

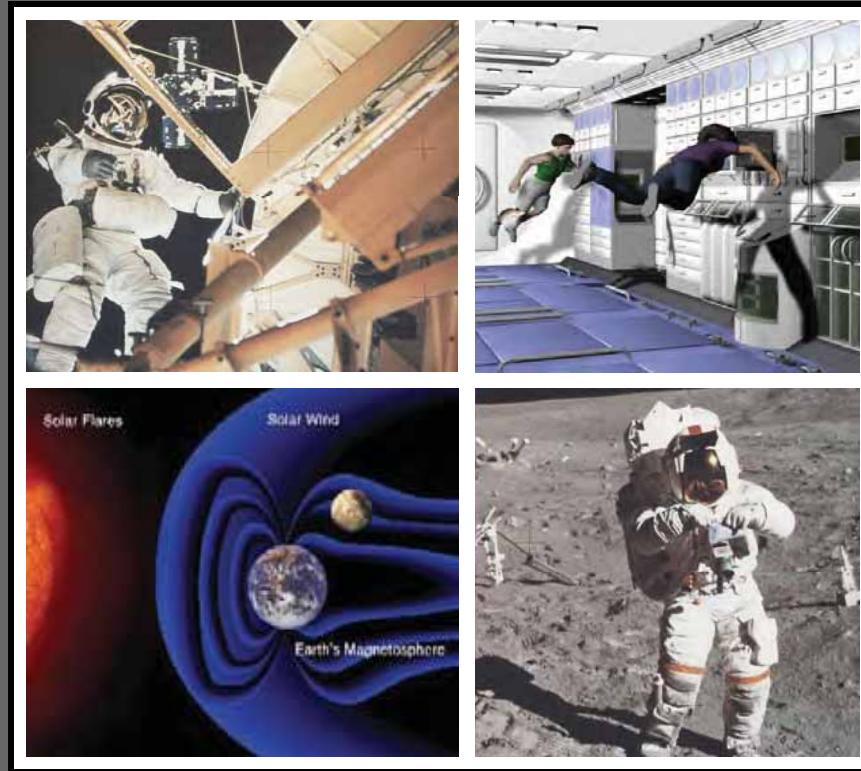


## SICSA SPACE ARCHITECTURE SEMINAR LECTURE SERIES

# PART II : HUMAN ADAPTATION AND SAFETY IN SPACE

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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](http://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 second 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.

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## HUMAN ADAPTATION AND SAFETY IN SPACE

## PREFACE



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

**GROUP ONE:**

- Part I : Space Structures and Support Systems
- Part II : Human Adaptation and Safety in Space
- Part III : Space Transportation, Propulsion and Pathways
- Part IV : Space Mission and Facility Architectures

**GROUP TWO:**

- Part V : The History of Space Architecture
- Part VI : The Nature of Space Environments
- Part VII : Natural and Artificial Life Support
- Part VIII : Habitats in Extreme Environments

**The SICSA Seminar Lecture Series**

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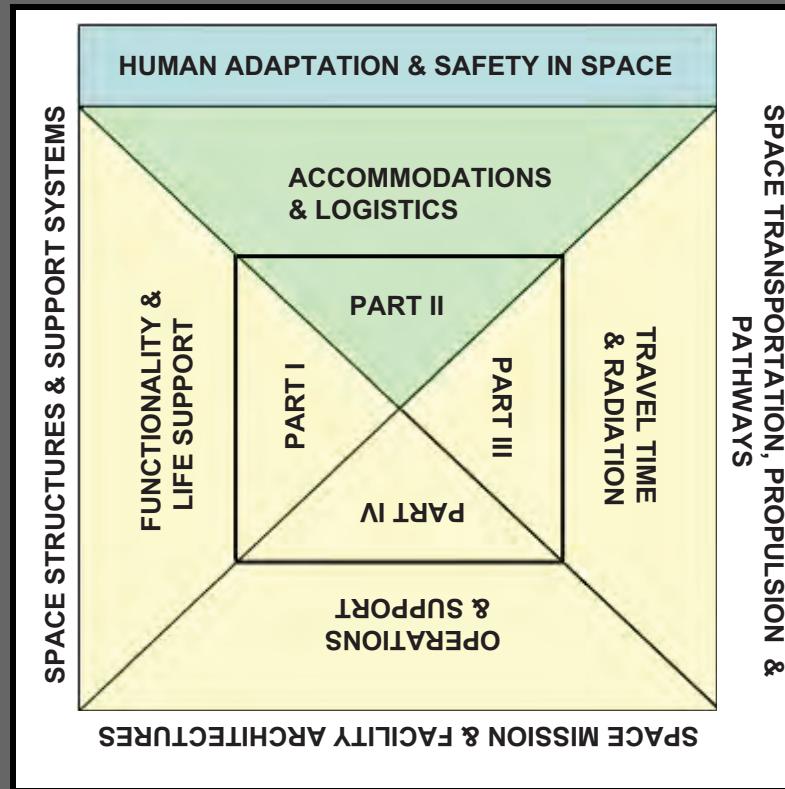
**HUMAN ADAPTATION AND SAFETY IN SPACE**

