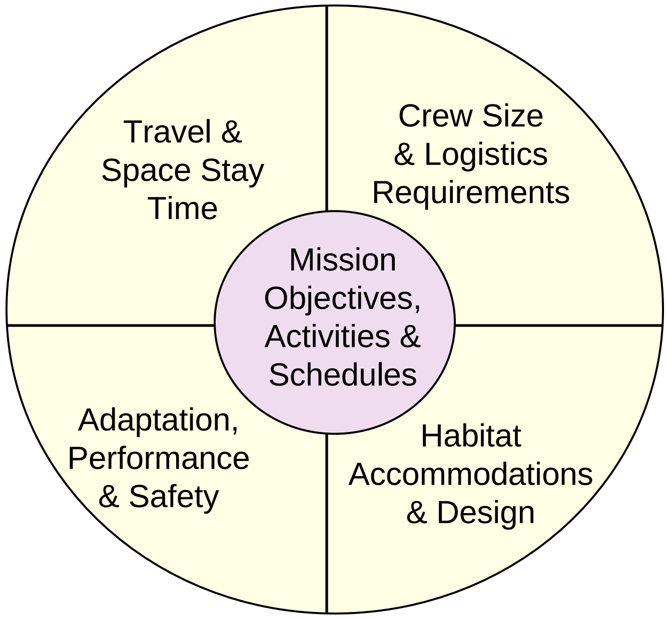
OF CONTENTS

SECTION E: HUMAN OPERATIONS & SUPPORT

Effective responses to mission objectives will require careful examination of relationships between mission time periods, crew resources needed, essential living and work environments, and means to ensure productive and safe operations.

Travel & Surface Stay Time	Crew Size & Logistics
▪ Mission goals and objectives ▪ Vehicle/propulsion/trajectory ▪ Launch & return windows ▪ Abort/rescue contingencies	▪ Mission-driven requirements ▪ Types/amounts of consumables ▪ Life support system closure ▪ Number of planned EVAs
Habitat Accommodations & Design	**Adaptation, Performance & Safety**
▪ Crew living & work areas ▪ Personal & general stowage ▪ Health maintenance facility ▪ EVA airlocks/ consumables	▪ Gravitational conditions ▪ Support equipment & amenities ▪ Radiation shielding/ safe havens ▪ Exercise & recreation

Interrelated Planning Factors



Mission and Option-driven Issues

Space exploration planning must anticipate and accommodate evolutionary program requirements:

- Habitats and support systems should enable incremental expansion and upgrades :
  - Primary structures and systems for lunar applications should be designed in a manner that takes future Mars mission requirements into account to avoid unnecessary and expensive new-start initiatives.
  - Elements should enable versatile modularity to support incremental expansion of mission activities, crew sizes and duration over time .
  - Plug-n-play habitat and system architectures are needed to enable technology upgrades to be incorporated and tested, including closed-loop life support and advanced automation technologies.

Research Outpost
- Establish an initial living capability.
- Explore, survey and prepare the base site.
- Deploy and check out limited science equip.
- Undertake short site excursions.

Operational Base
- Install additional hab/ lab facilities.
- Locate/ sample surface resources.
- Test resource harvesting methods.
- Expand science/ tech. experiments.

Expanded Base
- Harvest/ store/ utilize in-situ resources.
- Explore satellite outposts.
- Close the life support loop.
- Undertake advanced technology demos.

Industrial Facility
- Expand in-situ harvesting/prod.
- Undertake industrial research/ tests.
- Extend mission lengths.
- Support other exploration missions.

Possible Exploration Program Stages

Anticipating Evolutionary Needs

Planning for each mission stage must take a variety of strategic requirements and variables into account :

Crew Selection & Mix : • Specializations and work task assignments. • Availability of a doctor for medical interventions. • Gender and age-related radiation risk hazards. • International influences on communication and menu preferences.	**Mission Duration & Schedules :** • Influences on comfort, exercise and recreation needs. • Radiation exposures and other health/ safety risks. • Probabilities of equipment failures and repair requirements. • Contingencies for missed return windows.	**Logistics Support :** • Life support system closure to reduce imports. • Stowage/ inventory for equipment and rations. • Contingencies for missed resupply windows. • Use of in-situ materials to reduce logistics.
Operation Protocols : • Level of crew autonomy for critical decisions. • Military type vs. civilian organization structure. • Shared vs. assigned housekeeping roles. • Around-the-clock vs. day shift schedules.	**Safety Provisions :** • Redundancy/ spares for equipment failures. • Accommodations for emergency medical treatment. • Radiation safe havens and emergency egress. • Surface ascent/ crew return contingencies.	**Automation Support :** • Minimization of EVA requirements/ hazards. • Workstations/ viewing for telerobotic operations. • Backups for critical automation software/ equipment failures. • Evolutionary capabilities for expanded operations.

Mission Requirements and Variables

New generations of “smart” automation technologies are demonstrating great benefits for space applications, both for unmanned missions and to facilitate/ support crew operations.

- While many spectacular achievements have been accomplished with robots, human crews will have vital and unique roles in advancing space exploration progress :
  - People are need to make real-time observations and decisions in remote and unfamiliar locales.
  - Humans are versatile, enabling a broad variety of tasks to be undertaken as opportunities and needs arise.
  - People combine advantages of mobility and dexterity to access and respond to scientific and maintenance tasks.
  - Humans can make unscheduled repairs to mission-critical equipment that is essential for success.

Advantages	Disadvantages
Humans : • Intelligent and intuitive • Can flexibly adapt • Able to innovate • Good dexterity • Can multi-task	***Humans :*** • Require life support • Subject to stress/ injury • Limited strength •Need temperature controls • Get bored, make errors
Robots : • Don’t get bored • Precision capabilities • Can exert strength • Operate under extremes • Do hazardous jobs	***Robots :*** • Can’t innovate solutions • Can’t recover from errors • Limited versatility • Need instructions • Subject to failures

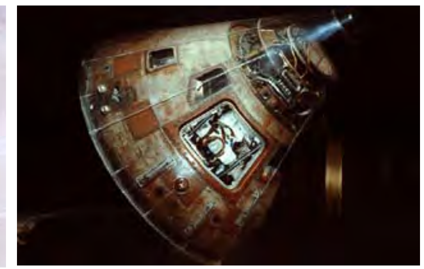
Human vs. Robots

Important Human Roles

As discussed in Part II, Section A of this lecture series, space exploration will present major human challenges :

- Previous dashes to the Moon have been similar to expeditions to the North and South poles early in this century:
  - -They have involved marathon endurance runs.
  - -While not lacking in courage, ingenuity and productive results, they have lacked permanence.
- US and Russian space station missions have demonstrated that humans can adapt to space for long periods of time:
  - -US Skylab astronauts lived and worked in space for as long as 84 days.
  - -Russian cosmonauts have lived in space for a year.
- Human missions to Mars are likely to require that people be able to survive and perform in space over periods of years:
  - -Crews must adapt and perform under weightless or artificial-g conditions in transit, and partial-g on the surface.
  - -They must be protected from radiation and other hazards.

Polar cap



Apollo

Mir

Skylab

Expanded Requirements

As discussed in Part II, Section G of this lecture series, radiation presents a primary health risk for space exploration :

- Overt human reactions to radiation exposure can be immediate or delayed:
  - -Near-term manifestations can include nausea, vomiting, decreased white blood cells, diarrhea, fever, hemorrhage and death.
  - -Delayed effects include cancer, birth defects in progeny, and miscarriages.
- Some people are more prone to develop cancers than others:
  - -Future astronaut selection for long-duration exploration missions may have to give family histories careful consideration.
  - -Selection of older candidates with low previous cumulative lifetime doses could also reduce risks of premature deaths due to cancers.

NASA

Effect in Healthy Adults	*Acute Dose*
• Blood count changes common	50 rad
• Vomiting, "effective threshold"	100 rad
• Mortality, "effective threshold"	150 rad
• LD_{50} minimal medical treatment	320-360 rad
• LD_{50} supportive medical treatment	480-540 rad
• LD_{50} bone marrow/blood stem cell transplant	1000 rad
Effects on Reproductive Systems	
• 50% temporary sperm count reduction	15 rad
• 100% sperm loss lasting a few months	100 rad
• Male sterility lasting 3 or more years (if subject survived high dose)	600 rad
• Possible menopause in 40 yr.-old woman	300 rad
• Possible temporary menstrual suppression in 20 yr.-old woman.	300 rad

Ionizing Radiation Effects
D.S. Nachtwey*, NASA Johnson Space Center

The Radiation Environments

Radiation risk assessments consider special vulnerability factors:

- Some parts of the human body are more vulnerable to radiation damage than others:

  -The skin and eyes are most accessible to a wide range of energy particles with limited penetration characteristics, yet are less susceptible to injury than many other parts of the body.

  -Certain deeper locations (bone marrow, lungs, pancreas and liver) are of special concern due to susceptibility to cancers.

  -Possibilities exist where doses to eyes and skin can be very high without BFO limits being approached (such as during EVAs in trapped electron belts), the reason ancillary eye and skin standards have been set.

- Individuals present different risks:

  -Women face added risks of breast cancers and damage of reproductive processes which can induce early menopause, birth defects in future children and miscarriages as delayed effects.

  -People with different backgrounds (geographic, occupational and age-related) have received varying radiation exposures that contribute to allowable career doses.

  -A 30-40 year old beginning astronaut will have a career limit between 200-275 rem, and a 50 rem annual limit will ensure that the career dose will be spread out over a protracted period.

Radiation Vulnerability Factors

Radiation hazard limitations and risks will increase as mission frequencies and lengths increase:

- There may never be "career" astronauts in the context of long-term, continuous professional livelihoods.

  -A 30 year-old male on his first 180 day LEO mission could look forward to a maximum of 5 more similar duty tours before exceeding the 200 rem career limit set for his age group and gender.

  -A 50 year-old male might spend up to a total of 5 years in space before reaching his 350 rem limit.

- Risks of exposures to major Solar Particle Events will become more likely during extended missions in LEO and beyond:

  -Routine missions extending throughout the Sun's 11 year cycle of activity will create a high SPE exposure probability for some crews.

  -A very large SPE in August, 1972 would have produced about 135 rem to BFO inside a module with 2.0 g/ cm2 (0.75 cm Al) shielding, potentially creating serious but non-lethal illnesses. (Acceptable 14 rem levels would require 20 g/ cm2/ 7.5 cm Al shielding.)

Radiation Dose Limitations on Careers

Better understanding about space radiation dangers and countermeasures is needed to prepare for missions beyond LEO including lunar/ Mars destinations:

- While general dose rates will be comparable to levels Apollo astronauts received, flight durations will be much longer:

  -Missions to Mars and back may require 3 years or more, demanding that we more fully understand the nature of space radiation, its effects upon health, and effective ways to mitigate the dangers.

- We presently lack a sound basis for developing reliable quality factors for GCR, and there is disagreement among researchers about appropriate dosage limits or how to translate the number/ intensity of encounters to rem.

  -Given rudimentary scientific knowledge of SPE causes, early warning systems are not presently available.

NASA

Mission	Radiation Source	Days	Dose (mSv)
Sortie to GEO[a] Long. 160° W, 2 g/cm² Al	Van Allen Belts GCRs	15	56
Lunar Mission 4 g/cm² Al	Van Allen Belts GCRs	90	74 1000
Mars Mission	Van Allen Belts GCRs, SPE[b] and Power Sources	1095	1800

[a] Geosynchronous
[b] Potential Solar Particle Event

Radiation Dose Estimates for Space Missions Beyond the Magnetosphere
R.J.M. Fry, Biology Division, Oak Ridge Nat'l Laboratory and D.S. Nachtwey, NASA Johnson Space Center

Radiation for Voyages Beyond LEO

There are three basic ways to minimize space radiation health risks in space:

1. Operationally Minimize Crew Exposures:

- Operate LEO spacecraft at lowest possible altitudes to benefit from Earths geomagnetic shield.
- Limit mission lengths and the number of astronaut duty tours.
- Use fastest practical transport vehicles and transfer trajectories.
- Restrict EVAs, using telerobotic and automated systems to the extent possible.
- Schedule missions beyond LEO to periods of lowest solar activity.

2. Carefully Screen Crew Candidates:

- Select people who are lowest cancer risks based upon family backgrounds and general health.
- Use older crews with low lifetime doses.

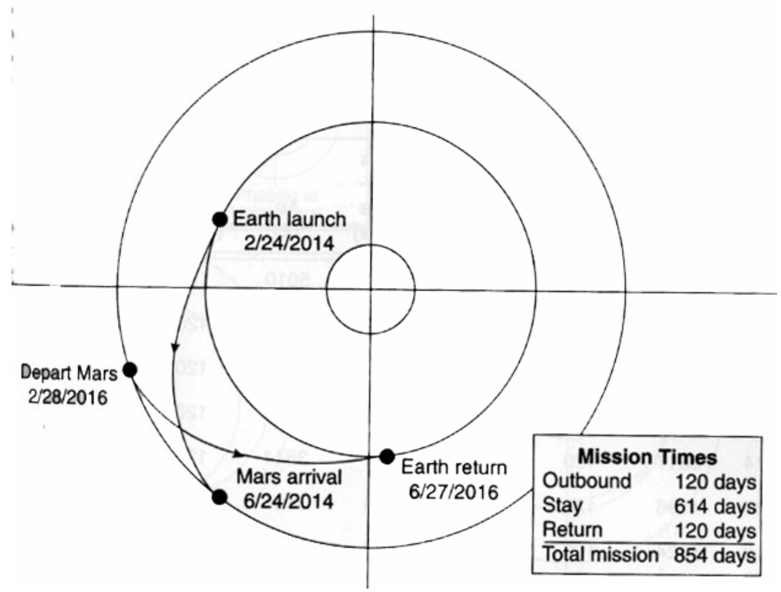
3. Provide Shielding and Storm Shelters:

- Supplement aluminum spacecraft pressure shells with additional shielding layers.
- Provide water bladders around crew areas/ radiation storm shelters using logistic water.
- Cover lunar/ Mars habitats with surface materials.

Radiation Risk Mitigation Factors

Travel and surface time schedules for lunar/Mars missions will have major influences upon space radiation exposure risks, habitat facility design and logistical requirements :

- As discussed in Part III, Section C of this lecture series, these requirements will be driven by launch/ return windows and the types of trajectories used :
  - Fast transit conjunction-class trajectories to Mars can require outbound transfers from Earth orbit to Mars orbit lasting about 120 days, surface periods of more than 600 days, and 120 days for return (approximately 2 years 4 months total).
  - While these travel times are faster than other conjunction-class options, they also require more fuel, and extend minimum surface time by more than 3 months.



Fast-transit Conjunction Trajectory

Mission Duration Influences

HUMAN SPACEFLIGHT

Launch Date	Δv TMI*	Outbound (days)	Δv MOI†	Mars Stay-Time (days)	Δv TEI	Return (days)	Total Mission Duration (days)	Δv Total**
4/03/01	3639	200	2532	545	2108	205	950	8278
6/08/03	3574	204	2095	547	2647	192	943	8316
8/20/05	3963	217	2038	492	2703	214	923	8704
10/06/07	4199	248	2032	437	2278	262	947	8509
11/08/09	4035	278	1988	374	2064	270	922	8087
11/28/11	3672	252	2532	418	1989	259	929	8193
1/17/14	3832	224	2794	458	1941	237	919	8567
3/11/16	3739	204	2677	529	1983	212	945	8399
5/11/18	3530	204	2230	553	2466	190	946	8227
7/27/20	3807	207	2031	517	2746	203	927	8584

TMI Trans-Mars Injection
MOI Mars Orbit Insertion
TEI Trans-Earth Injection

* Launch from ISS altitude orbit
† 500 km circular orbit at Mars
** Assumes direct entry upon Earth return (all velocities in m/s)

This data assumes that aerocapture will be used to make propellant Delta-V for Earth braking unnecessary.

Typical Conjunction-class Missions

Launch Date	Δv TMI*	Outbound (days)	Δv MOI†	Mars Stay-Time (days)	Δv TEI	Return (days)	Total Mission Duration (days)	Δv Total**
09/12/05	4850	120	4130	624	5010	120	864	13,990
11/01/07	5706	120	5749	622	6392	120	862	17,848
12/10/09	6141	120	6882	621	6641	120	861	19,664
01/16/12	6213	120	6998	618	5593	120	858	18,804
02/24/14	5817	120	6157	614	3844	120	854	15,818
04/11/16	4996	120	4649	624	2888	120	864	12,533
06/12/18	4224	120	3345	639	3373	120	879	10,942
08/20/20	4525	120	3559	624	4431	120	864	12,515
10/14/22	5346	120	5192	624	5946	120	864	16,485
11/25/24	6055	120	6509	621	6706	120	861	19,270

TMI Trans-Mars Injection
MOI Mars Orbit Insertion
TEI Trans-Earth Injection

* Launch from ISS altitude orbit
† 500 km circular orbit at Mars
** Assumes direct entry upon Earth return (all velocities in m/s)

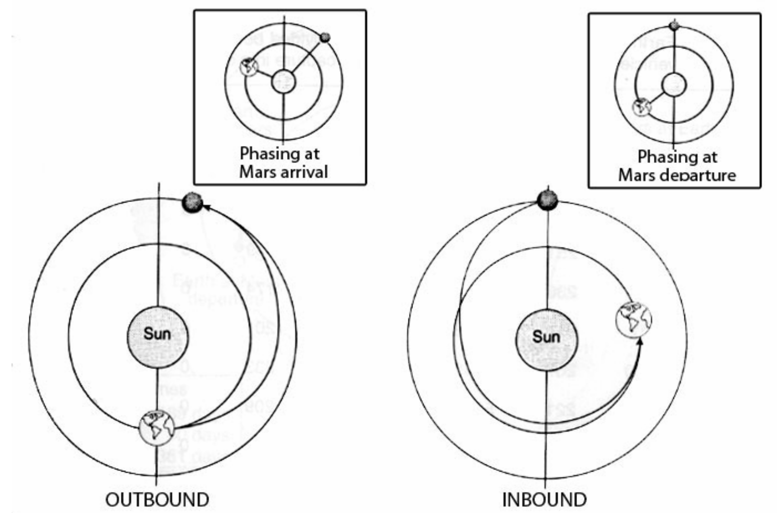
A flight time of 120 days was selected to be within current US mission experience. Earth aerocapture is assumed.

Fast Transit Conjunction Missions

Conventional & Fast Transit Conjunction-class Parameters

Opposition-class (high-energy) trajectories can reduce total mission durations by half over all conjunction-class missions, but at the cost of more fuel :

- The spacecraft arrives at Mars as Earth is leaving opposition with Mars (the Sun and Mars are on opposite side of the Earth):
  - Surface stay time is relatively short (20-40 days), after which the spacecraft must get back on a return trajectory to catch up with Earth which is moving out of phase.
  - The vehicle must move inside Earth orbit (closer to the Sun) in order to achieve the high velocity needed to catch up, adding substantial fuel requirements.
  - Approximate 3-6 week surface times may be adequate for most human Mars missions, and combined with reasonably short travel times may afford significant crew health/ safety advantages.



These trajectories have 2 unequal transfer "legs" which afford options of placing the longer leg on either the outbound or inbound mission segment as desired.

Phasing of Arrival and Departure

Opposition-class Missions

Virtually all space missions present common types of basic support requirements which differ primarily in size and capabilities :

- Responses to these requirements must take both individual and group needs into account :
  - Living environments must afford the same essential features in space that people enjoy on Earth, including places to pursue private pastimes, socialize, and maintain clean and healthy lifestyles.
  - Medical professionals and systems must be available at some level for preventative care and emergencies, and habitats must be made as safe as possible from all hazards.
  - Equipment and tools must be provided to support work tasks, including science and maintenance.
  - Schedules and spaces must adequately accommodate leisure time and work tasks to support performance and minimize stresses.