**PREFACE**



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

- Part II (this report) discusses human adaptation and safety influences and requirements that are governed by special mission and environment conditions which relate to topics that are elaborated more in the other three parts :
  - Habitat accommodations and logistics support determined by crew size and activities must be correlated with functionality and life support requirements/ constraints imposed by Space Structures and Support Systems (Part I).
  - Crew accommodations and logistics as well as safety will be directly impacted by travel time and radiation exposures related Space Transportation, Propulsion and Pathways (Part III).
  - All human facility and operations will be driven by planning for Space Mission and facility Architectures (Part IV).



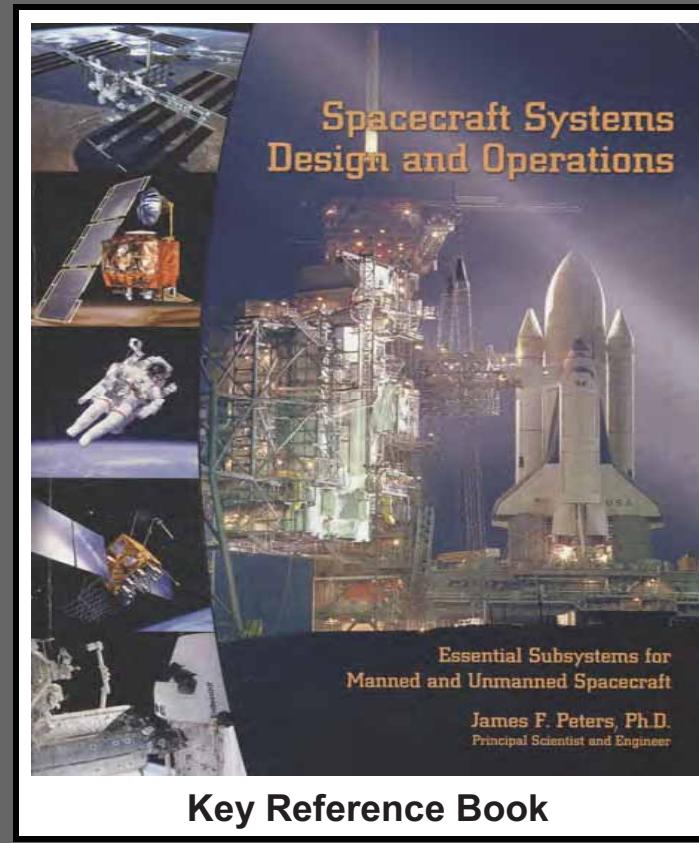
### Key Relationships to Other Lectures

## SICSA SEMINAR SERIES

## PART II EMPHASES



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**

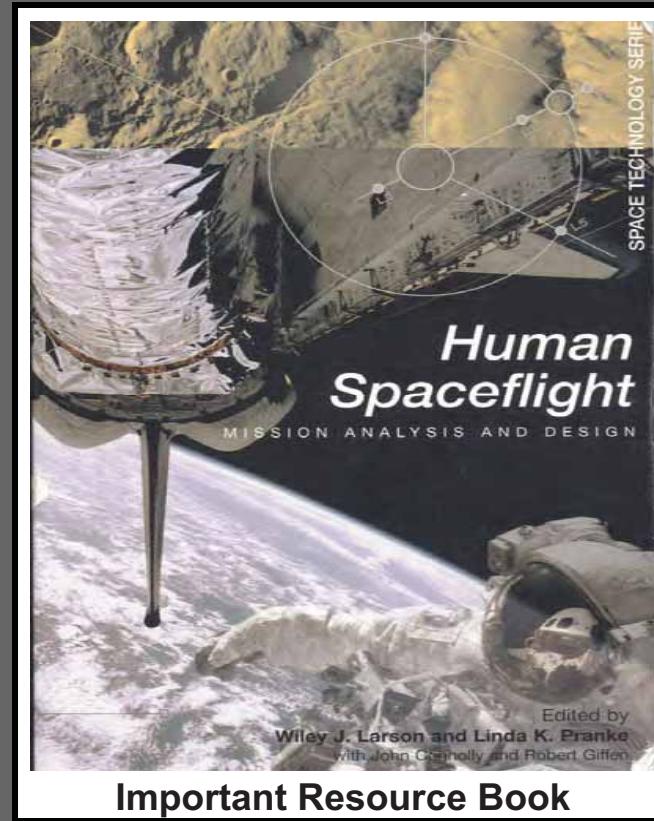
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## HUMAN ADAPTATION AND SAFETY IN SPACE

## SPECIAL CREDITS



"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.