Design Factor	Individual Factors	Group Factors
Living areas	Leisure privacy Personal stowage Outside viewing Toilet/ hygiene	Food preparation Dining/ socialization Exercise/ recreation General stowage
Health/ safety	Preventative medicine Emergency medical Radiation monitoring Exercise/ nutrition	Medical personnel ECLSS controls Radiation shielding Safe haven(s)
Activity support	Personal computers Information systems Specialized equipment Training tools	Network computers Information systems Workstations/ labs Communications
Activity schedules	Work vs. leisure Duty rotation cycles EVA tasks Autonomy level	Daily team schedule Available volume Mission length Team independence

Individual/ Group Design Factors

Basic Support Requirements

HUMAN SPACEFLIGHT

Crew Accommodations Subsystem	Inputs	Outputs
Galley, Food System and Wardroom	• Mission duration • Crew size • Human nutritional requirements • Crew tastes and preferences • Anticipated workload and caloric requirements • Need for emergency rations • Need for inventory maintenance • Potential for resupply • Available stowage volume • Daily schedules	• List of food, supplies, and galley hardware • Mass and volume of food, supplies, and hardware • Power consumption and duty cycle of galley hardware • Specification and conceptual design of galley and food system • Specification of sleep quarters, if applicable
Sleep Accommodations and Crew Quarters	• Mission duration • Crew size • Daily schedules • Available habitat volume • Privacy needs	• Mass and volume of bedding and restraints • Specification and conceptual design of sleep hardware
Personal Hygiene	• Crew size • Mission duration • Other environmental factors (e.g., lunar dust, workload, EVA) • Potential for resupply	• List of hygiene supplies and hardware • Mass and volume of supplies and hardware • Power consumption and duty cycle of hardware • Conceptual design of personal hygiene system
Clothing	• Crew size • Mission duration • Needs for special clothing • Crew preferences • Potential for resupply • Closed or open-loop water supply • Potential load on the water reclamation system or other ECLSS resources • Available power • Thermal dissipation capacity • Available stowage volume	• Decision: clothes washer or no washer • List of clothing items • Quantities of each • Methods of storage • Mass, volume • Power consumption and duty cycle of washer, if any • Conceptual design of clothing system

Crew Accommodations Subsystem	Inputs	Outputs
Crew Health Care	• Crew size • Mission duration • Activities that modify medical risks • Probabilities of potential medical problems • Potential for resupply • Crew medical skills • Emergency Earth-return options	• List of hardware and supplies • Mass, volume • Power consumption and duty cycle of hardware • Conceptual design of system • Crew medical skill requirements • Crew rescue provisions
Emergency Provisions	• Potential emergencies • Crew size • Nominal mission duration • Maximum potential mission duration • Potential for resupply	• List of emergency provisions • Mass, volume • Power consumption and duty cycle
Recreation Hardware	• Mission duration • Crew size • Crew preferences • Anticipated free time • Resources available for personal items • Potential for resupply • Available volume	• List of shared recreational hardware • Resources required: mass, volume, power • Conceptual design • Specification of resources available for personal items
Crew Compartment Maintenance	• Mission duration • Crew size • Potential failures and results of failure • Volume available for spares and supplies • Mission approach to reliability and spares • Potential for resupply • Accessibility and maintainability • Crew skills	• Conceptual design for a maintenance system and spares/supplies • Mass, volume required • Power consumption and duty cycle • Redundancy requirements • List of hardware and supplies
Housekeeping and Trash	• Mission duration • Crew size • Potential for resupply • Available stowage volume • Waste disposal philosophy	• List of hardware and supplies • Mass and volume • Resources: power, water, etc. • Waste disposal methods

Crew Support Influences

As discussed in Part II, Section A of this lecture series, crew volumetric requirements expand as a function of crew size and mission length :

- The first space voyagers enjoyed few comforts/amenities:
  -Mercury astronauts were primarily observers (40 cu. ft. capsules).
  -Gemini enabled astronauts to pilot spacecraft through complex orbit changes and rendezvous maneuvers (60 cu.ft. capsules)… two very cramped people.
- Apollo Command Modules offered about 4 times the volume of Gemini (240 cu. ft.):
  -Navigators visually guided spacecraft to safe sites.
  -Astronauts surveyed the Moon's surface on foot and in rovers, and returned samples.
- After Apollo was completed, an effort was made to apply the hardware for an Earth-orbital lab; Skylab (1969-73):
  -Skylab was generous in volume (9,950 cu. ft.)… 45 times the volume of Apollo.
  -The facility provided 2 levels of space… areas for work, sleep, eating and bathing/ personal hygiene.
  -It was visited by 3 crews (the third mission was 84 days).

Mercury

Gemini

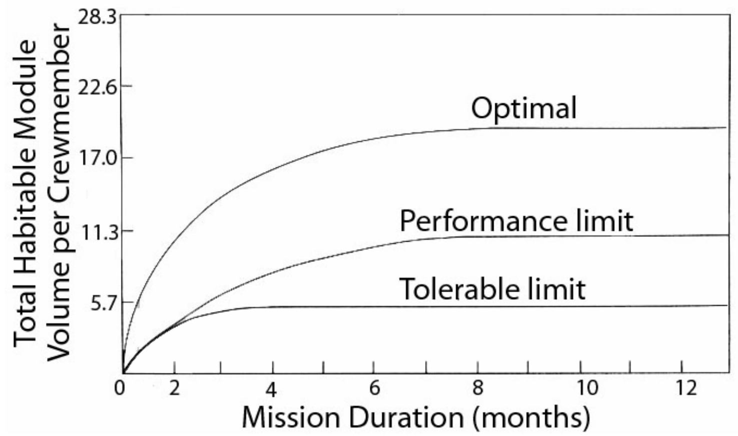
Apollo

Skylab

Habitable Volume Considerations

As missions become extended into several weeks, months and years, more free crew volume will be required to reduce psychological stresses and to provide comfort, privacy and functional amenities :

- For lunar reference missions lasting less than one month, these requirements are reasonably well understood from experience, but for Mars missions lasting 500 days or more, much remains to be learned.
  - Partial-g conditions on the Moon and Mars will not enable the same volume utilization advantages afforded under weightlessness where ceilings can serve as work areas, and sleep can occur in any orientation.
  - Longer missions must place fuller emphasis upon private crew quarters and larger personal hygiene, grooming and stowage accommodations.
  - Adequate places for meal preparation/ dining, exercise, recreation and group meetings will take on additional importance, along with expanded stowage for all functions.



The NASA-STD-3000 document defines volume/ crewmember relationships for “tolerable” (survival), acceptable performance and optimal conditions.

Relationships Between Mission Lengths and Volume Requirements/ Crewmember

Volume vs. Mission Length

From a crew support standpoint, habitat mass/volume budgets may benefit from certain economies of scale :

- Some accommodation requirements will have limited crew size or mission length influences :

  - Galley/ food preparation systems must offer basic oven and hydration capabilities, whether to support 2 people or a dozen.

  - Refrigerated storage needs will expand as a function of crew size and mission length, but some equipment might be located in less volume-limited logistical facilities.

  - Numbers of toilets may be based more upon fail-safe redundancy for longer-term missions than upon crew size, since their use is relatively infrequent.

  - Showers may have fold-up deployable features to conserve volume when not in use .

  - Airlock sizes must increase in relation to crew size and expanded EVA operations, but volumetric/ mass efficiencies will improve with larger diameters.

Crew Size	Mission Length
Sleep, food preparation & toilet/ hygiene needs	Living & life support consumables required
Living & leisure accommodations	Expanded amenities & exercise/ recreation
Levels of activity specialization	Facility support for expanded functions
Dedicated medical specialist	Preparedness for greater problem risks
EVA airlock size & suit stowage	Extended EVA numbers, consumables & spares
Housekeeping & maintenance supplies	Additional equipment, spares & tools

Crew Size - Mission Length Relationships

Accommodations vs. Mission Length

Galley Consumables & Equip.	454 ft3	7,595 lbs
• Food (frozen /refrigerated /ambient)	100ft3	1,680 lbs
• Water heater (20 gallons)	3ft3	50 lbs
• Dry stowage (empty)	14ft3	230 lbs
• Food trash stowage (empty)	12ft3	200 lbs
• Refrigerator/ freezer	150ft3	2,500 lbs
• Ovens (microwave/conventional)	90ft3	1,500 lbs
• Utensil/ appliance stowage	20ft3	335 lbs
• Housekeeping supplies	65ft3	1,100 lbs
Personal Hygiene & Waste Management:	99ft3	1,870 lbs
• Wet wipes/ towels stowage	35ft3	500 lbs
• Personal hygiene supply stowage	35ft3	600 lbs
• Waste collection system equipment	12ft3	200 lbs
• Waste collection system supplies	5ft3	70 lbs
• Contingency urine/ fecal bags	12ft3	200 lbs
Medical Facility & Stowage	99ft3	1,670 lbs
• Medical/ dental equipment	66ft3	1,100 lbs
• Medical/ dental consumables	33ft3	570 lbs
Overall Volume/ Mass Estimates	652ft3	10,835 lbs

Example volume Mass Estimates for a 4-person, 100 Day Reference Mission

Habitats/ Elements	Short <28 days	Medium 28-180 days	Long >180 days
Habitat:			
• Total pressurized vol./ person	< 10m^3	20-50m^3	> 50m^3
• Total mass/ person	< 750kg	1500-5000kg	> 5000kg
• Total power/ person	< 5kW	5-10kW	> 10kW
Laboratory :			
• Total pressurized vol./ person	< 5m^3	5-10m^3	> 10m^3
• Total mass/ person	< 75 kg	1500-5000kg	> 5000kg
• Total power / person	< 5kW	5-15kW	> 15kW
Airlock :			
• Total pressurized vol./ person	< 5m^3	5-10m^3	> 10m^3
• Total mass/ unit	< 500kg	500-1500kg	> 1500kg
• Total power/ unit	< 2kW	2-10 kW	> 10kW

ROM Volume/ Mass/ Power Estimates Correlated with Mission Lengths

Volume, Mass & Power Estimates

HUMAN SPACEFLIGHT

Equipment and Stowage Elements	Mass	Mass Subtotal (kg)	Volume	Volume Subtotal (m)
Galley and Food System				
Food	2.3 kg/p/d	6900	0.008 m^3/p/d	24.00
Freezers	400 kg (empty)	400	200 m^3 (less food vol	2.00
Conventional oven	50 kg	50	0.25 m^3	0.25
Microwave ovens (2 ea.)	70 kg	70	0.30 m^3	0.30
Kitchen/oven cleaning supplies (fluids, sponges, etc.)	0.25 kg/d	125	0.0018 m^3/d	0.90
Sink, spigot for hydration of food & drinking water	15 kg	15	0.0135 m^3	0.01
Dishwasher	40 kg	40	0.56 m^3	0.56
Cooking/eating supplies (pans, plastic dishes, plates, etc.)	5 kg/p	30	0.0014 m^3/p	0.08
Waste Collection System				
Waste collection system (2 toilets)	90 kg	90	4.36 m^3 for both	4.36
WCS supplies (toilet paper, cleaning solutions, filters, etc.)	0.05 kg/p/d	150	0.0013 m^3/p/d	3.90
Contingency fecal and urine collection mittens/bags	0.23 kg/p/d	20	0.0008 m^3/p/d	0.07
Personal Hygiene				
Shower	75 kg	75	1.41 m^3	1.41
Handwash/mouthwash faucet	8 kg	8	0.01 m^3	0.01
Personal hygiene kit	1.8 kg/p	10.8	0.0050 m^3/p	0.03
Hygiene supplies	0.075 kg/p/d	225	0.0015 m^3/p/d	4.50
Clothing				
Clothing	99 kg/p	594	0.336 m^3/p	2.02
Washing machine	100 kg	100	0.75 m^3	0.75
Clothes dryer	60 kg	60	0.75 m^3	0.75
Recreational Equipment & Personal Stowage				
Personal stowage/closet space	50 kg/p	300	0.75 m^3	4.50

Example Estimates for 6-person, 500 Day Mars Surface Safety

Crew Support Equipment

MS-SPACE ARCHITECTURE
SICSA

HUMAN SPACEFLIGHT

Equipment and Stowage Elements	Mass	Mass Subtotal (kg)	Volume	Volume Subtotal (m)
Housekeeping				
Vacuum (prime + 2 spares)	13 kg	13	0.07 m^3	0.07
Disposable wipes for housecleaning	0.3 kg/p/d	0	0.002 m^3/p/d	0
Trash compactor/trash lock	150 kg	150	0.30 m^3	0.30
Trash bags	0.05 kg/p/d	150	0.001 m^3/p/d	3.00
Operational Supplies & Restraints				
Operational supplies (diskettes, ziplocks, velcro, tape...)	20 kg/p	120	0.002 m^3/p	0.24
Restraints & mobility aids	100 kg	100	0.54 m^3/kg	0.54
Maintenance: All Repairs in Habitable Areas				
Hand tools and accessories	300 kg	300	1.00 m^3	1.00
Spare parts/equipment & consumables	--	--	--	--
Test equipment (oscilloscopes, gauges, etc.)	500 kg	500	1.50 m^3	1.50
Fixtures, large machine tools, gloveboxes, etc.	1000 kg	1000	5.00 m^3	5.00
Photography				
Equipment (still & video cameras, lenses, etc.)	120 kg	120	0.50 m^3	0.50
Film (assumes all digital approach)	0 kg	0	0.00 m^3	0.00
Sleep Accommodations				
Sleep provisions (sleep restraints only)	9 kg/p	54	0.10 m^3/p	0.60
Crew Health Care				
Exercise equipment	145 kg	145	0.19 m^3	0.19
Medical/Surgical/Dental suite	1000 kg	1000	4.00 m^3	4.00
Medical/Surgical/Dental consumables	500 kg	500	2.50 m^3	2.50

Example Estimates for 6-person, 500 Day Mars Surface Safety

Crew Support Equipment

HUMAN SPACEFLIGHT

Estimated power consumption and duty cycles for electrical hardware must be determined on the basis of projected crew sizes, activity schedules and equipment selection features for baseline missions :

- The example shown is for illustrative purposes only, and assumes that the mission will provide particular functional items noted :
  - Average power (kW) values are based on types/ features of currently available equipment systems, which may ultimately be upgraded for higher efficiencies.
  - Powered time (% of day) will be influenced by specific crew tasks and scheduling of work/ leisure activities.
  - Energy (kW-h) may have to be coordinated within allowable power/ heat rejection budgets that take other competing spacecraft system requirements into account..

Number of Days 500	Average Power (kW)	Powered Time (% of a day)	Energy (kW·h)
Galley and Food System			
Freezers	1.4	100.0	16,800.00
Conventional ovens (2 in operation at one time)	2.5	12.0	3,600.00
Microwave ovens (2 in operation)	1.8	6.0	1,296.00
Dishwasher	1.2	8.0	1,152.00
Waste Collection System			
Waste collection system (2 toilets)	0.09	2.5	27.00
Personal Hygiene			
Shower	1	8.0	960.00
Clothing			
Washing machine	1.5	8.0	1,440.00
Clothes dryer	2.5	8.0	2,400.00
Recreational Equipment & Personal Stowage			
Personal stowage	0.7	4.0	336.00
Housekeeping			
Vacuum	0.4	1.0	48.00
Trash compactor/trash lock	0.85	1.0	102.00
Maintenance: All Repairs in Habitable Areas			
Test equipment (oscilloscopes, gauges, etc.)	1	0.1	12.00
Fixtures, large machine tools, gloveboxes, etc.	1	0.1	12.00
Photography			
Equipment (still & video cameras, lenses, etc.)	0.4	8.0	384.00
Crew Health Care			
Exercise equipment	0.145	50.0	870.00
Medical/Surgical/Dental suite	1.5	1.0	180.00
		TOTAL ENERGY (kW·h)	29,619.00

Estimated Power Required, 6-person, 500 day Mission

Crew Support Power

While the amount of food and water needed to support crewmembers will vary with individuals, typical quantities can be used for general planning purposes :

- The mass balance for a person doing normal activities is about 5kg/day of basic metabolic needs and 5kg/day of effluences :
  - Crews require about 3.5 kg of potable water/person/day (drinking, food preparation and food content).
  - People can get by with about 3.5 kg/person/day of water under degraded or emergency conditions.
  - Estimates of food weight vary with different sources and depend upon percent of hydration that is assumed.
  - A final value of 2.3 kg/person/day of food is reasonable, and a total value of all potable water and food might generally assume 4.1-4.2 kg / person/day.

Input		Output (Wastes)	
Solids, food	0.62kg	Solids, in urine in feces in sweat	0.06kg 0.03kg 0.02kg
Liquids (water) drinking	1.62kg	Liquids urine	1.50kg
Liquids (water) food preparation	0.75kg	Liquids, sweat & expired air	2.28kg
Liquids (water) food content	1.15kg	Liquids fecal water	0.09kg
Gases (oxygen)	0.84kg	Gases (CO_2)	1.00kg
Total	4.98kg	Total	4.98kg

This table assumes that a normal crewmember eats 11,300 kJ/d (2,700kcal/d) and generates 137W of heat. Values are listed in kg/person-day.

Typical Profile for Metabolic Balance

Food/ Water Consumables & Outputs

NASA

Water is a primary consumable which will contribute substantial mass requirements for extended human exploration missions :

- In addition to drinking and food preparation/ hydration, water will also be needed for other purposes, with amounts dictated by strategic planning decisions :
  - The frequency and means for clothes washing.
  - Water budgets for dish/ utensil cleaning, also considering waste treatment/ sanitary implications.
  - Provisions for showers vs. wet wipes for body hygiene and associated rationing.
  - Degree of water reclamation/ recycling from the waste management loop, including fecal materials.
  - Possible utilization of stored water for radiation protection around a safe haven or more general locations, potentially driving total mass budgets.

Input		Output	
Personal hygiene		Personal hygiene	
Hand/face ;shower	7.0kg	Hand/face ;shower	7.0kg
Urinal flush	0.5kg	Urinal flush	0.5kg
Clothes wash	12.5kg	Clothes wash	
		Liquid	11.9kg
		Latent	0.6kg
Dish wash	5.4kg	Dish wash	5.4kg
Total	25.4kg	Total	25.4kg

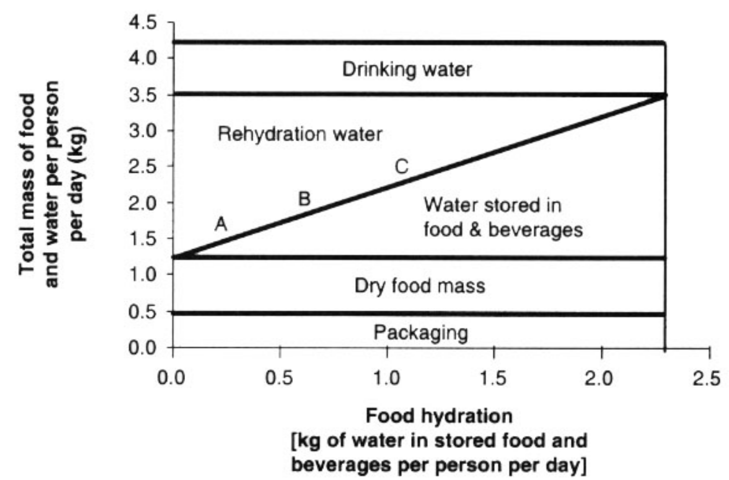
Assumptions regarding personal hygiene, clothes washing and dishwashing requirements may vary according to strategic planning decisions.

Typical Person/ Day Requirements for Hygiene/ Washing

Water Budgeting

Space food storage forms range from complete dehydration to full hydration, and preservation methods include canning, thermo-stabilization, irradiation and freezing :

- As a general rule, the higher the water content, the better the food tastes, which becomes increasingly important as mission lengths extend longer :
  - Assuming a daily person ration of 3.5kg (total mass), about 0.5kg of the stored mass may be packaging, 0.7kg dry food mass, and upto 2.3 kg water.
  - A daily ration of completely dehydrated food would have a mass of about 1.3kg vs. 3.5kg for fully hydrated.
  - Food for a Mars mission might be similar to the International Space Station (point C on the chart), about 2.3kg/day for crew comfort (requiring a storage volume of 0.008m^3/ person/ day).



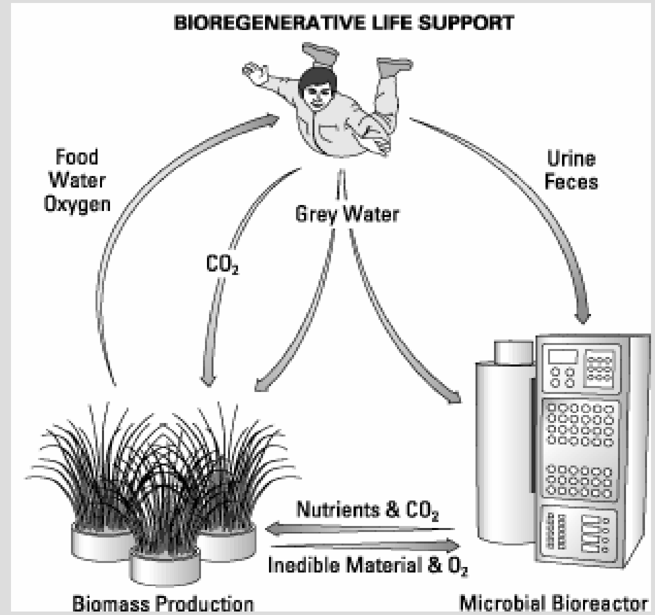
A completely dehydrated food system is near point A on the diagonal line above; Shuttle food is at point B; and ISS food will be near point C. (Add another 0.9kg of drinking water for a 2-hour/day exercise period or similar physical activity.

Relationship Between Food & Water Consumed per Crew Day as Function of Food Water Content

Food /Water /Packaging Mass

As discussed in part I, Section C of this lecture series, all space habitats require life support systems to provide atmosphere, water 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).