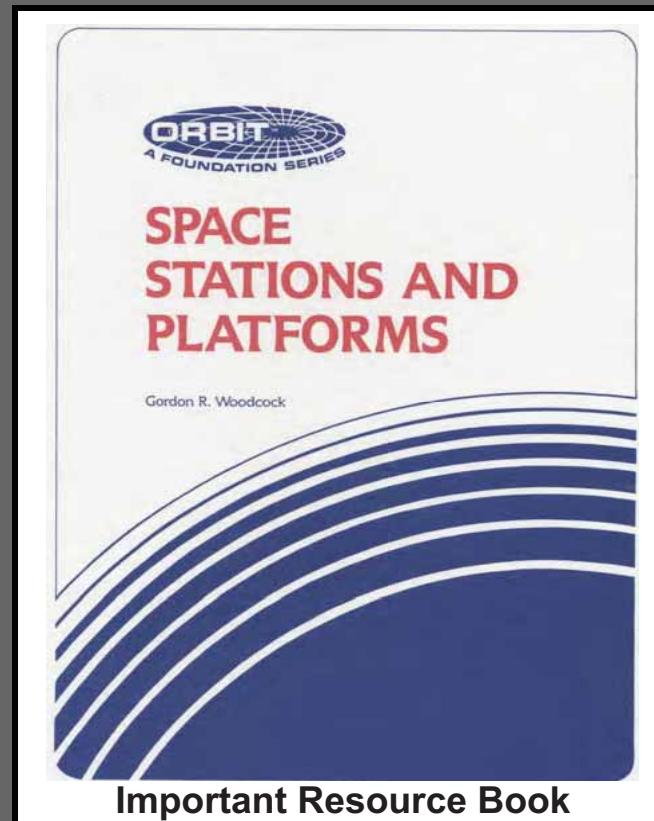


## HUMAN ADAPTATION AND SAFETY IN SPACE

## SPECIAL CREDITS



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



**Important Resource Book**

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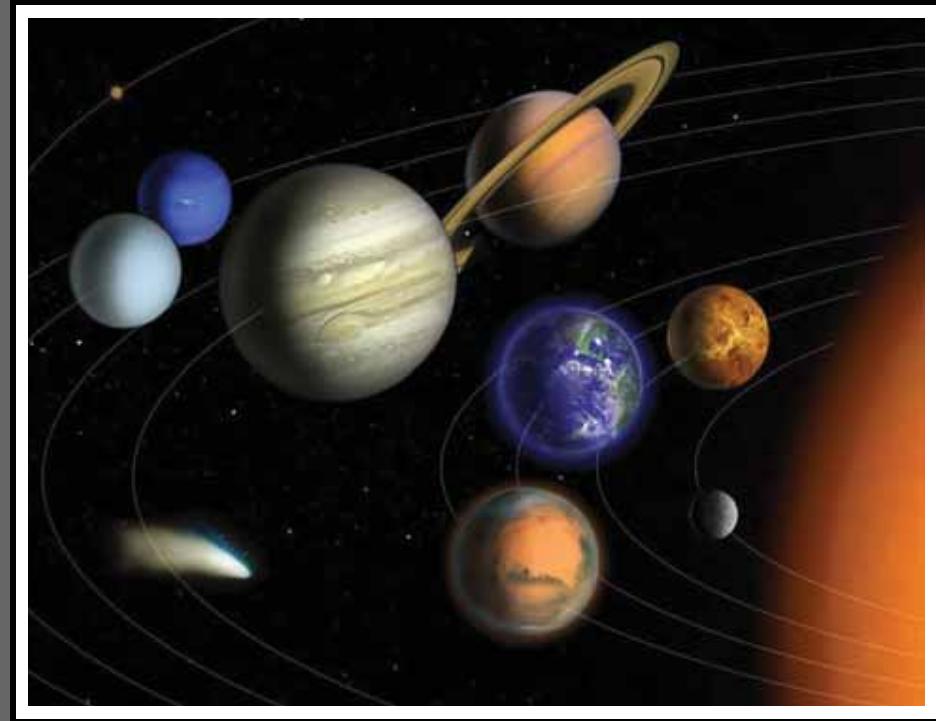
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## SECTION A: BACKGROUND

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Extreme environments on Earth and in space test human abilities to adapt, survive and undertake difficult/ dangerous tasks:

- Hardships include:
  - Harsh climate conditions.
  - Remoteness with restricted access/ return capabilities.
  - Limitations on available equipment/ support services.
  - Ever present life-threatening safety risks.