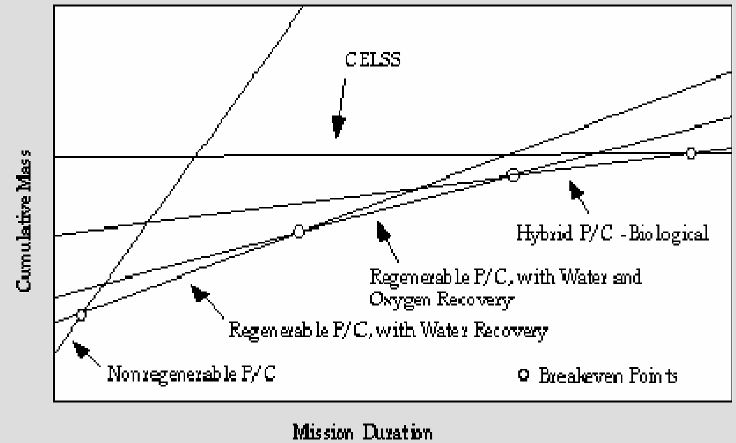
This illustration is closed with respect to mass, but is still open in regard to energy output.

Partially Closed Life Support

Life Support Consumables

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

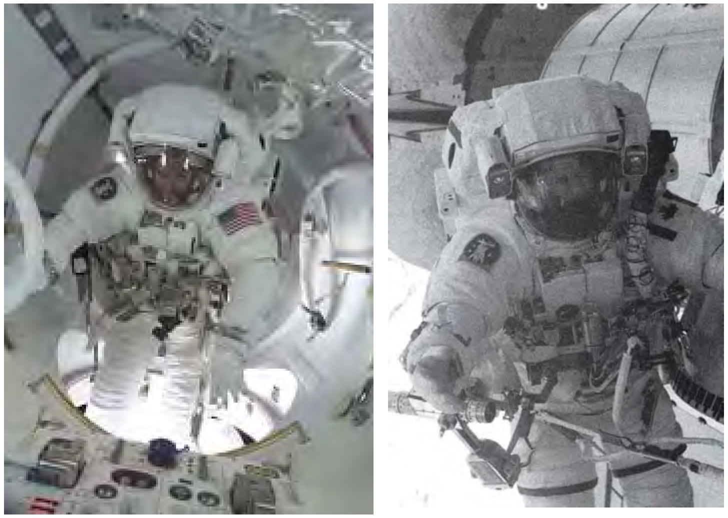
Closed-loop Life Support

Future lunar/ planetary habitats may include separate or attached plant and animal growth facilities for food production and research , such as SICSA's proposed inflatable MarsLab concept

Food Production

Habitat structure, airlock design and EVA requirements will have large impacts on consumables:

- Loss of atmosphere through leaks and airlocks will present a major resupply burden:
  - Dry air plus water can be expected to seep out at a constant rate throughout all pressurization periods.
  - A substantial amount of atmosphere will be sacrificed during each airlock cycle, particularly when requirements call for large multi-person capacities.
  - Surface operations calling for frequent EVA and /or pressurized rover dockings must provide sufficient consumables on hand to replenish atmosphere under nominal and pressure failure emergencies.
  - Potentials exist for oxygen to be obtained from lunar regolith and CO_2 in the Mars atmosphere.



ISS Airlock (Inside and Exterior)

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.

Atmosphere Replacement

More detailed information about many topics addressed in this section, along with reference and additional information sources, is offered in all three of the preceding parts of this lecture series. The book "Human Spaceflight" is recommended as a particularly relevant source.

BACK TO THE LIST OF CONTENTS

SECTION F: INTERIOR ARCHITECTURES & ELEMENTS

This section applies the integrated "systems of systems" perspective to look more closely at human factors and habitability considerations within broader issues discussed in preceding parts and sections of this lecture series.

- Briefly highlighted, key foundation issues include:
  - Transportation vehicle selection determining total allowable habitable volume and mass.
  - Mission windows established by vehicle propulsion and pathway selection that will determine travel, surface and return times.
  - Crew requirements, including size and activities, influencing how much volume/equipment will be needed throughout the period of each mission.
  - Logistics and support strategies that will be driven by crew size, mission length, the level of life support closure, EVA requirements and other decisions.
  - All of these combined factors that will influence how large habitats can be, and what accommodations will be needed.

Foundation Considerations

Key Planning & Design Influences

Humans in space have evolved from observers (Mercury); to pilots (Gemini); to explorers (Apollo); to workers/ scientists (Skylab). Next may come colonists on much longer missions (Moon and Mars):

- Future crews may be different from previous ones:
  - -Selection may be mixed (gender, age, profession and culture).
  - -They may be less tolerant to difficulties/ inconveniences (a shift away from "the right stuff" mentality).
- Good "habitability" design will be essential:
  - -To influence how effectively/ safely tasks are accomplished.
  - -To influence how thoroughly/ rapidly crews adapt.
  - -To influence how they feel about their surroundings and peers.
  - -To influence how healthy they remain over time.
- To provide good habitability/ human factors design, we must understand the space environment, including:
  - -Influences of zero, artificial and partial gravity.
  - -Environmental issues influencing safety and operations.
  - -Psychological and social issues affecting crew relationships, morale and performance.
  - -Ways to optimize habitat utilization, comfort and safety features.

Habitability Issues

Human factors planning and design addresses ways to integrate the crew with the spacecraft environment, equipment and operations in order to optimize health, morale, performance and safety:

- Interfaces between people and functional systems:
  - -Equipment systems that enable convenient and efficient operations, maintenance and repairs.
  - -Information systems and software for effective decision-making, fault detection and responses.
  - -Stowage and inventory systems to accommodate needed supplies, equipment spares and tools.
  - -Control devices that reflect a good understanding of changes in body posture, leverage and other conditions imposed by weightlessness or reduced gravity.
- Habitat living/ work accommodations:
  - -Features and amenities that have a positive influence upon crew adaptation, comfort and use of surroundings.
  - -Provision for privacy, hygiene, recreation, social activities, exercise and other basic needs.

Crew members can be viewed as human systems:

- Sensors (eyes, ears and touch).
- Mechanical actuators (fingers, arms and legs).
- Self-propulsion (walking or push-off floating).
- On-board processing (brain).
- Communications (voice, gestures and device actuators).
- Emergency response (mechanical/ electrical interfaces).

Human systems require special support accommodations:

- Maintenance (sleep, hygiene, medical and exercise).
- Fuel (food and water).
- Operating environment (atmosphere and thermal control).
- Sanitation (waste treatment and contaminate protection).
- Environmental safety (space radiation and debris).
- Visual enhancements (lighting, windows and displays).
- Functional enhancements (restraints and mobility aids).

Human Factors Planning

"Habitability" generally refers to environments and accommodations that can be incorporated into space habitats to optimize crew safety, health, satisfaction and performance:

- To have a positive influence upon how effectively and safely people can accomplish mission tasks.
- To provide medical and exercise facilities to monitor and maintain physiological conditions throughout the missions.
- To create interior areas that are comfortable, convenient and attractive.
- To design environments, facilities and equipment to emphasize ease of understanding, use and maintenance.

Humans in space have the same basic needs that apply on Earth, but their isolated, crowded and constrained living and work conditions add special challenges :

- Variety and versatility in the design and use of habitats is essential to mitigate feelings of isolation and boredom.
- Facilities and schedules should accommodate exercise, recreation and social activities necessary for health and morale.
- Private places are needed for reading, listening to music and other leisure activities.
- Means to maintain hygienic conditions are vital, since closed space habitats are vulnerable to rapid microbial growth.

Habitability Needs and Challenges

A “habitable“ environment is one that enables people to readily adapt to unique space conditions, maintain physiological and psychological well-being, achieve high performance levels over time, and be protected from health safety hazards:

- Design must respond to requirements imposed by the space environment:
  -Gravitational influences in orbit, transit and on a lunar/ planetary surface.
  -Special radiation and debris exposures requiring special safeguards.
- Design must respond to requirements imposed by the space mission and transportation systems:
  -Habitat dimension, volume and mass constraints imposed by launch, transfer and landing/ reentry vehicles.
  -Crew size, activities and mission duration influencing operational and support needs.

Space Gravity Conditions: •Influences of weightlessness on design/ adaptation. • Artificial-g design options/ considerations. • Partial-g lunar/ planetary surface environments.	Psycho-Social Factors: •Mission influences on crew support requirements. • Isolation/ confinement issues. •Operational factors influencing morale.
Habitat Volume/ Configuration: • Launch vehicle & landing constraints. • Fixed and expandable module options. • Accommodations for evolutionary growth.	Functional Areas/ Accommodations: •Crew support facilities/ systems. •Work stations & support equipment. •Flight mission operations & maintenance support.
Space Radiation Hazards: • Primary sources & characteristics. • Allowable crew dose exposures. • Shielding options/ requirements.	Extra-Vehicular Activities: •Mission-driven EVA requirements. •EVA airlocks, suits & equipment devices. •Telerobotic support systems/ operations.

Crew Support Considerations

Habitability Design Drivers

Accommodations for comfort, morale and performance:

- Adequate volume with proper functional layout.
- Places for both private and group activities.
- Variety and means to change the environment.
- Appropriate design of lighting and décor (materials, color and textures).
- Prevention of intrusions (noise, odors and light).
- Communication with outside world (windows and electronic).
- Scheduling to avoid work overload and sensory deprivation.
- Ease of maintenance and repair operations.

Habitability

Design for comfort, convenience and safety:

- Appropriate equipment and layout design for acceleration/deceleration periods and gravity levels.
- Design responses to neutral body posture and other anthropometric changes in weightlessness.
- Visual reference cues to prevent spatial disorientation in weightlessness.
- Restraint systems and mobility aids for weightlessness.
- Functional equipment groupings/ relationships for changed reach envelopes and procedures in weightlessness.
- Systems designed for easy maintenance, repair and replacement in weightlessness.

Human Factors

Special Human Concerns

Habitability planning must work to normalize living conditions under constrained circumstances to the extent possible :

- **Effective volume utilization :**
  - Essential accommodations and equipment for work and living.
  - Appropriate functional relationships between activities, tasks and equipment.
  - Flexible, versatile use of space and equipment through adaptability and modularity.
  - Opportunities for privacy from intrusive activities, sounds/noises, light and odors.
  - Aesthetics and amenities for physical and psychological comfort.
  - Spatial efficiency to maximize useful volume under weightless and partial-g conditions.

- **Variety and personal choice options :**
  - Interior systems that afford opportunities to change and personalize spaces.
  - Colors that avoid monotony and drabness criticized by individuals on Skylab.
  - Variable lighting levels to counteract observed fatigue and visual/mental acuity losses.
  - Menus that offer variety and personal choices for mealtime and snack satisfaction.
  - Outside viewing for recreation/ leisure as well as operational and scientific purposes.
  - Music and recreational amenities for individual and group enjoyment.

Important Planning Priorities

Crew comfort and performance during extended space missions will require habitats that can support all essential living and work requirements :

- Floor areas must be large enough to accommodate necessary activities and equipments and avoid claustrophobic psychological conditions.
- Overall volumetric configurations should enable efficient design and integration of functional areas and equipment systems in a versatile and modular manner.
- The horizontal and vertical internal circulation layouts should be planned for safety and convenience, and should not unduly compromise functional space utilization.
- Configuration and layout design must be appropriate for mission applications, considering g-levels/ orientations, emergency egress, outside viewing and other factors.

Functional Design Drivers

Habitable module selection and design options are influenced by conditions and constraints imposed by broader mission drivers :

- They must comply within limitations established by payload shroud dimensions and mass-lift capacities of available/selected launch vehicles that will place them in orbit.
- Lunar/ planetary applications must consider means/ requirements for landing, transporting and connecting habitats and other elements on the surface.
- Some elements may need to be positioned, assembled and deployed in orbit under weightless conditions or on lunar/planetary surfaces with primary reliance on automated operations.
- Mission goals will determine functional needs/ capacities associated with crew size/activities, equipment/logistical support requirements and evolutionary growth plans.

Mission Design Drivers

Key Influences and Requirements

Planetary exploration missions, and particularly those to Mars, will expose crews to extended periods of gravitational conditions which are unlike those on Earth :

- Part II, Sections B,C and D discuss special health, adaptation and habitability influences of weightlessness, artificial gravity and partial gravity which will have major impacts upon many aspects of human operations and support planning :
  - Crews enroute to Mars and back, as well as well as those who remain in lunar/Mars parking orbits will experience long periods of weightlessness unless artificial gravity is provided.
  - Decisions to provide artificial gravity, whether using onboard devices or using rotational spacecraft will drive the design of structures, systems and human operations in fundamental ways.
  - Many questions remain regarding physiological and psychological effects of artificial and partial gravity due to inconclusive research.

Threshold Issues	Adaptation Issues
A-g levels required to maintain long-term health and fitness (bone, muscle, cardiovascular and neurovestibular).	Effects of “spinning down” a rotating spacecraft, and/or aerobraking to reduce kinetic energy at Earth/Mars.
Acceptable/optimal ranges of radii and angular velocities for human health, comfort and task performance.	Abilities of people to adapt to repeated A-g to 0-g to A-g transitions (neurovestibular and cardiovascular systems).
Maximum threshold to avoid nauseogenic effects of cross-coupled out-of-plane vestibular stimulation.	Requirements/benefits of combined A-g conditons and exercise during long Mars orbit transfer and surface periods.

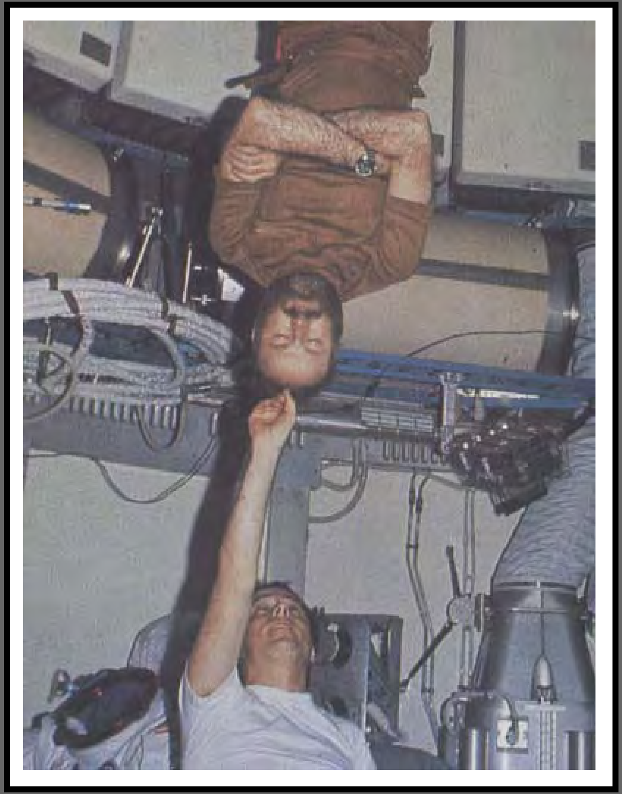
Unresolved Artificial Gravity Issues

Conditions & Questions

As is discussed in Part II, Section B of this lecture series, weightless conditions in space have many important influences on habitat design and operations:

- Requires reexamination of nearly everything we take for granted on Earth:
  - Vertical references are established by design, not by Earth orientation (“up” and “down" are relative).
  - Full 3-D interior volume can be used for activities.
  - Mobility is easy but anchorage is the problem.
  - Body posture is altered to a neutral buoyancy position, but the torso becomes longer.
  - The reach envelope increases (no center of gravity limitations).
  - “Heavy” equipment can be moved easily, but may be difficult to stop due to mass inertia.
- Zero-g influences design in many ways:
  - Ceilings, walls and floors are interchangeable.
  - People can float in all directions, but anchorage is needed.
  - Storage must avoid the “Jack-in-a-box” effect.
  - Horizontal surfaces on tables are arbitrary.
  - Chairs aren’t needed (no gravity to hold the body bent).
  - People can sleep in any orientation.

NASA



Weightless Conditions

INTERIOR ARCHITECTURES AND ELEMENTS

GRAVITY LEVEL INFLUENCES

Body posture is altered significantly under weightless conditions:

- Physiological changes:

  -Without gravity to compress the spinal chord, the human torso elongates a few inches, but is not as stiffly erect as on Earth.

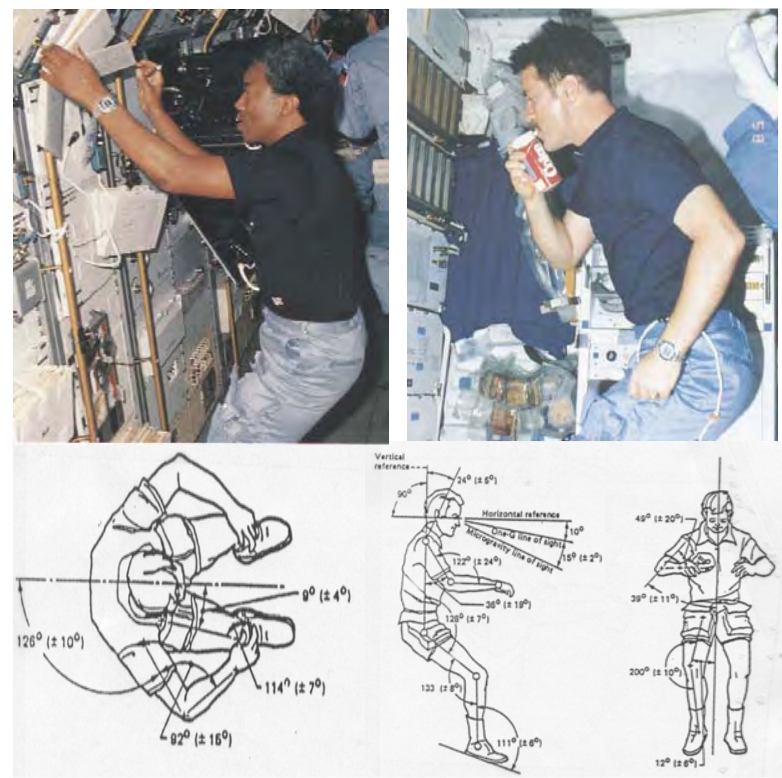
  -Sitting in standard chairs is uncomfortable, requiring constant tensing of stomach muscles to keep bodies bent.

- Posture changes:

  -The relaxed state of bodies unstressed by gravity tends to mimic a fetal position :torso curved concavely; head angled slightly downward; legs extended slightly in front; body bent at hips and knees; feet pointed downward; and arms floating out in front.

  -Tables and other work surfaces should be positioned at crouching heights of users (and can be tilted since items placed on top must be secured to keep them from drifting away).

NASA



Neutral Buoyancy Posture

NASA

Neutral Buoyancy Posture

INTERIOR ARCHITECTURES AND ELEMENTS

GRAVITY LEVEL INFLUENCES

Weightless conditions present special operational advantages and disadvantages:

- Habitat volume utilization efficiencies:
  - -Ceiling areas can be easily accessed for work-places, stowage, outside viewing and other functions to optimize habitat capacity.
  - -Sleeping quarters/ accommodations can be oriented vertically to conserve useful floor areas.
- Locomotion and lifting benefits:
  - -Floating with a push-off is a rapidly achieved skill that enables easy movement in all directions.
  - -Massive elements can be moved and manipulated without effort for logistics transfer, equipment maintenance/ repairs and other activities.
- Leverage and anchorage disadvantages:
  - -Astronauts require handholds and other body restraints to perform activities requiring arm torque force and stationary work task positioning.
  - -Means are required to prevent equipment, tools and other items from floating away.

Functional Advantages/Constraints

Weightless Operational Factors

NASA

Crew adaptation to weightlessness can be facilitated by responsive human factors design:

- Interior layouts and visual cues:
  - -Spatial references are essential to prevent confusion in areas occupied by multiple individuals positioned above/ below each other in varying body orientations.
  - -Colors and graphics can establish floor, wall and ceiling "local vertical" references.
  - -Graphic information should be designed for easy comprehension in different orientations.
- Locomotion techniques and safeguards:
  - -Most exposed spacecraft surfaces and equipment are used as push-off points.
  - -Care must be taken to avoid design of fragile devices that can be kicked by floating astronauts, open switches that can be bumped and exposed items that can cause electrical shocks and burns.
  - -Sharp corners on equipment should be avoided to prevent bruises and laceration injuries.

Meal Time Mixed with play in Space

Health Maintenance in Space

Adaptation to Weightlessness

A variety of anchorage devices are often needed to secure people and loose items in place.

- Foot restraint systems:

  -Skylab crews inserted cleats on their shoes into triangular grid openings in floors.

  -Simple loop straps have been tried, but feet tend to slip out too easily.

  -Suction cups and Velcro have proven too weak to contain strong leg muscle forces effectively.