- Space is very different in many respects from human terrestrial environments:
  - Total dependence on artificial systems.
  - Altered gravity conditions that affect most activities.
  - Extreme radiation, temperature and operational conditions.
  - Stresses related to isolation and confinement.
- To accomplish proper planning we must understand characteristics of space environments:
  - Reduced gravity levels and their implications.
  - Radiation hazards and health risks.
  - The space radiation environment.
  - The micrometeoroid/ space debris environment.
  - Special lunar/ Mars environment considerations.

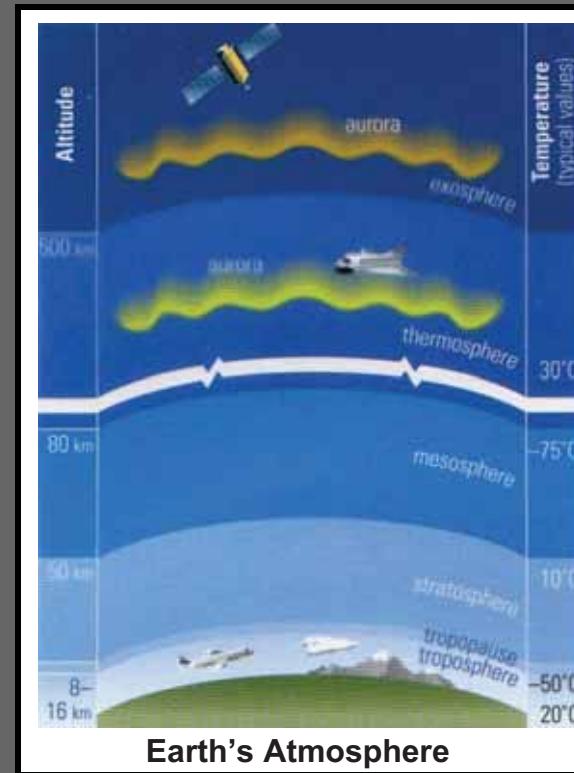


## BACKGROUND

## THE NATURE OF SPACE

The transition to near-Earth orbital space:

- Earth's atmosphere is acted upon by 2 principle forces:  
 -Gravity that holds the gaseous envelope in place.  
 -Solar thermal radiation that causes atmospheric gases to expand into surrounding volumes.
- Since these forces remain in relatively constant balance, the atmosphere maintains a distinct vertical density/ pressure profile:  
 -In the outer border of atmosphere ("near-Earth space" – about 700 km above the Earth), collisions between air molecules are very rare.  
 -Above this level (the exosphere), free moving air molecules thin out to "true space". (In some zones the density of gas particles is still as high as 1-10 particles per cu. centimeter.)
- The transition zone from Earth's atmosphere into space has 2 points of special interest to spacecraft designers:  
 -At the "von Karman line" (about 80 km), aircraft control surfaces don't function and reaction jets are needed.  
 -At 180-200 km, resistance to air becomes insignificant (represents a mechanical border between the atmosphere and space).
- Inertial and relational forces acting on astronauts enroute to/ from space have important adaptation and design implications:  
 -Acceleration/ deceleration forces cause physiological changes effecting operations and vision.  
 -Weightlessness occurs when the Earth's gravity is exactly counterbalanced by the centripetal force acting on the spacecraft.



## BACKGROUND

## THE NATURE OF SPACE

As curious creatures, it is our human nature to explore:

- Sometimes exploration is necessary for survival:
  - To seek new places for hunting.
  - Seasonal migrations to find food and shelter when weather changes.
  - Escapes from natural disasters (e.g. floods) and conflicts (wars).
- Sometimes exploration is for new opportunities:
  - For new resources and commercial trade (Columbus's voyage to America).
  - For a better place to live (settlement of the US western territories).
- Sometimes exploration is for adventure:
  - Climbing a mountain "because it is there".
  - Achieving what has never been done before.
- And sometimes it is done to understand the universe and our place in it:
  - Sending people beyond previous limits.
  - Opening our minds beyond previous limits.



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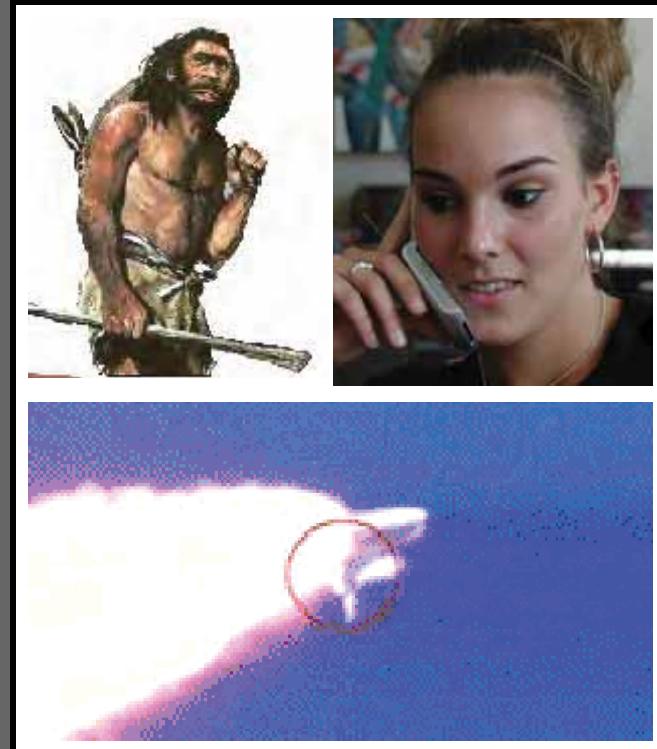
## BACKGROUND

## WHY GO TO SPACE?



Without exploration humans would still live in caves and trees:

- Exploration forces and teaches us to adapt.
  - To obtain food and shelter.
  - To adjust to new environments that are different.
  - To form new communities and societies.
  - To be versatile and resourceful.
- Sometimes exploration leads to tragedies:
  - Challenging “the unknown” can be dangerous.
  - We don’t always find what we expect and are sometimes unprepared for the results.
- But often, the results bring great benefits:
  - Better understanding of our world .
  - New ways of doing things.
  - New technologies for everyday life.
  - Evolution in our intellectual and cultural development.
  - Knowledge about human capabilities.



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## BACKGROUND

## WHY GO TO SPACE?

Humans first went to space only with their eyes and imaginations:

- In 1610 ,the invention of the astronomical telescope changed humankinds understanding of the universe:  
-Galileo Galilei, the great Italian mathematician and astronomer was among the first to use it.
- On October 4, 1957 (more than 300 years later) another ancient device (the rocket) was paired with a new device (the spacecraft):  
-The USSR's Sputnik escaped the Earth's atmosphere and initiated "the space age".
- Scientific exploration since that time is providing important information about the early history of our Earth, and perhaps also about its future:  
-Why did Earth evolve differently than Venus which had similar characteristics in the beginning?  
-Was there ever life on Mars (and is there still)?  
-Can life on Earth survive the predicted "greenhouse effect" of global warming (and how can we prevent it)?