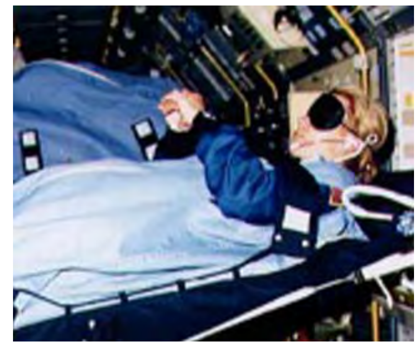
  -Devices similar to ski bindings offer possibilities, but have not yet been successfully demonstrated.

- Item stowage and attachment devices:

  -Velcro and bungee chords have found popular use for temporary and makeshift means to secure small equipment, tools and other items.

  -Hang-up type soft stowage systems with transparent content viewing pockets offer promising solutions for clothing, hygiene supplies and other personal items.

Foot Restraint Concept



Sleeping Bag/Restraint

Loose Items Float

Restraint Systems for Weightlessness

Exercise to counteract muscle and cardiovascular deconditioning was practiced on Skylab missions, and will be even more important for longer lunar/ planetary voyages:

- Recent mission experiences:
  - -The exercise program on Skylab was considered to be successful; the Skylab 4 crew returned after 84 days in good physical condition.
  - -Adherence to active exercise programs on longer Mir missions was not clearly documented.
  - -Soviet cosmonauts sometimes used “penguin suits” consisting of trousers with elastic cords to maintain tension on leg muscles.
- At least 1-2 hours of exercise are believed necessary to maintain good muscle/ cardiovascular health:
  - -Typical devices include bicycle ergonometers and treadmills, as well as vacuum equipment that produces a negative relative pressure around legs to stress the heart.
  - -Exercise on machines tends to be boring, suggesting the need for incorporating some forms of entertainment such as TV displays.
  - -Accommodations for two or more people to exercise at one time can facilitate work schedules and conversations.

Russian Penguin Suit

Exercise in Weightlessness

Weightless conditions can produce disturbing spatial orientation and cognitive problems:

- Zero-g inversion illusions:

  -A sensation of feeling continuously upside down (reported from US and Russian experiences).

  -Continues even after eyes are closed.

  -Attributed to combined effects of gravitational unloading of inner ear otilith organs, elevation of viscera, and fluid shifts.

- Visual reorientation illusions:

  -A sensation while floating that floors, ceilings and walls change identities.

  -A surface below the feet seems like a “floor”, and surfaces parallel to the body are “walls”.

  -The sight of a crewmate floating inverted nearby can make one feel upside down.

  -Earth viewed through a window or on an EVA spacewalk can provide a powerful “down”.

- Disoriented element recognition difficulties:

  -Familiar places and objects can be difficult to recognize when viewed from changed orientations.

  -Information and control systems (including words, graphic displays and switches) may be ambiguous.

- Height vertigo effects:

  -Looking “down” towards habitat areas below one’s feet can produce anxious feelings of falling.

  -EVA astronauts viewing Earth below them can be inclined to “hang on for dear life”.

- 3-D spatial memory difficulties:

  -Crew members traversing between space station modules with non-aligned visual local verticals can become lost .

  -Some Shuttle crews visiting the Mir Space Station had problems finding their way back.

  -These problems can be dangerous during emergencies (particularly when darkness or smoke obscures vision).

Cognitive Influences of Weightlessness

Planning and design must take a variety of factors and requirements into account:

- Internal equipment layouts and designs:
  - -Optimum utilization of walls, floors and ceilings with orientation references.
  - -Avoidance of sharp corners/ protrusions that can cause injuries when bumped.
  - -Protection of fragile fixtures and control surfaces that can be bumped.
  - -Design for maintenance procedures that take weightlessness into account.
- Anthropometric and ergonomic factors:
  - -Influences on work surface heights.
  - -Influences on reach envelopes and general task procedures/ performance.
  - -Influences on force requirements and leverage constraints for various tasks.
- Restraints and mobility aids:
  - -Hand-holds, foot and body restraints.
  - -Means to secure loose items.
- Exercise accommodations:
  - -Areas/ equipment to support exercise and monitor health.

Summary Weightlessness Requirements

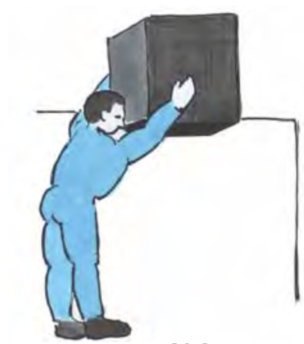
Partial-gravity conditions experienced on lunar/planetary surface missions will be for more Earth-like than those associated with weightlessness or artificial-g.

- Astronauts will adapt quite easily, rapidly learning how to modify their locomotion and activities accordingly.
- Habitats will be designed with a familiar normal-g vertical orientation where “up” and “down” are constant, sleeping is always horizontal, and floors, ceilings and walls are traditional.
- Toilet and hygiene equipment will function in a familiar, gravity-assisted fashion, and restraint systems will generally not be needed to hold people and loose items in place.
- While exercise will still be important to maintain good physical fitness, the deconditioning effects experienced in weightlessness may be less severe.
- Particulate matter in the internal habitat atmosphere which can present hygiene and health hazards will settle to the surface where it is more controllable.
- There will be no Coriolis forces associated with A-g to detrimentally effect sensory and operational functions, and no gravity level transitions or gradients that impose special medical concerns or activity challenges.

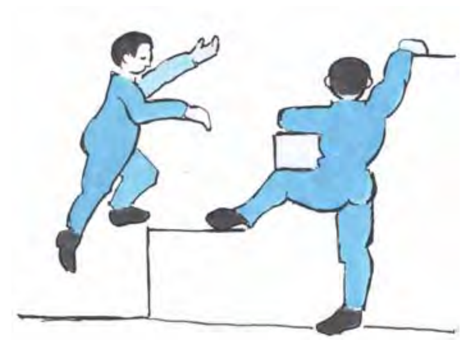
Partial-g Conditions

Advantages:

Reduced gravity conditions benefit activities that require lifting objectives that would be too heavy for the same number of people on Earth, and vertical movements involving jumping or climbing.



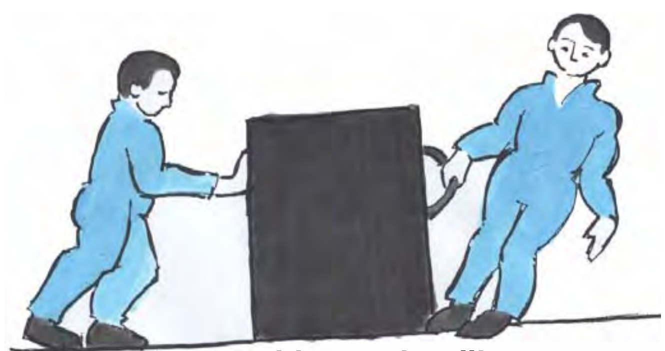
Lifting



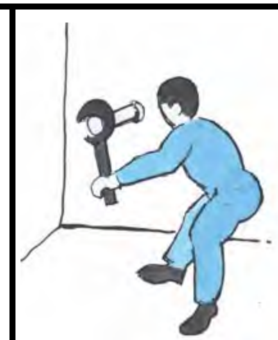
Jumping and Climbing

Disadvantages:

Reduced gravity conditions present disadvantages for activities that require surface traction, or which involve using body weight to overcome resistance such as pushing down on a torque wrench.



Pushing and Pulling



Torquing Down

Partial-g Benefits & Limitations

As discussed in Part II, Section F of this lecture series, functional areas and systems common to different space habitats include:

- **Galley and Wardroom:**
  -Dining, social, briefing and recreational space.
  -Food preparation appliances and utensil stowage.
  -Ambient and refrigerated food stowage.
  -Handwash unit and means for untensil cleaning.
- **Exercise and Recreation:**
  -Possible inclusion in wardroom area.
  -Possible connection with health maintenance area.
  -Equipment (fixed and/ or stowage)
  -Towel and clothing stowage.
- **Health maintenance:**
  -Patient support/ restraint systems.
  -Diagnostic and monitoring devices.
  -Instrument and medicine stowage.
  -Medical information system.
- **Personal Hygiene:**
  -Handwash and possible shower.
  -Stowage for personal toiletries/ clothing.
  -Laundry/ waste containment systems.
  -Stowage for cleaning agents and equipment.
- **Waste Management:**
  -Commode and urinal units.
  -Handwash and/ or other hygiene equipment.
  -Solid waste holding and processing systems.
  -Sanitary supplies and disposal containment.
- **Sleeping Quarters:**
  -Sleeping bags (0-g) or beds.
  -Clothing and other personal stowage.
  -Personal computer and audio/ visuals.
  -Deployable keyboard and writing desk.
- **Ancillary Areas:**
  -Scientific laboratories and work stations.
  -Maintenance shop with spares and tools.
  -Command and communications facilities.
  -Airlocks and emergency safe havens.
- **Support Systems:**
  -Outside viewing windows.
  -Fixed and portable lighting.
  -Environmental control systems.
  -Utility standoffs and lines.

Galley and wardroom areas support a variety of important functions:

- Dining periods are important times for crews to relax and socialize:
  - -Meal times provide daily schedule highlights and task breaks for morale and team bonding.
  - -Menu variety is important to ward against advancing boredom and dissatisfactions.
  - -Individual taste preferences will be influenced by cultural backgrounds (e.g., international crews).
  - -Wardrooms can support group meetings and recreational activities.
- Facility and equipment design should optimize food preparation and housekeeping convenience:
  - -Cooking and cleanup operations should be simplified to preserve precious time.
  - -Surfaces should be designed for easy access and wipedown to control bacterial growth.
  - -Handwash, utensil cleaning and trash management systems are needed for contamination protection.
  - -Inventory tracking/ management systems are essential to monitor supplies and consumption.

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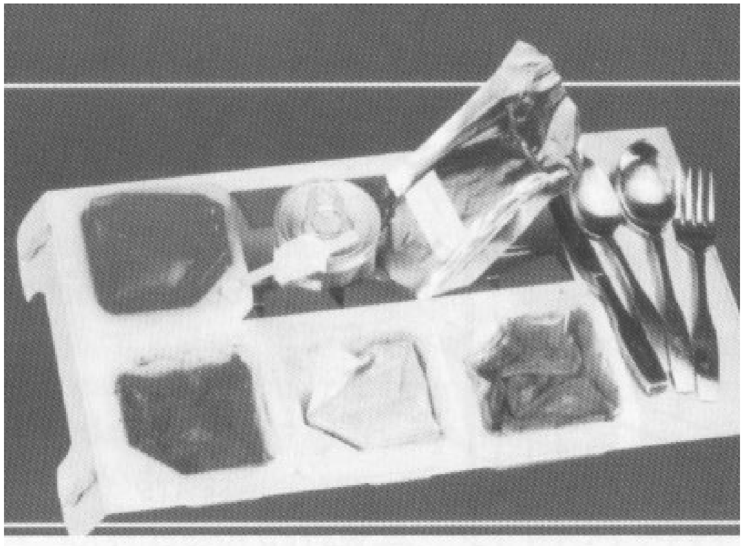
Galley & Wardroom

Previous space missions have revealed important food preparation challenges:

- Achieving proper nutrition:
  -Astronauts often experience loss of appetite.
  -Some complain that food tastes different (bland) in space (Appetizing menu is important.)
- Preservation of food from spoilage:
  -Long shelf life will re required for exploration missions.
- Preparation and eating:
  -Loose crumbs will float freely in weightlessness.
  -Freeze-dried foods can be difficult to rehydrate. (Special plastic packs enable water gun nozzles to be inserted.)
- Lightweight and compact packaging:
  -Early missions used some pureed foods that was squeezed out of aluminum tubes like toothpaste. (Containers sometimes weighed more than the contents.)
  -Packaging weight/ volume will be a major exploration vehicle design problem.



This Shuttle food tray meal consists of (left to right, top row) fruit punch, butterscotch pudding in the can, smoked turkey in foil bag, (bottom row) strawberries, mushroom soup, and mixed vegetables.

Special Galley Considerations

Shuttle missions allocate 3 one-hour daily meal periods which include eating and cleanup time:

- Schedules:

  -Breakfast, lunch and dinner are scheduled as close to regular times as possible.

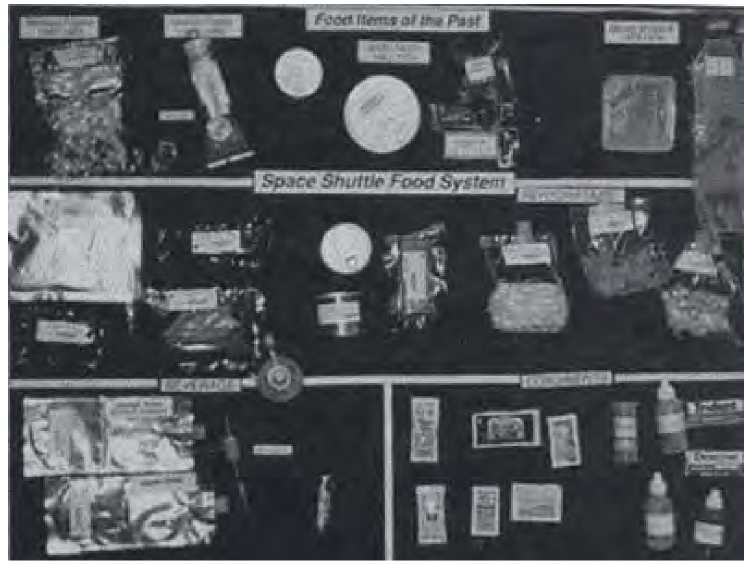
  -Dinner is scheduled at least 2-3 hours before preparations for sleep.

- Menu and pantry food:

  -Menu food consists of 3 daily meals/ crew member (average 2,700 calories/ day).

  -Pantry food for Shuttle is a 2-day contingency supply with in between meal snacks/ beverages and opportunities for menu changes (average 2,100 calories/ person/ day).

  -Food types include fresh, thermostabilized, rehydratable, irradiated, intermediate-moisture, and natural food/ beverages.



To rehydrate food, a water dispenser needle penetrates the rubber septum on a special container and a specified amount of water is discharged.

The Space Shuttle Orbiter food preparation system consists of a water dispenser, food warmer, trays and accessories:

- Water dispenser:
  - -This element provides ambient and chilled water for drinking and reconstituting food.
  - -It includes a housing assembly, rehydration station, water quick disconnect and water lines.
  - -The rehydration station electronically dispenses 2, 3, 4 and 8 ounces of water.
- Food warmer:
  - -Is a portable heating unit that can warm a meal for at least 4 people within an hour.
  - -Heats food be thermal conduction on a hot plate (thermostatically controlled between 165°-175° F).
- Food trays:
  - -Are color-coded for each crew member.
  - -Velcro on the bottom secures them for preparation; leg straps can secure them to the user's leg .

Magnetic strips hold eating utensils and binder clips hold condiment packages and wet wipes. Tray cutouts secure food packages, cans and pouches of various sizes.

Shuttle Food Tray & Packages

Special Galley Considerations

Exercise and recreation are vital to help maintain crew health and morale:

- Exercise can help mitigate bone, muscle and cardiovascular deconditioning effects of reduced gravity:
  - -Active programs are essential for extended missions.
  - -Versatile, stowage equipment can conserve space.
  - -Physical condition monitoring devices are important,
  - -Multi-person facility use can facilitate crew schedules.
- Exercise can be combined with recreation to support crew morale and interpersonal relationships:
  - -Video screens/ projections can add to satisfaction.
  - -Pairs of exercycles can enable competitive “races”.
  - -Special games can be designed for low-g conditions.
  - -Wardroom areas can afford recreation spaces.

SICSA Design Concept

Exercise & Recreation

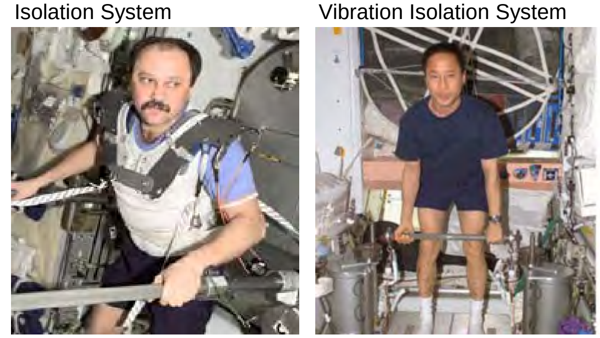
Exercise will become increasingly important to keep astronauts healthy as mission lengths increase:

- Schedules:
  - -At least 15 minutes/ day of vigorous exercise is recommended for Shuttle flights up to 2 weeks, and 30 minutes/ day for Shuttle missions up to 30 days.
  - -Astronauts on ISS will require up to 2 ½ hours/ day for extended missions.
  - -Russian cosmonauts wear “penguin” suits for force-resistance exercise, run 2 miles/ day on a treadmill, and eat special high protein diets. (Yet they still experience calcium loss and muscle weakening that can require days or weeks to recover after Earth return.)
- Equipment:
  - -Main ISS equipment includes a treadmill with a vibration isolation system (TVIS), Interim Resistive Exercise Device (IRED), and Cycle Ergometer with Vibration Isolation System (CEVIS).

NASA

ISS Treadmill with Vibration Isolation System

ISS Cycle Ergometer with Vibration Isolation System



Astronauts on ISS using exercise devices equipped with Interim Resistive Device (IRED)

Special Exercise Considerations

Accommodations must be provided to support prevention and responses to crew health problems:

- Special space-related concerns include:
  - -Deconditioning effects of reduced gravity.
  - -Treatment and isolation of airborne infections.
  - -Healing of burns, lacerations and fractures.
  - -Minor surgery requirements (e.g., tooth extractions).
- Important facility requirements include:
  - -Health monitoring/ assessment systems.
  - -Telemedicine connections with Earth experts.
  - -Ambient and refrigerated medicine stowage.
  - -Isolation of people with contagious illnesses.

SICSA Design Concept

Health Maintenance

Crew health maintenance systems provide preventative, diagnostic and therapeutic care capabilities:

- ISS systems include:
  -Crew Medical Restraint System (CMRS)
  -Defibrillator Respiratory Support Pack (RSP)
  -Advanced Life Support Pack (ALSP)

- Shuttle Orbiter Medical Systems (SOMS) (many also used on ISS) include:
  -Airway Subpack
  -Drug Subpack
  -Eye, Ear, Nose and Throat (EENT) Subpack
  -IV Administration Subpack
  -Saline Supply Bags
  -Sharps Container
  -Contaminant Cleanup Kit (CCK)
  -Resuscitator
  -Operational Bioinstrumentation System (OBS)
  -Restraints
  -Medical Extended Duration Orbiter Pack (MEDOP)

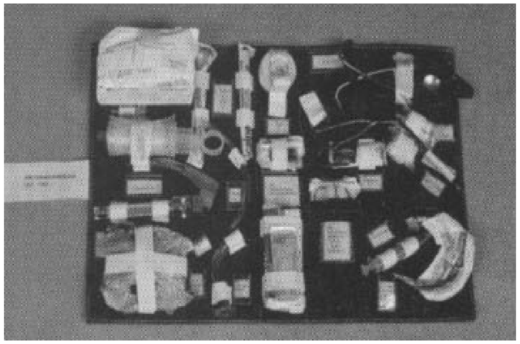
Equipment	Function
Ambulatory Medical Pack (AMP)	Provides in-flight medical care (e.g. first aid,treatment for minor illness or injury) Includes oral, topical, and injectable medications and exam instruments including a portable clinical blood analyzer.
Crew Contaminant Protection Kit (CCPK)	Protects the crew from toxic and non-toxic particulates and liquids. Contains eyewash; eye, respiratory, and skin protection; and waste containment bags.
Advanced Life Support Pack (ALSP)	Provides advanced cardiac and basic life support capabilities. Contains airway, drug, emergency surgery, assessment, intravaneous administration, and intravaneous "packs" and related emergency medical supplies.
Crew Medical Restraint System (CMRS)	Provides restraint and electrical isolation for an ill or injured crewmember and for the crew medical officers (CMO's) attending the patient.
Defibrillator	Provides defibrillation and ECG and heart rate monitoring, analysis, and downlink.
Respiration Support Pack (RSP)	Provides resuscitation for a crewmember with impaired pulmonary function. Automatically ventilates an unconscious crewmember, provides oxygen assistance to a conscious crewmember, and allows the CMO to manually resuscitate a patient

Space Station Equipment

Health Maintenance Equipment

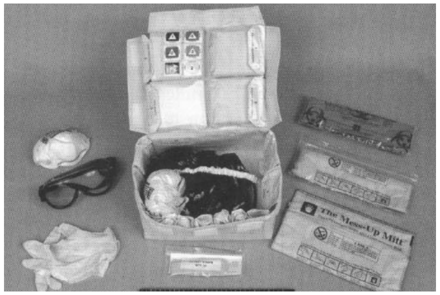
SPACECRAFT SYSTEMS
DESIGN & OPERATIONS


Trauma Subpack


Airway Subpack


Advanced Life Support Pack


Respirator Support Pack


Containment Cleanup Kit

Health Maintenance Supplies

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Personal hygiene and grooming are important for crew health and morale:

- Facility accommodations must include means for:
  - -Hand, face and body cleansing.
  - -Responses to chemical contamination events.
  - -Hair cleansing and trimming/ shaving.
  - -Personal toiletry article stowage.
- Space conditions require special adaptations:
  - -Spatial volumes will be constrained.
  - -Restricted water and volume may limit or preclude showers.
  - -Under weightless conditions, hair trimmings and splashed water must be controlled to prevent escape into the spacecraft atmosphere.

Bell & Trotti, Inc. Concept/Mockup

Personal Hygiene

NASA

Weightless conditions present special conditions and problems for personal hygiene operations:

- Body washing:

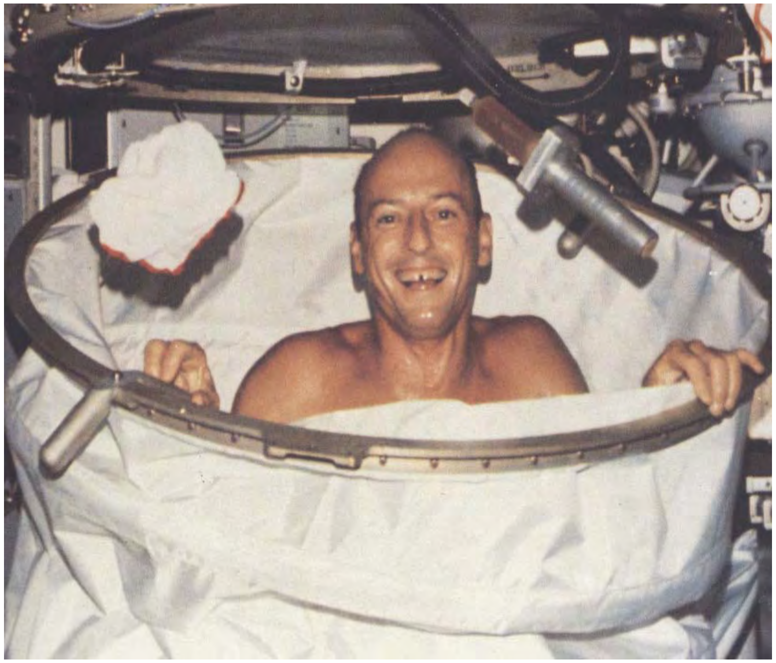
  -Skylab used a deployable shower enclosure with a spray device and vacuum cleaner to remove water. (Water often escaped and had to be chased around.)

  -Shuttle crews use a squirt gun to wet a wash cloth to soap up, and a second wash cloth to rinse off. Towels, wash cloths and other items can attach to walls with Velcro.

- Shaving:

  -Dry shaving with electric razors cause whiskers to float around and produce eye/ lung irritation and equipment damage, so wind-up shavers with vacuum attachments work better.

  -Depilatory creams or gels can be used, and shaving cream with safety razors seem to work best. (Some astronauts prefer to avoid shaving and grow beards.)



Shower in Skylab

Special Hygiene Considerations

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The design and use of personal waste management systems present special challenges in weightlessness:

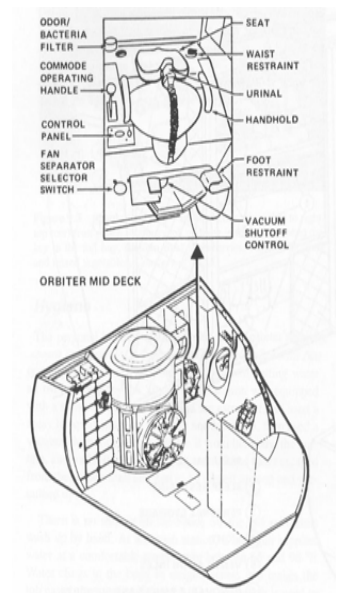
- Operational functions differ from conditions on Earth:
  - -Fecal eliminations are more problematic without gravity to assist the process.
  - -Neutral buoyancy body posture and tendencies to float impose restraint requirements.
  - -Urinal- body interface devices must be provided and adapted to gender differences.
- Contamination prevention safeguards are of vital importance:
  - -Spilled waste fluids and solids can escape and spread into surrounding areas.
  - -Fecal products and other unsanitary materials must be safely contained/ treated.
  - -Compartment surfaces and devices must be designed for easy wipe-downs.

Bell & Trotti, Inc. Concept/Mockup

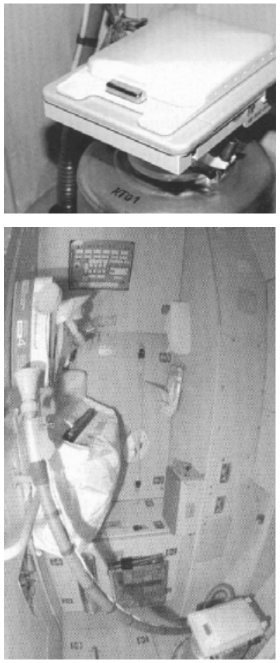
Waste Management

While future long-duration exploration missions may need to recycle human wastes, current systems used for weightless conditions on the Shuttle Orbiter and ISS do not:

- Waste Collection:
  -Urine collection interfaces must accommodate for anatomical gender differences. (While collection from men can be easily accomplished using tubes, women have experienced annoying difficulties.)
  -Toeholds, handholds and thigh or waste restraints are needed to hold the occupant firmly in place to assure a good seal with the commode seat.
- Waste Treatment:
  -Commodes must have separate receptacles for feces and urine. (Without gravity, high speed air streams carry solid and liquid waste into respective receptacles.)
  -Solid waste is vacuum dried, chemically treated with germicides to prevent odor and bacteria growth, and stored for return to Earth. Liquid is stored and dumped overboard.



Shuttle Orbiter System



ISS System

Special Waste Management Considerations

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Personal sleeping quarters can offer private places where individuals can pursue leisure activities:

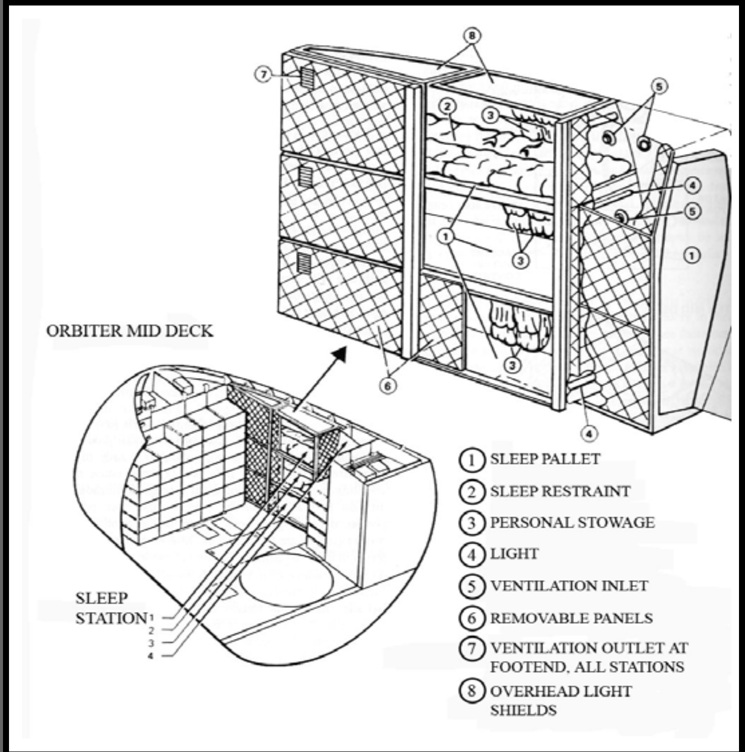
- Privacy is important to enable crew member to "escape" and enjoy quiet pastimes such as:
  - -Reading, watching videos and listening to music.
  - -Undertaking work/ study tasks, compiling notes and communicating using laptops and audio recording devices.
- Weightless conditions present unique design considerations:
  - -Compartments can be oriented in any direction since "up" and "down" are terms that are relative to the local vertical that is established.
  - -Astronauts will float around the compartments unless secured (e.g., sleeping bags).
  - -Stowed clothing and other items must be secured/ contained in place (e.g., using soft stowage systems with pockets).
  - -Active ventilation is needed to prevent exhaled carbon dioxide from collecting around a sleeping person's face causing oxygen deprivation.

Bell & Trotti, Inc. Concept/Mockup

Microgravity Sleeping Quarters

Under weightless conditions, astronauts need not lie “down” to sleep, and some have slept while simply floating around the spacecraft:

- Sleep Styles:
  - -After sleeping for a short time, some astronauts have tried to roll over, and woke themselves up flailing their arms and legs.
  - -Some awoke feeling dizzy from their weightless heads bobbing around, and preferred to use forehead straps to avoid this sensation.
  - -Some people like waist straps that press their bodies against the support to have the sensation of lying on a mattress.
- Sleep Conditions:
  - -In a 200 mile orbit, the sun rises and sets every 1 ½ hours, so there is no long dark night. Eye shades and ear muffs can reduce disturbing light and noise for those who want to use them.
  - -If an entire crew sleeps at the same time, at least 2 must wear communications headphones in case an emergency arises or ground controllers call.



Special Sleeping Considerations

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US space station planning following Skylab has emphasized a modular approach for creating “functional units” and equipment racks with standardized dimensions and utility interfaces to facilitate easy relocations, change-outs and maintenance.

- Functional units are enclosures for crew occupancy and activities, including:
  - -Sleeping compartments
  - -Showers/ personal hygiene facilities
  - -Waste management (toilet) units
- Racks are used to integrate and support equipment and supply items, including:
  - -Environmental life support systems
  - -Laboratory experiments and materials
  - -Food preparation and stowage items

Functional Unit

Rack

Modular Approach

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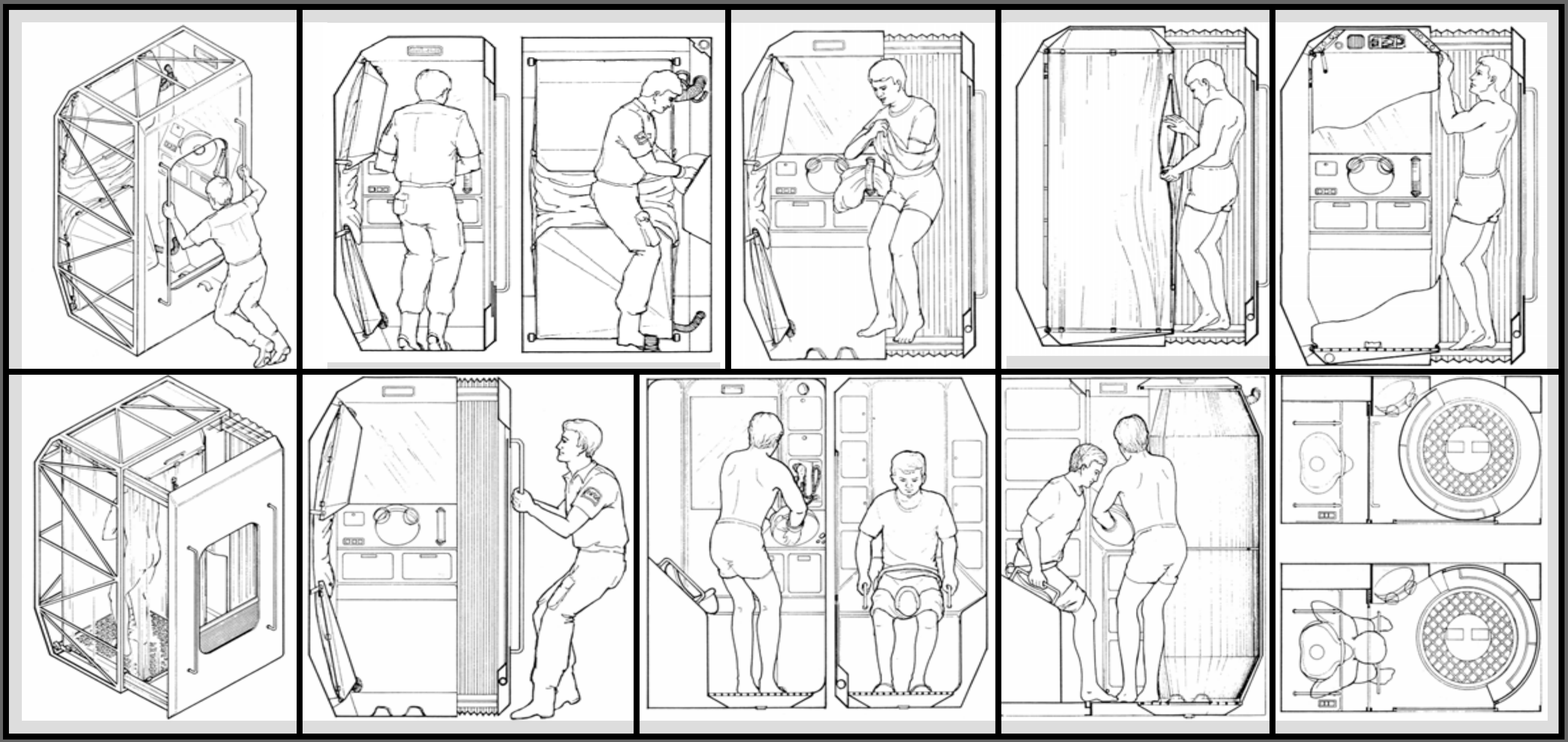

Bell & Trotti, Inc. Functional Unit Concepts

A capability to rapidly and easily remove racks from utility system attachments has been an important requirement in space station planning:

- Hinged connections and quick-release latches enable racks to be pivoted or slid out for routine and emergency maintenance access to utility interfaces and the module pressure hull.
- Rapid access is of particular importance to repair possible module debris penetrations, fluid line leaks, and hazardous electrical problems.
- Weightless and reduced-g conditions can benefit rack disconnect/ repositioning operations, but must accommodate special design adjustments for changes in human leverage and body posture.

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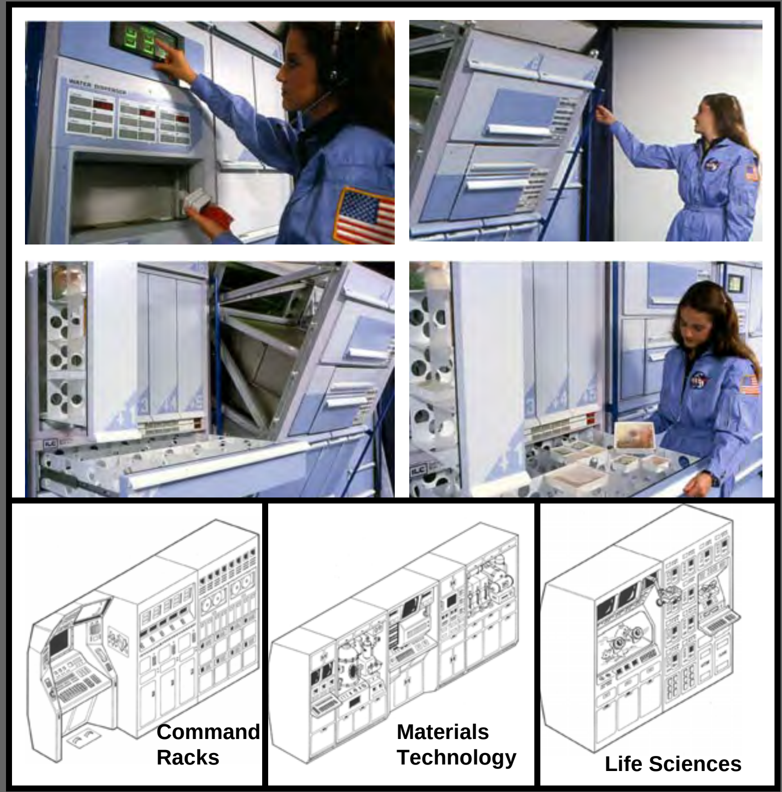


Bell & Trotti, Inc. Rack Concepts

Effective habitat design and layout must take spacecraft orientation and safety issues into account :

Spacecraft and Module Orientation:

- **Outside Viewing:**
  - Window orientations to Earth (NADIR).
  - Obstructions presented by spacecraft elements.
  - Viewport size and type characteristics.
  - Priority locations for mission and crew.

- **Local Verticals:**
  - Orientation within individual modules.
  - Orientation of modules to NADIR viewing.
  - Consistency of orientations between modules.
  - Visual cues to assist crew adaptations.

Safety Assurances:

- **Internal Circulation:**
  - Emergency egress to safe havens/airlocks.
  - Dual egress options to safe zones.
  - Access to back-up life/safety-critical equipment.
  - Pathway identification under smoke conditions.

- **Hazard Avoidance/ Containment:**
  - Pressurized bulkheads between compartments.
  - Independent sector life support systems.
  - Isolation of hazardous materials/ activities.
  - Radiation storm shelters/ shielded areas.

Habitat design and layout planning must consider ways to optimize effective and efficient use of limited space.

Functional Relationships:

- **Shared Functions and Systems:**
  - Co-location of interdependent activities.
  - Co-location of shared equipment/ storage.
  - Adjacencies of utility line connections.
  - Conversions for multipurpose uses.
- **Intrusion Avoidance:**
  - Noise isolation separations/ barriers.
  - Odor isolation separations/ barriers.
  - Places for private, solitary activities.
  - Protection from circulation disturbances.

Public and Private Spaces:

- **Activity Levels and Schedules:**
  - Separations of noisy and quiet areas.
  - Avoidance of traffic intrusions.
  - Planning of multipurpose areas.
  - Scheduling of active/quiet crew periods.
- **Color, Graphic and Lighting Devices:**
  - Colors and gradients to active/quiet areas.
  - Means to personalize private spaces.
  - Illumination levels to identify day/night cycles.
  - Lighting systems for leisure/task conditions.

Design & Layout Considerations

Reliable and safe operations/repair of systems is vital to prevent potentially dangerous or catastrophic failures:

Operations and Maintenance Problems:

- Weightless conditions can cause small components to get loose and lost, and reduce human leverage for procedures requiring torque.
- Complex systems present difficult operational and repair requirements that may exceed available crew skills and time.
- Severe work and environmental conditions with crew fatigue over time can increase error and failure risks.
- Available volume to store equipment spares, parts and tools can impair routine and emergency repair operations.
- Access to problem areas is often restricted due to crowded equipment and operating conditions (particularly with pressure suits).
- Cleaning solvents and repair processes are restricted due to fire, contamination, grinding particles and other safety hazards.

Special Design Countermeasures:

- Avoid creating small components that can get loose and provide attachment/ containment devices to prevent lost pieces.
- Design user-friendly systems that are easy to understand, operate and repair under routine and emergency conditions.
- Plan for "corrective maintenance" that weighs benefits gained vs. efforts expanded for repair-replace decisions.
- Design systems with standardized parts, interconnects and repair processes to minimize necessary spares and tools.
- Provide quick-release fasteners, "remove and replace modularity" and good physical and visual access for maintenance.
- Minimize the need for soldering/welding/bracing operations and toxic solvents that present health and safety hazards.

As discussed in Part I, Section B of this lecture series, utility lines contained within standoff structures distribute fluids, power and data/ communication links within modules:

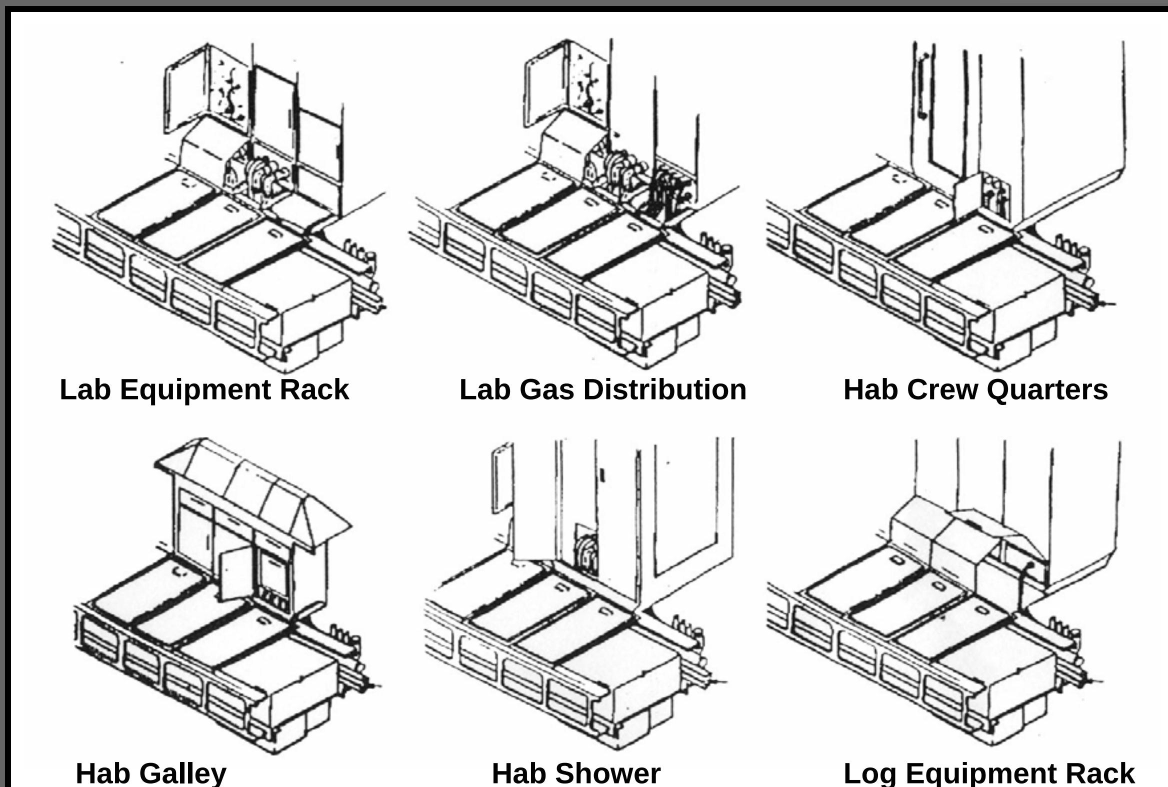
- The standoff configuration defines the organizing geometry for all equipment layouts and functions:
  - To minimize fluid distribution mass, it is desirable to group equipment and functions that depend upon these connections along one line and/or as near to one another as possible.
  - Fluid lines should be separated from data/communication lines, and electric equipment should be prevented from leak hazards.
  - All utility lines should be accessible for inspection and repair, including maintenance by an EVA-suited person with gloved hands in event of a module pressure loss.
  - The entire utility infrastructure should be modular to enable evolutionary change outs and extensions.

Utility Systems:	**Planning Considerations:**
▪ Standoffs	Number/locations
▪ Line types	Ducts,power,fluids &data/comm.
▪ Line isolation	Separation of fluid and data/comm.
▪ Distributions	Passthroughs between modules
▪ Interfaces	Types of connected equipment
▪ Maintenance	Normal & emergency access
▪ Modularity	Opportunities to reconfigure
Equipment Systems:	**Planning Considerations:**
• ECLSS	Air purity /temp /humidity control
• Atmosphere	Resupply & fans/ ducts
• Power	Generation/ control & storage
• Water & gases	Storage & locations of use
• Waste mgmt.	Contamination control/ recycling
• Lighting	Fixed & task requirements
• Data/ comm.	Localized & networks

Elements and Considerations

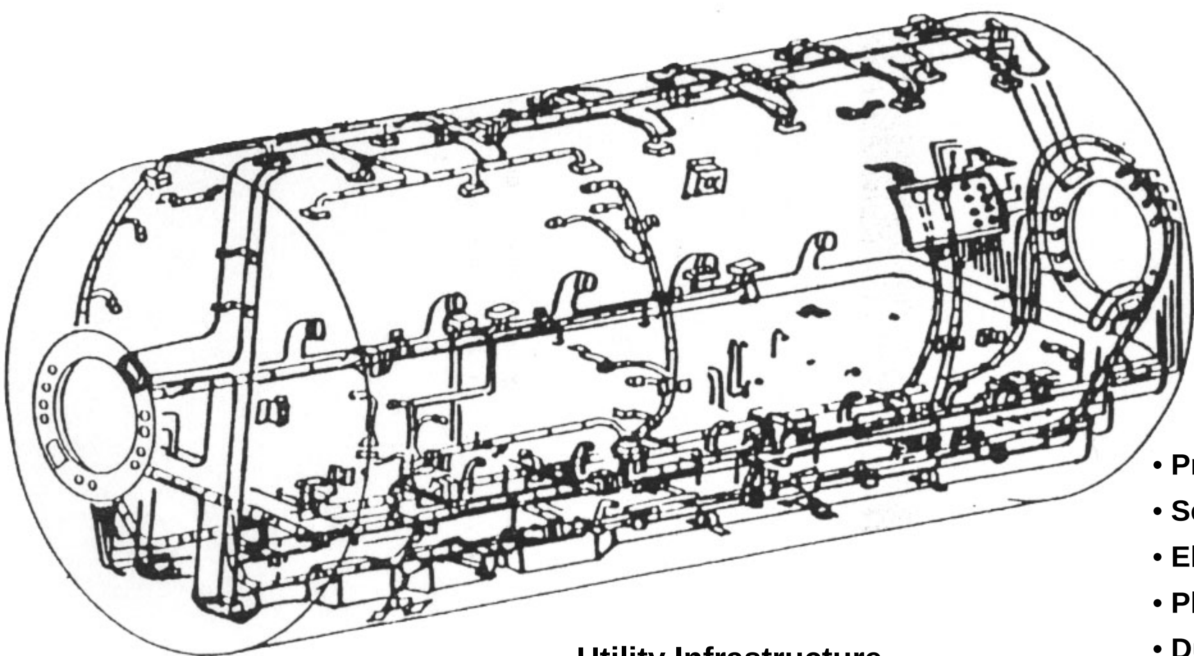
Utility Infrastructure & Systems

BOEING



Space Station Freedom Utility Interface Concepts

ROCKWELL
INTERNATIONAL

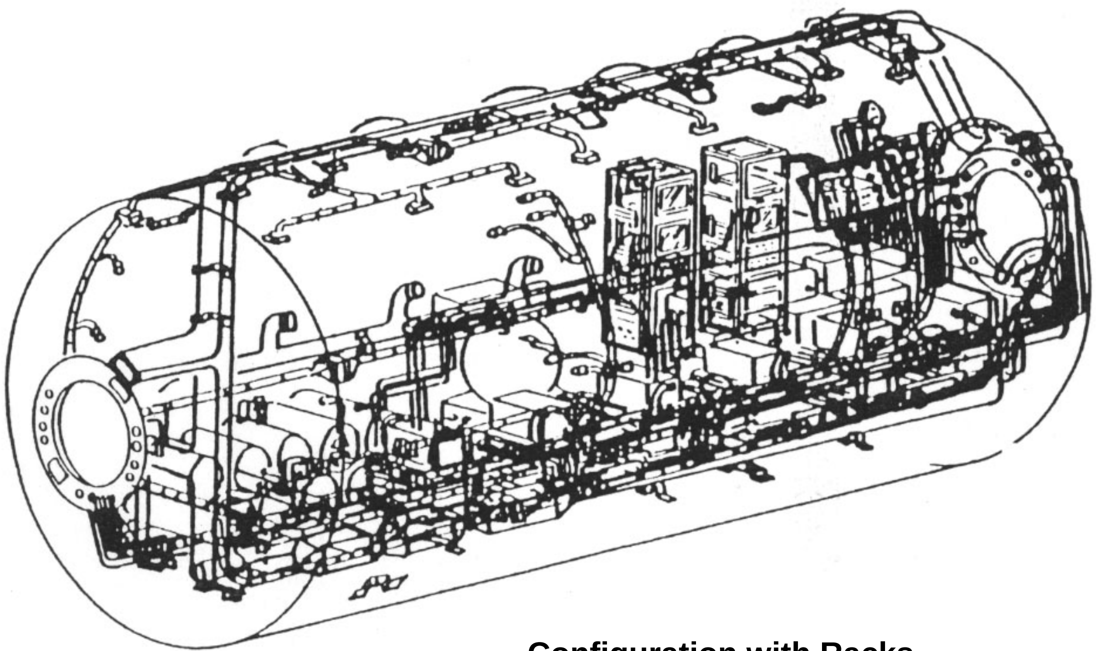


Utility Infrastructure

- Primary Structure
- Secondary Structure
- Electrical Distribution
- Plumbing- Tubes
- Ducting

Space Station Freedom Utilities Concept

ROCKWELL
INTERNATIONAL



Configuration with Racks

- Primary Structure
- Secondary Structure
- Electrical Distribution
- Plumbing- Tubes
- Ducting
- Systems
- System Modules

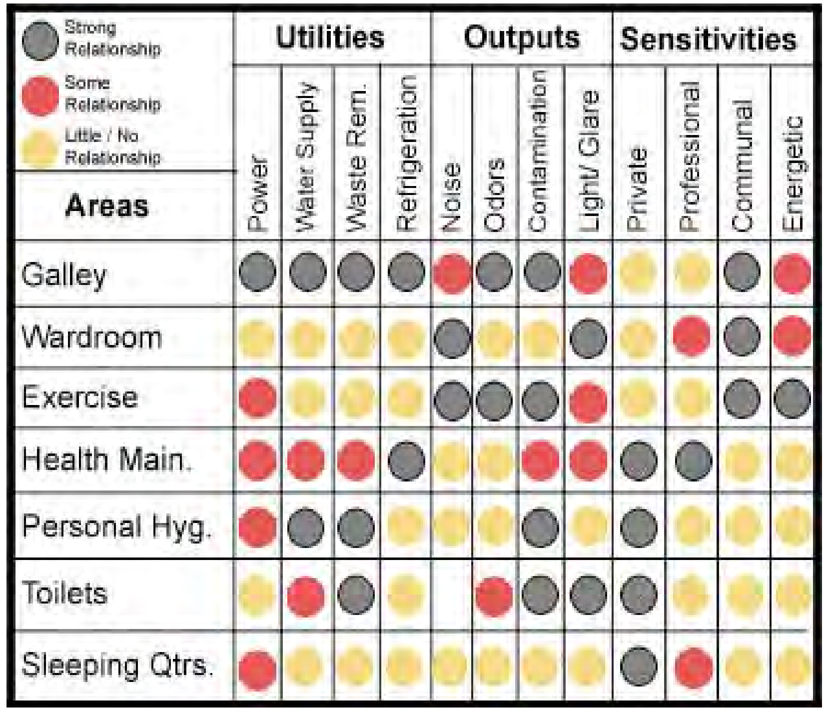
Space Station Freedom Utilities Concept

In addition to utility connections, layout planning should also consider relationships between activities and functions that share common support needs, and those which are most and least compatible for nearby locations.

It is desirable to separate or isolate areas that produce certain outputs that can interfere with activities that are sensitive to those conditions.

Features	Shared/ Common Users
Outside Viewing	Science, Proximity Operations and Recreation
Refrigerated Storage	Biological Science, Health Maintenance and Galley
Diagnostic Monitors	Health Maintenance and Exercise Facilities
Waste Management	Hygiene/ Toilets, Galley and Clothes Wash

Shared Dependencies

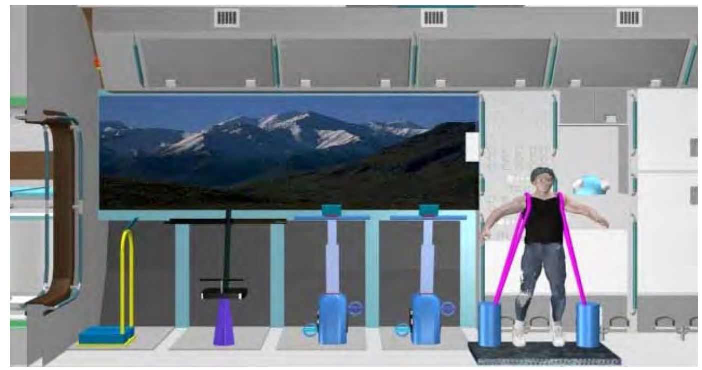


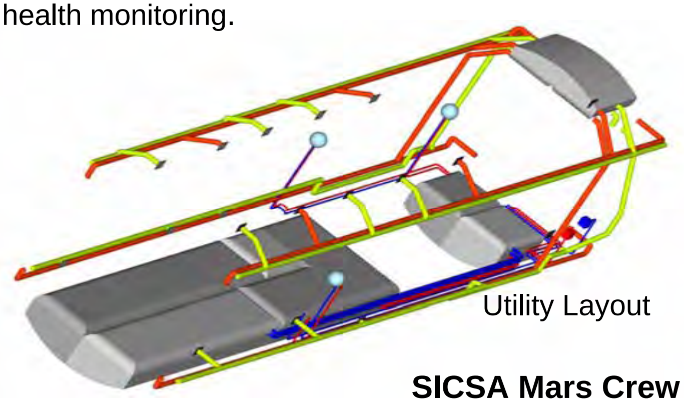
Dependencies, Outputs and Sensitivities

System & Activity Relationships

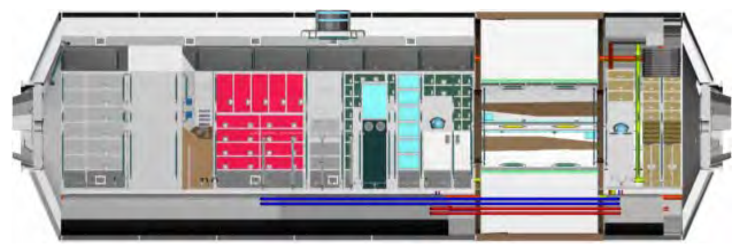
A conventional type Mars Crew Transfer Vehicle concept proposed by SICSA separates functions for crew comfort and utility efficiency:

- Crew sleeping quarters are located distant from noisy galley and exercise areas.
- Waste management and personal hygiene are located in the same area to utilize common waste collection and treatment systems.
- The medical and exercise functions are data-linked for health monitoring.





Utility Layout

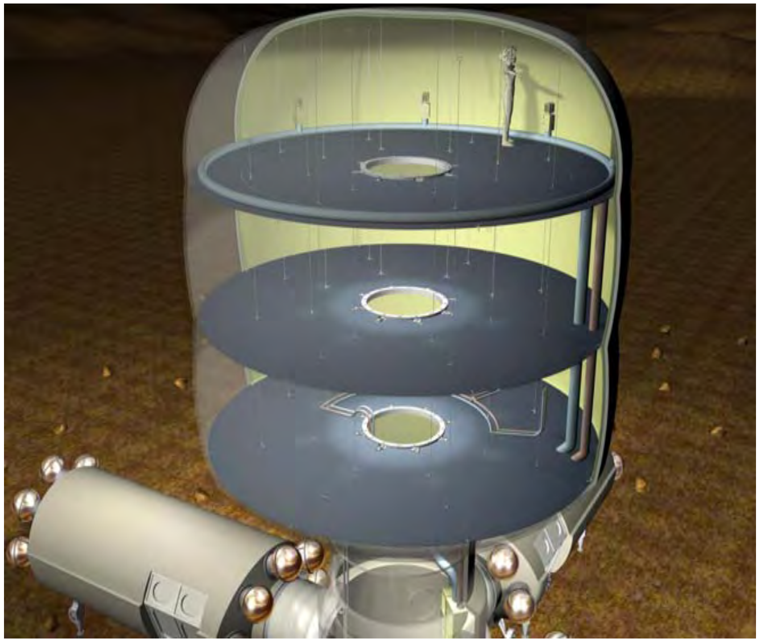


Crew Transfer Vehicle Elevations

SICSA Mars Crew Transfer Vehicle Concept

An inflatable lunar/Mars surface module concept proposed by SICSA emphasizes means to rapidly deploy the structure, easily incorporate internal equipment, and concentrate utilities where essential :

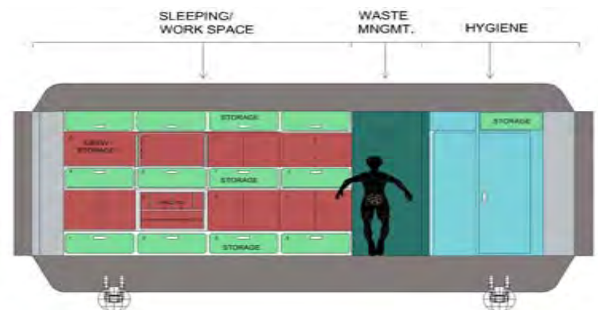
- Utility intensive systems including personal hygiene and waste management are located in a connecting "hard" conventional module with pre-integrated interfaces.
- Functions requiring minimal fluid connections such as handwash and laboratory areas are placed at the lower and middle level to limit utility line lengths.
- The quiet sleeping space is located at the top level away from other more active areas and requires no fluid connections.



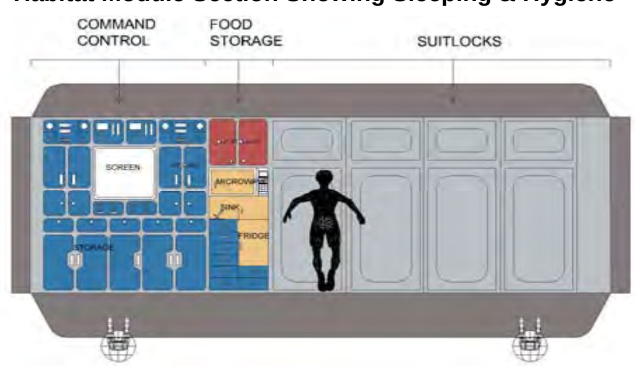
SICSA Inflatable Module Concept

A conventional type lunar/Mars surface scheme proposed by SICSA concentrates utility intensive functions in conventional modules, and others in inflatables :

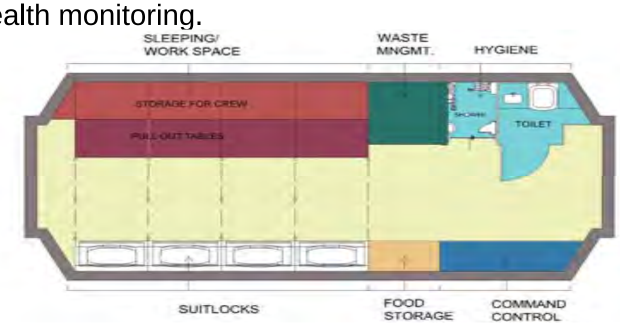
- Sleeping and work spaces located in this element can be relocated into a connecting inflatable module following its deployment as larger living capacities are required.
- Waste management and personal hygiene facilities remain in this module, along with command control and suitlock accommodations.
- The medical and exercise functions are data-linked for health monitoring.



Habitat Module Section Showing Sleeping & Hygiene



Habitat Module Section Showing Command Control & Suitlocks



Habitat Module Plan Showing Workspace

SICSA Surface Module Concept

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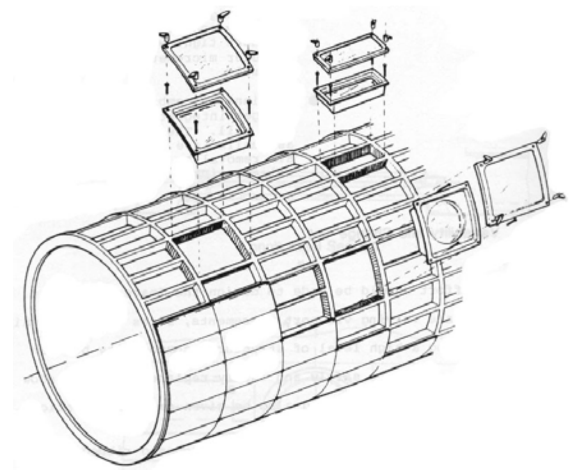
As discussed in Part I, Section B of this lecture series, the importance of outside viewing has been clearly demonstrated throughout all human space missions, including:

- 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

Outside Viewing Considerations

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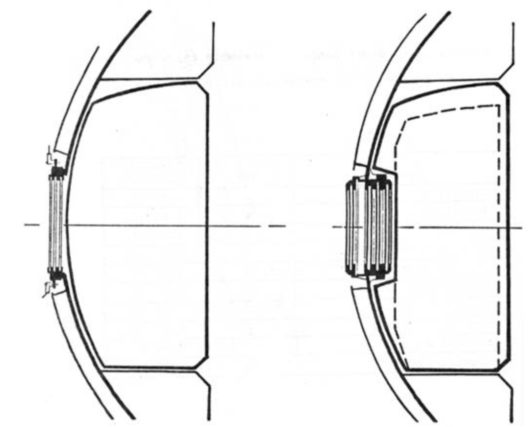
Spacecraft windows add substantial structural mass, introduce pressure seal and transparency maintenance problems and can reduce wall space available for equipment and other uses:

- 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.



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 Design & Placement

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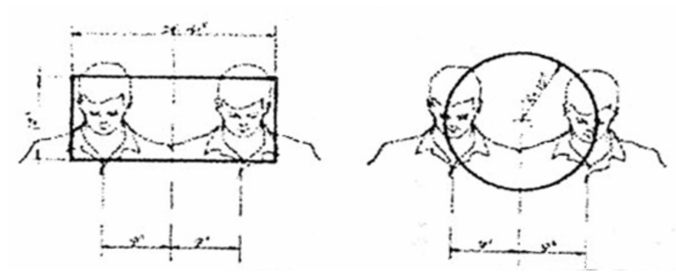
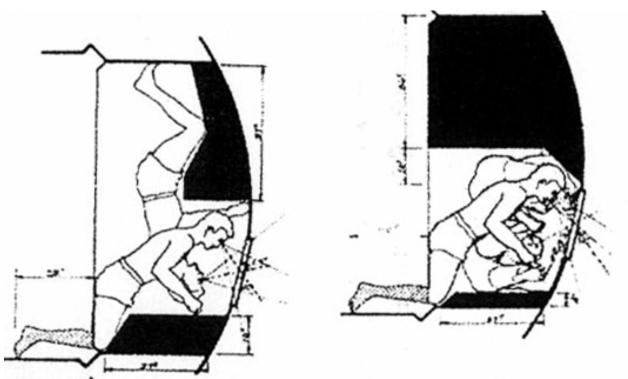
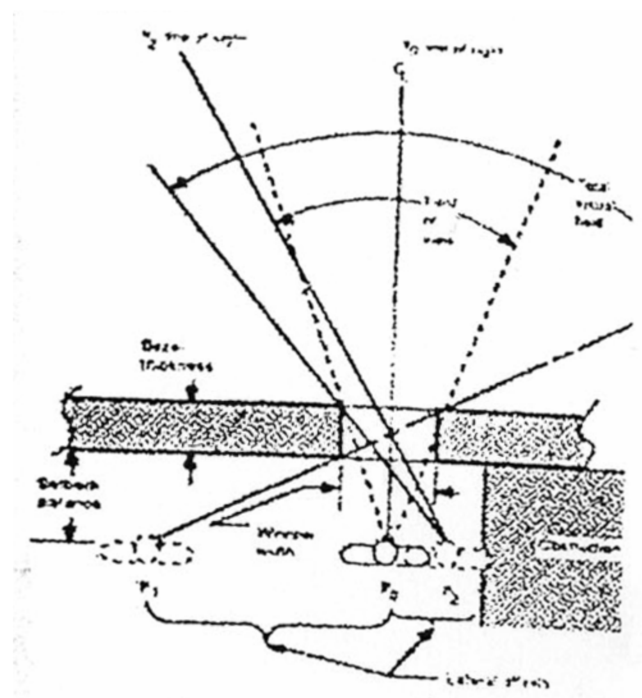


Window Shapes and Sizes



Single and Multiple Viewer Positions



Eye Position Locations

Outside Viewing Positions

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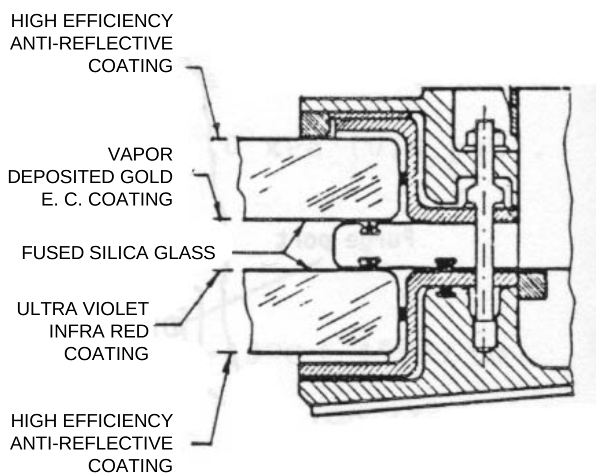
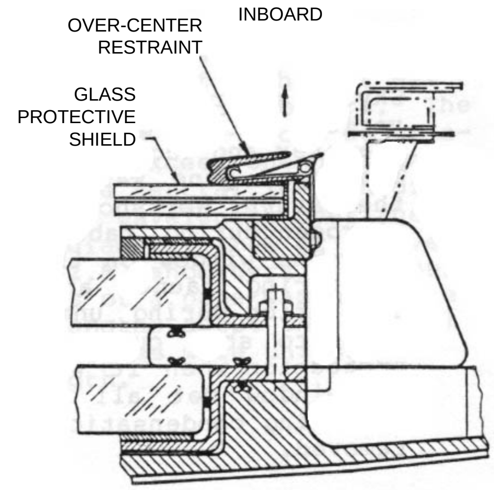


Materials



Components

Skylab Wardroom Window Construction

INTERIOR ARCHITECTURES AND ELEMENTS

PLANNING AND DESIGN

Minimum lighting system requirements are established by NASA-STD-3000, Vol. IV. Man Systems Integration Standards (3.3.9):

- The standards place special emphasis upon task-specific lighting needed for certain locations:
  - The general galley area
  - Food preparation areas
  - Crew dining areas
  - Health maintenance facilities
  - Private crew sleep stations
- Psychological factors, illumination control and maintainability are also emphasized :
  - Higher ambient levels are associated with beneficial effects on morale.
  - The systems should provide a dialable variability from full bright to off.
  - All units should be modular for replacement/ repair.

General Space Station	108 lux (10ftc)
Galley Area	185 lux (20ftc)
Dining	235 lux (25ftc)
Food Preparation	280 lux (30ftc)
Stowage Areas	95 lux (10ftc)

Space Vehicle Food Illumination
Levels established by NASA-STD-3000 Vol.IV, Man Systems Integration Standards

General Residential	95 lux (10ftc)
Restaurant	95 lux (10ftc)
Cleaning	185 lux (20ftc)
Reading Print	280 lux (30ftc)
Commercial Kitchen	648 lux (70ftc)

Residential & Commercial Illumination
Levels recommended by the Illumination Engineering Society/ Architectural Graphic Standards

Lighting Systems & Levels

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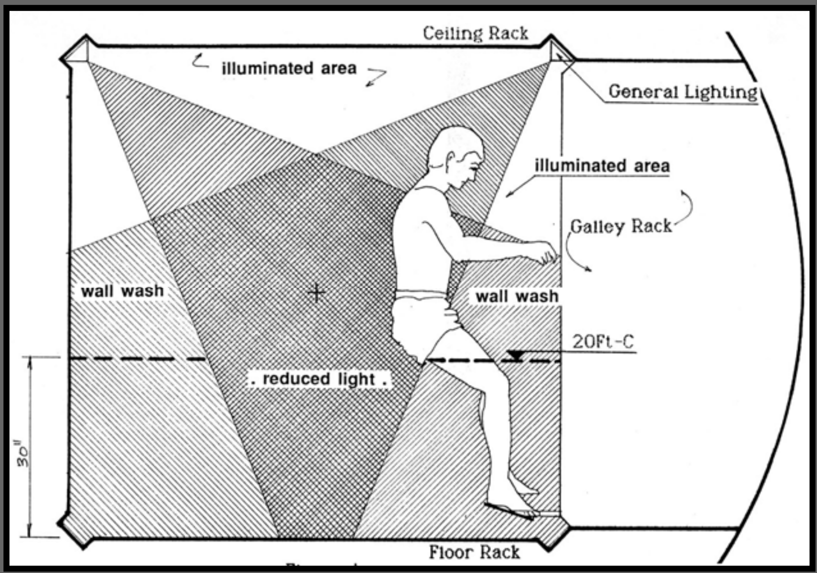
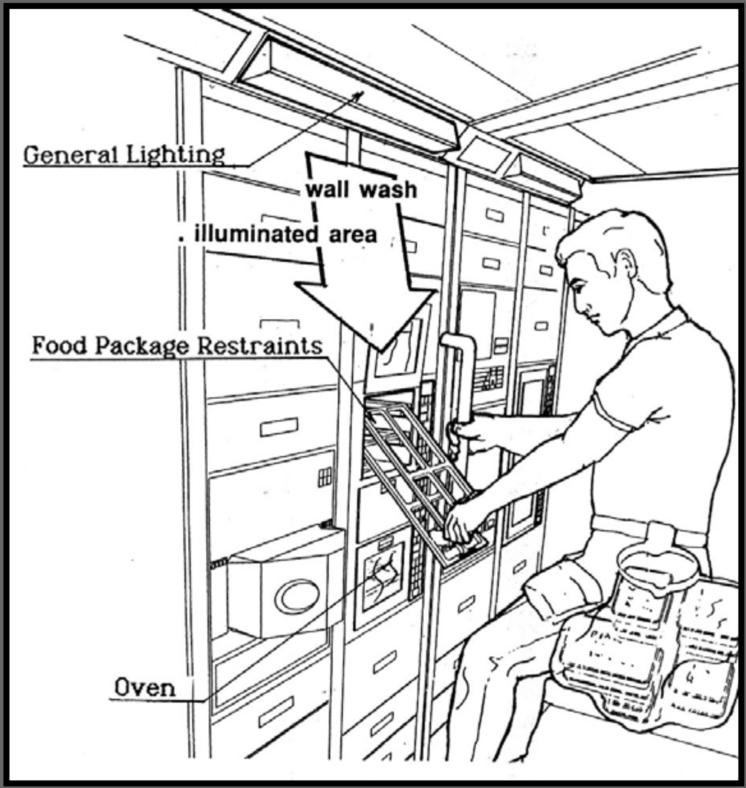
Lighting system design must consider general ambient and special task requirements based upon the nature of crew amenities in each area, providing means for control and replacement.





Lighting Systems

Habitat accommodations for crew support and leisure activities must compete with other operational necessities for very limited volumes:

- Mission schedule and activity programming inevitably entails tradeoffs between comfort amenities and other operational priorities:
  - If all crewmembers share the same daily work-leisure schedule, it will require that food preparation, exercise, hygiene and other high demand facilities be adequate for these concentrated demands.
  - Although not ideal, split shifts may enable downsizing of food preparation, and allow “hot bunking” where 2 individuals alternately use a single sleeping unit.
  - Time allocated for leisure/exercise must be correlated with available space and equipment needed for individual vs. shared use.
  - Longer missions will require more volume for logistics/ equipment stowage, potentially in competition with expanded crew comfort needs.

Crew Schedule Influences on Use	Diurnal cycles (reference hours/day) Duty schedules (common vs. split shifts) Dining Schedules (variant or communal) Exercise (time allocated/day)
Crew Living Accommodations/ Volume	Private sleeping quarters vs. communal Galley food preparation equipment/ time Communal dining/ wardroom capacity Exercise space (single vs. multiple use)
Logistics & Equipment Stowage Requirements	Consumables vs. crew size/mission length Equipment spares/ parts/ tools needed Housekeeping equipment & supplies Trash management
Operations & Contingency Facilities & Support	Airlocks (internal or attached) Labs/ workstations (in module or separate) Emergency egress circulation space Radiation shelters (integrated or separate)

Factors Influencing Volume Utilization

Competing Volume Requirements

The ultimate space habitat planning and design challenge is to address, reconcile and accommodate all competing human, equipment and support needs under extremely constrained mass and volume allowances:

- Fundamental priorities include the following:
  - Provide modularity that enables internal configurations and elements to be adapted to near-term and evolutionary mission needs applying a standardized “kit of parts" approach.
  - Design structures, utilities and equipment for rapid and easy deployment, outfitting and repairs/ upgrades using Quick Disconnect (QD) interfaces.
  - Group functions and utility dependant elements to minimize plumbing/wiring lines and associated mass and maintenance.
  - Design furnishings to be as compact/ stowable and lightweight as possible through innovative design and material use.

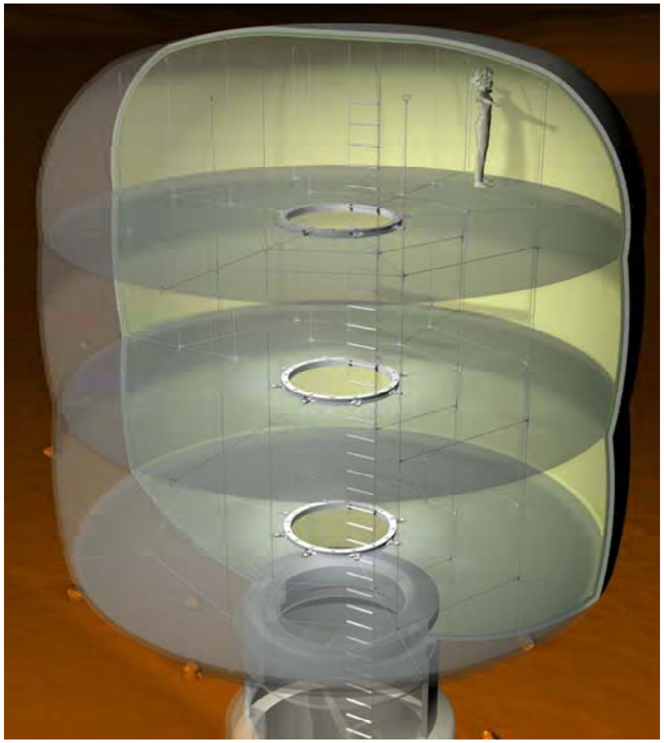
Modularity • Utility lines & air ducts • Equipment & stowage racks • Functional enclosures/ partitions • Sleeping & personal hygiene units	**Deployment Ease** • Pressure vessel- utility interfaces • Utility system- equipment interfaces • Plug-n-play experiments/upgrades • Access for maintenance/ repairs
Economic Groupings • Activities using shared equipment • Refrigeration- dependant functions • Water/ waste management functions • Stowage of volatile materials	**Vol./Mass Reduction** • Crew exercise equipment • Crew shower enclosures • Tables & other furnishings • Crew/ housekeeping stowage items

Strategic Approaches

Optimizing Efficiency & Versatility

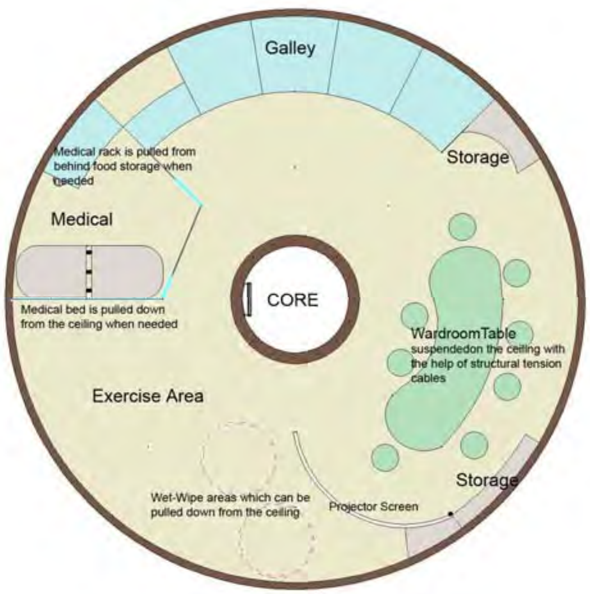
Relatively large interior areas afforded by inflatable structures such as SICSA's pop-out concept can enable greater versatility for arranging crew living area functions, but place higher dependence upon utility system modularity than conventional modules:

- The axial "web" of tension cables used to retain the deployed pressure envelope into a desired shape can provide attachments for the utility lines and connected equipment :
  - The most utility-dependant functions would be located at the lowest level to minimize plumbing runs.
  - Laboratory facilities that require electrical power but limited water might be incorporated at the middle level.
  - Sleep/leisure areas which have only minimum electrical requirements but need noise isolation are proposed at the upper level.



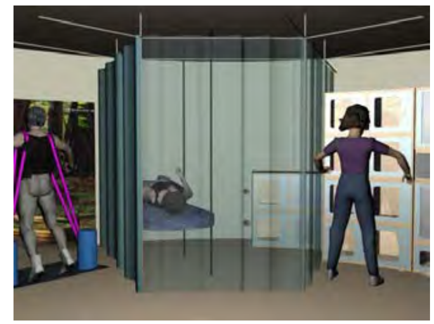
SICSA's "Pop-out" Inflatable Concept

Interior Layout Examples

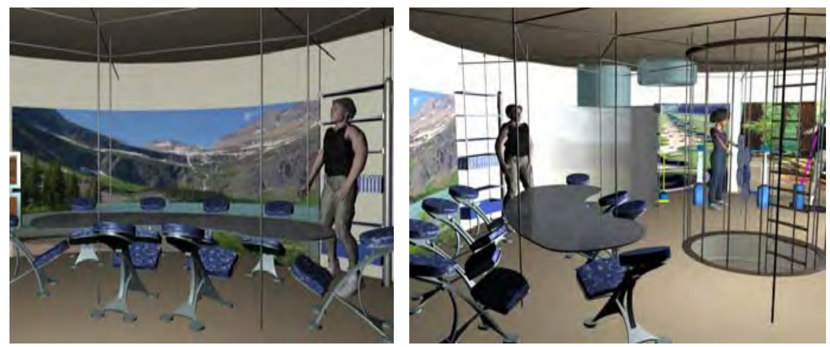


Inflatable Lower Level Plan

Exercise Area



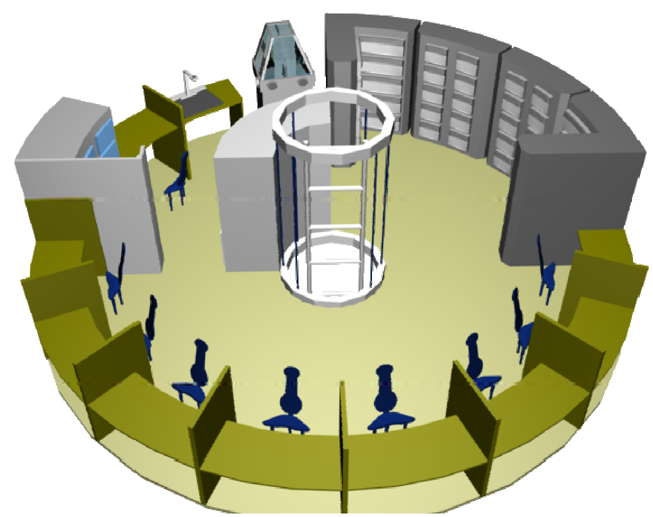
Medical Area



Wardroom Area

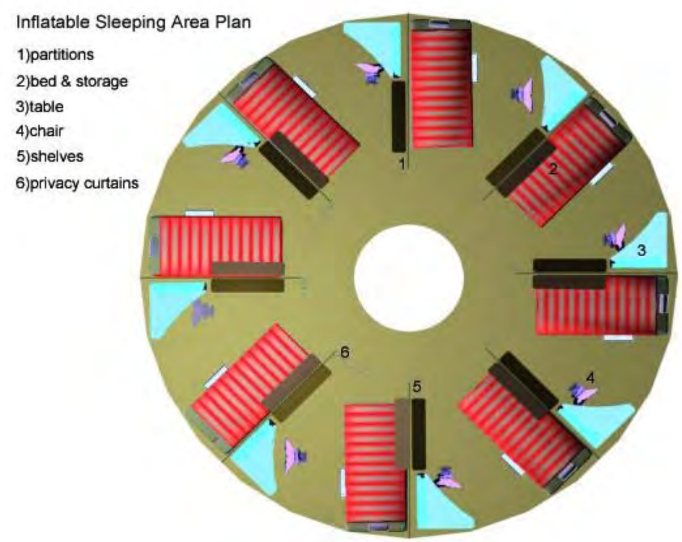
Interior Layout Examples

Inflatable Second Level Plan

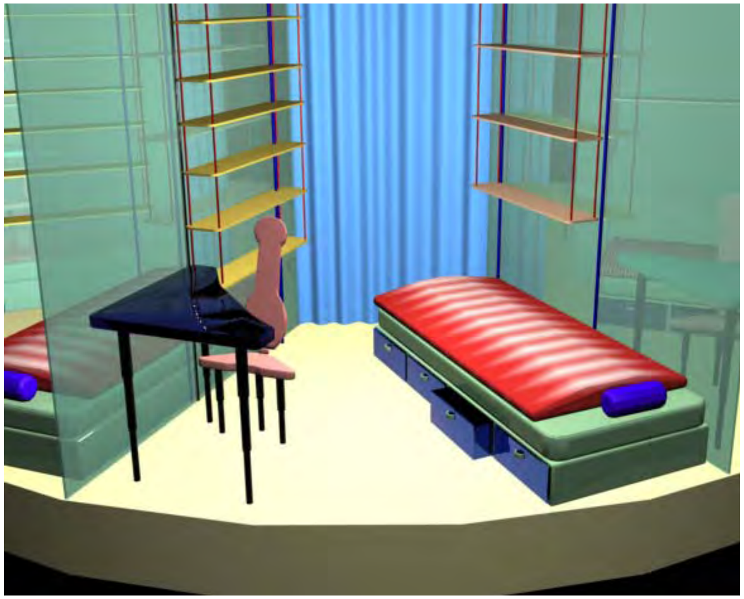


SICSA Inflatable Module Concept –Lab Facilities

Interior Layout Examples



Inflatable Upper Level Plan

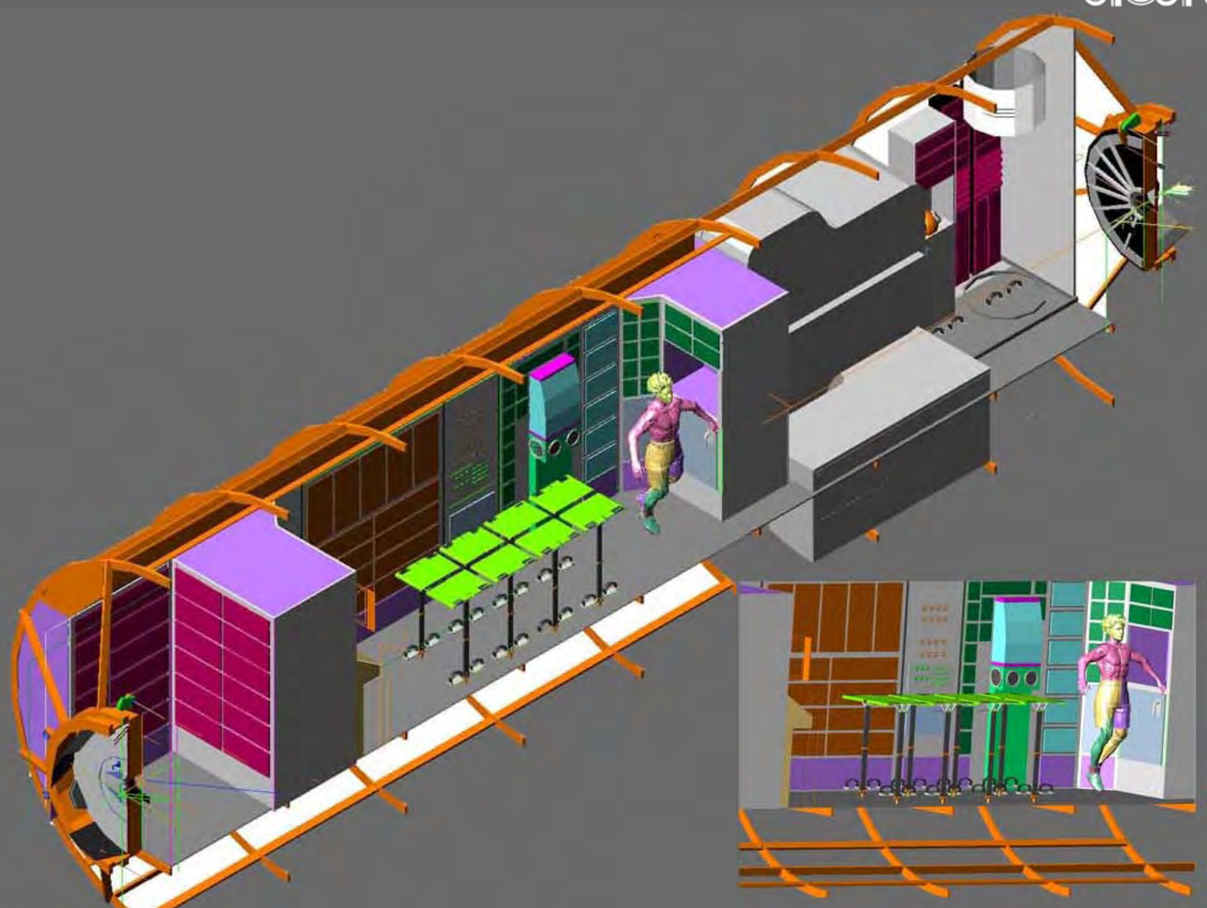


SICSA Inflatable Module Concept
Sleeping Accommodations

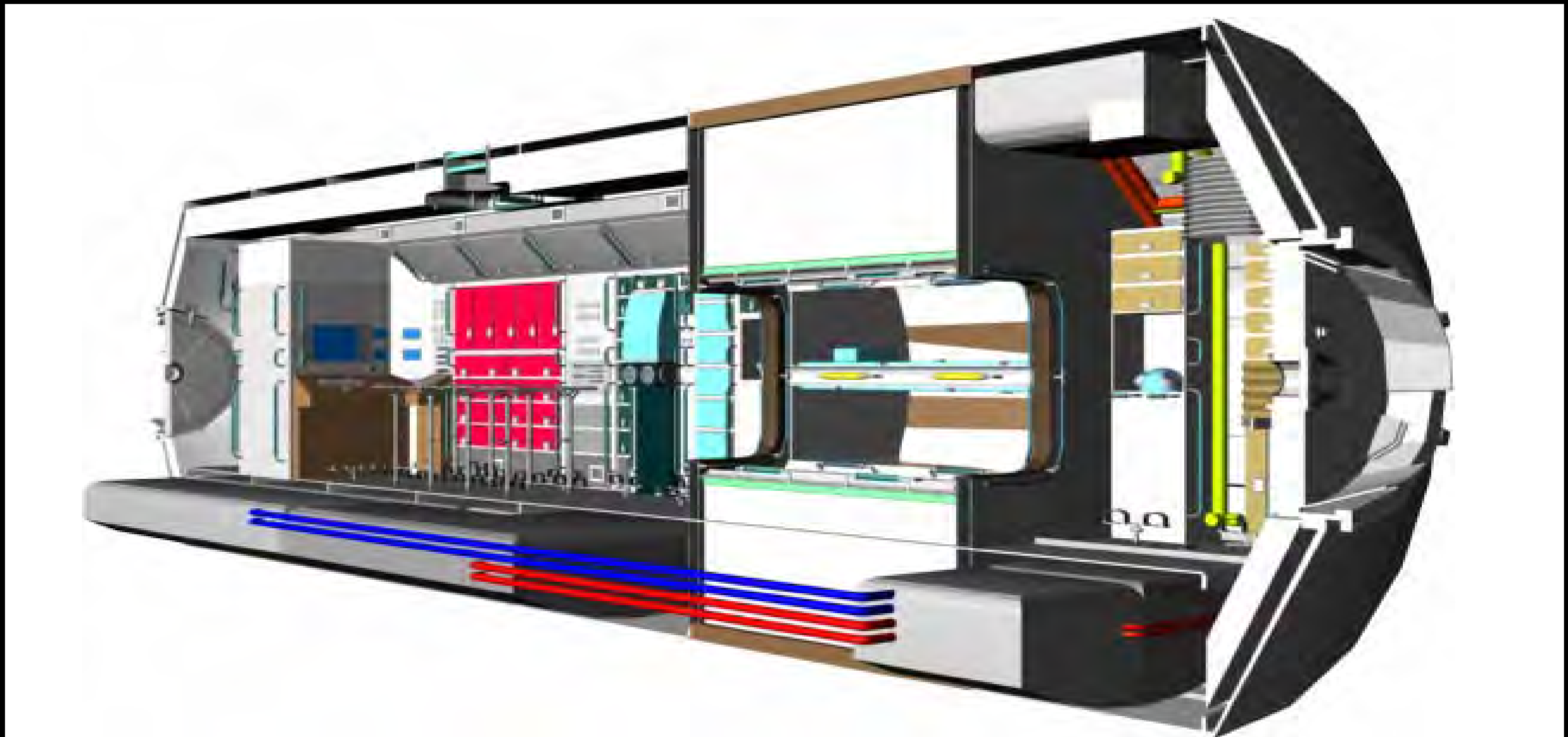
Interior Layout Examples

A proposed Mars Crew Excursion Vehicle illustrates some interior layout and equipment outfitting considerations for a conventional hard module :

- Sleeping and personal hygiene functions are placed at one end for privacy away from the more active galley/ dining area :
  - The relatively small module size minimizes the length of water and waste transfer lines, and ECLSS systems are located in the wardroom area.



Interior Outfitting Examples

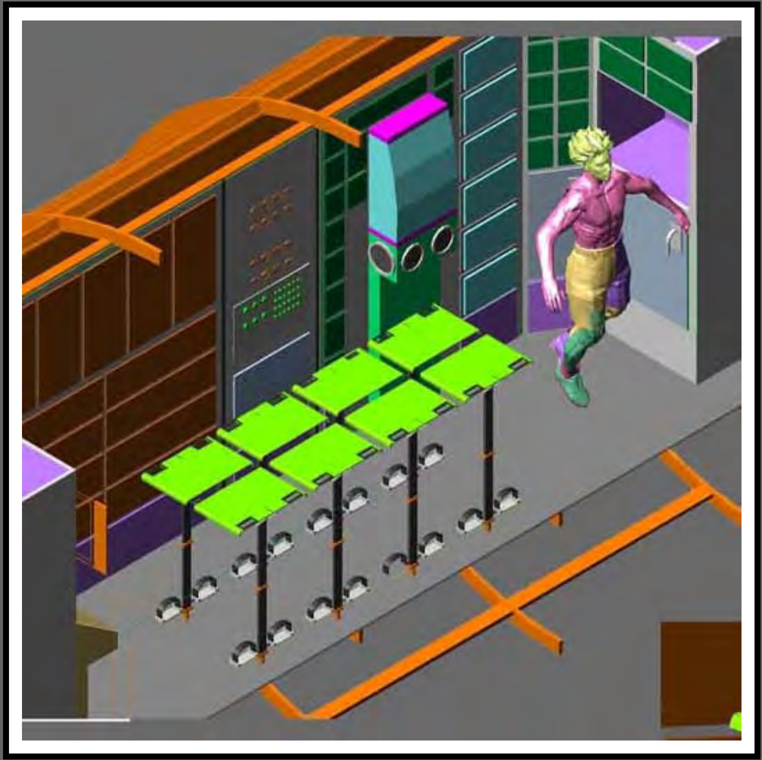


SICSA Mars Crew Transfer Vehicle

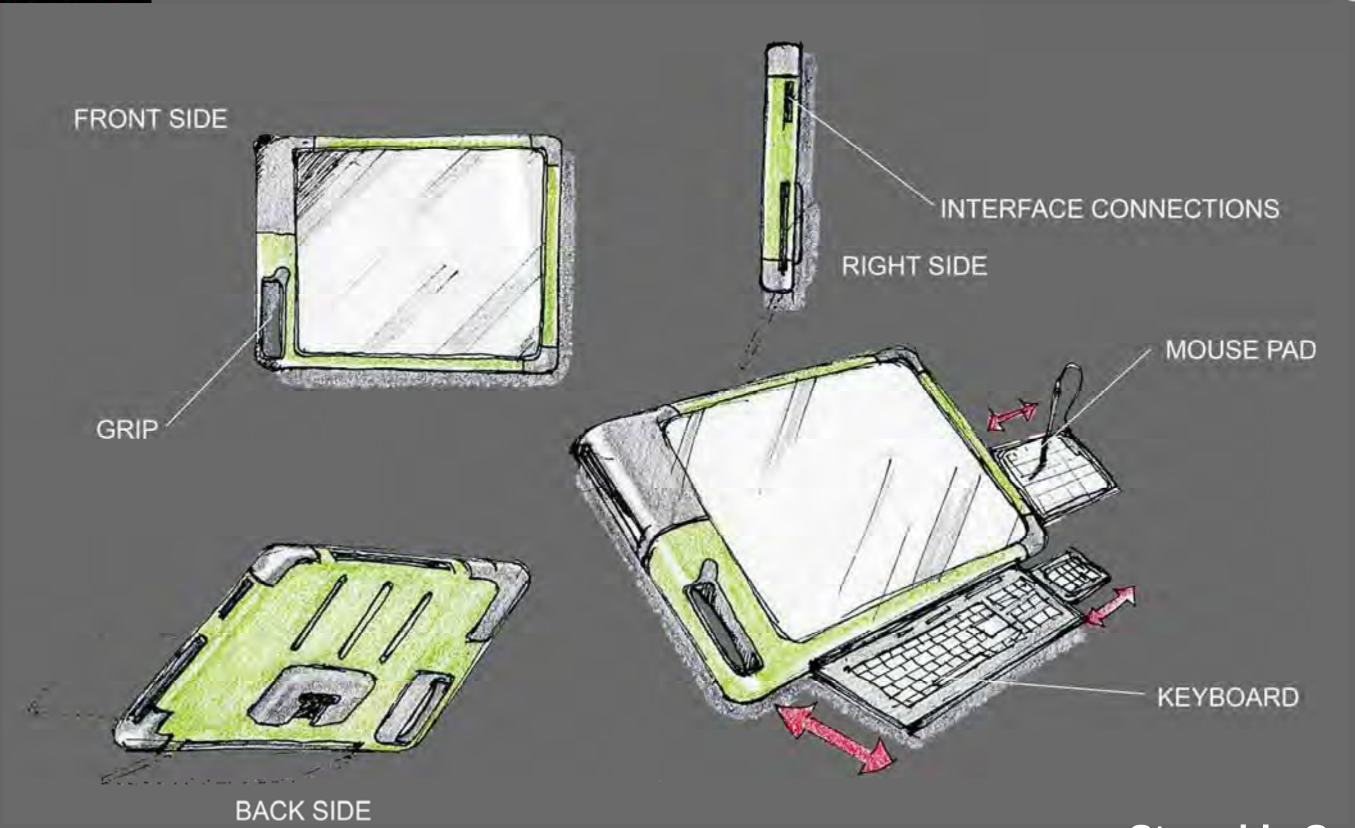
Design & Layout Examples

Diverse needs exist for innovative solutions to provide lightweight, compact/stowable crew support amenities for space habitat applications :

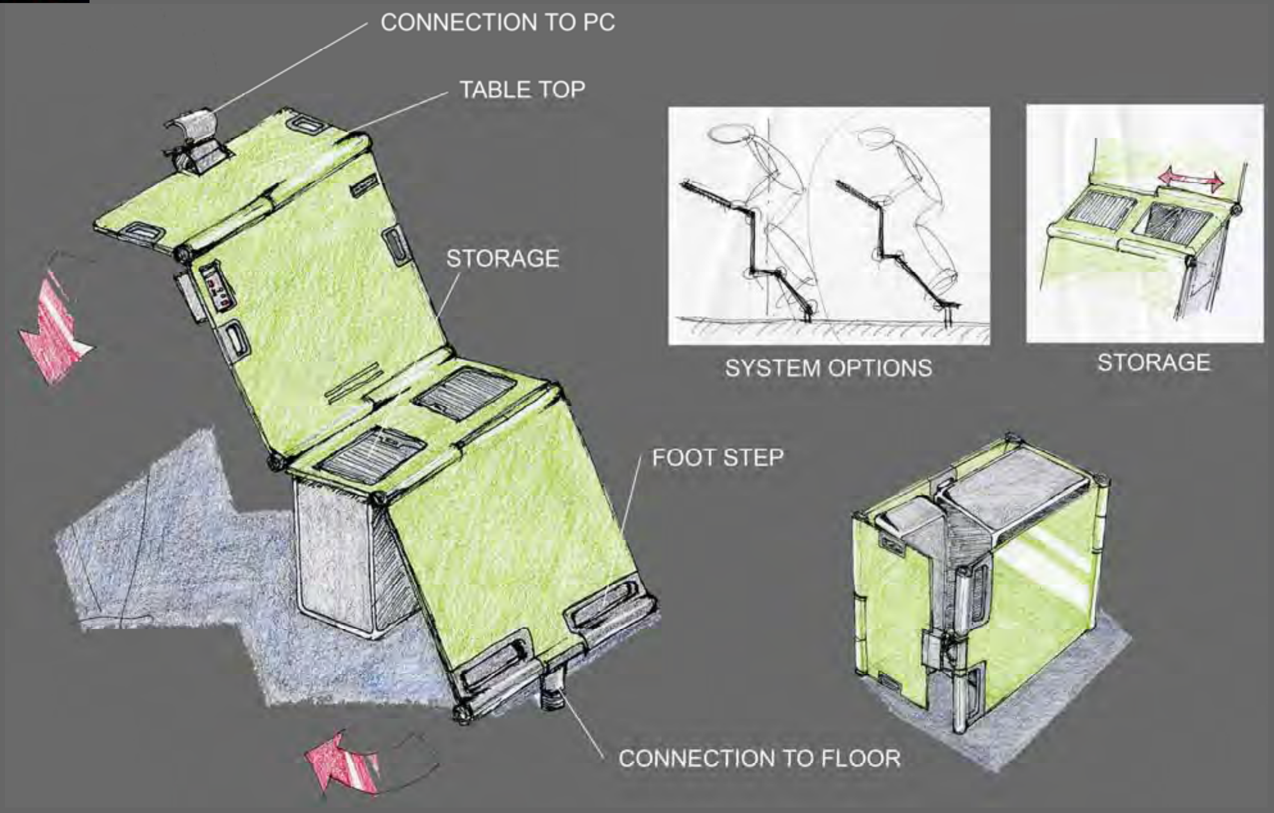
- Representative opportunities include :
  - Means to secure food trays, computers and other items under weightless and partial-g conditions without heavy/fixed tables.
  - Use of fabric/foldable partitioning systems and privacy screens to separate functional areas and traffic corridors.
  - Soft/ foldable containment systems for personal and general stowage.
  - Open shelving systems that reduce rack mass, yet provide means to secure equipment in place to resist launch and aerobraking/ surface landing loads.
  - Portable plug-in restraint/ mobility devices and lighting/ ventilation units.



Interior Outfitting Examples



Stowable Concepts

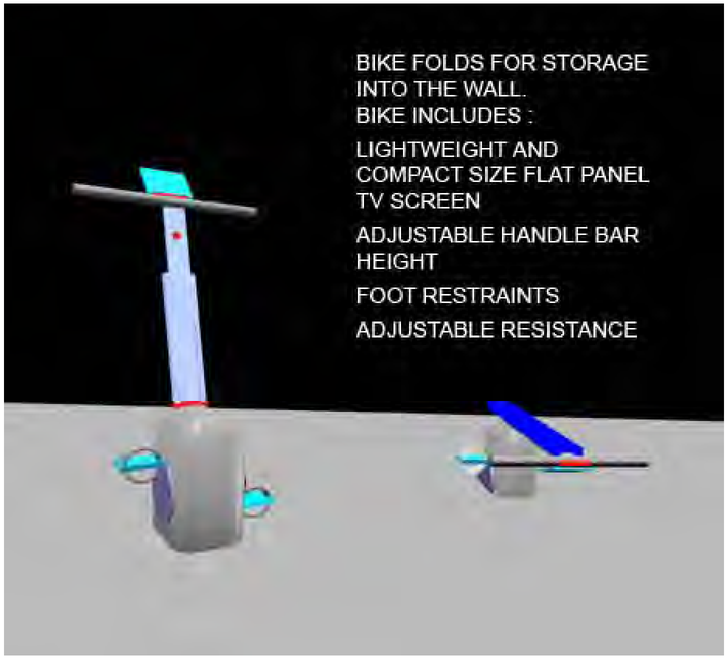


Stowable Concepts

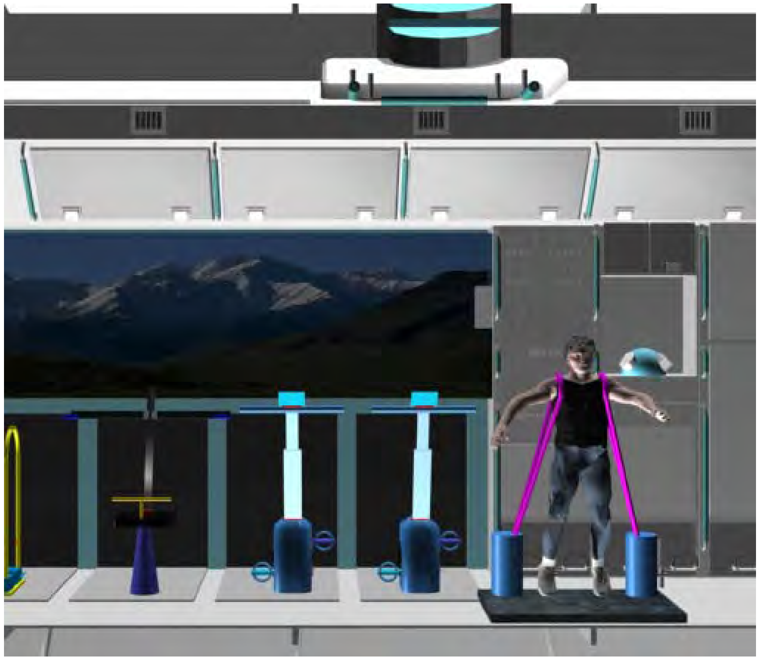
Stowable Concepts

INTERIOR ARCHITECTURES AND ELEMENTS

PLANNING AND DESIGN



Stowable Exercycle



Exercise Area and Equipment

Stowable Concepts

More detailed information about many topics discussed in this section, along with reference and additional information sources, is offered in Part I and Part II of this lecture series. Additional information regarding these and other SICSA projects can be obtained on www.sicsa.uh.edu

BACK TO THE LIST OF CONTENTS

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

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

ACRONYMS

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

ACRONYMS

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

ACRONYMS

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