## BACKGROUND

## WHY GO TO SPACE?

When John Glenn made the 1st US orbital space flight on February 20, 1962, scientists questioned the ability of humans to survive in space:

- One of his mission objectives was to eat lunch in space to determine:
  - Would the food go down in weightlessness?
  - Would it digest properly?
- The 1st astronauts returning from the Moon were quarantined in an air-tight mobile home to see if they had brought back foreign bacteria:
  - If so, would the bacteria grow?
  - Would this be an uncontrollable, incurable growth?
- Since then we have learned much about the abilities of humans to live and work in space:
  - People can function well in weightlessness.
  - People can eat and digest food naturally.
  - No alien bacteria have been encountered.
  - People can work in a productive and versatile manner.



**John Glenn**



**First Astronauts in Isolation Room**

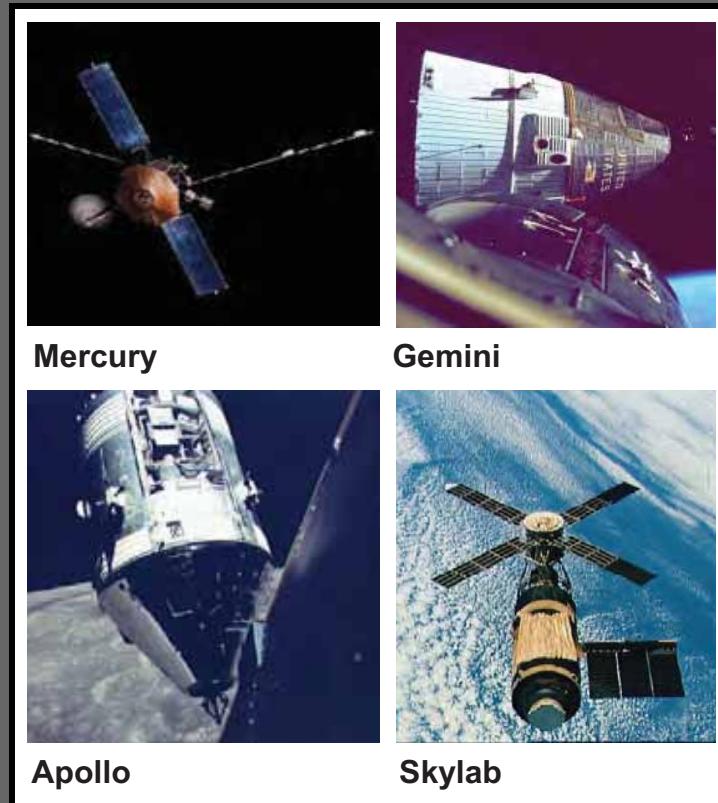
## BACKGROUND

## LIVING IN SPACE



The capability for space habitation has been a key NASA objective since the beginning of the agency:

- 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).



## BACKGROUND

## LIVING IN SPACE



Orbiting space stations have been a long-term NASA priority:

- Shortly after Mercury program started (1958), considerations for a small “manned” laboratory began:
  - During Mercury (1958-63) an orbiting laboratory and lunar mission were leading options for the future.
  - President Kennedy committed the US to a lunar landing as the national goal for the 1960s.
  - A space laboratory continued to be studied as a secondary objective, but never got beyond preliminary planning.
  - While Skylab was underway, new space station concepts continued to be studied, ranging from 6-24 people.
- Following Skylab, the US lagged behind the Soviet Union in orbital space experience:
  - Soviet stations have supported prime crews of 2 or 3 cosmonauts on much longer missions.
  - Salyut 6 stayed aloft 4 years and 10 months, hosting 30 cosmonauts (receiving 33 flights of manned and unmanned supply ships).
  - The Mir space station has been occupied for as long as one year (Vladimir Titov and Musa Manarov).



Salyut-7



Mir

Russian Space Stations

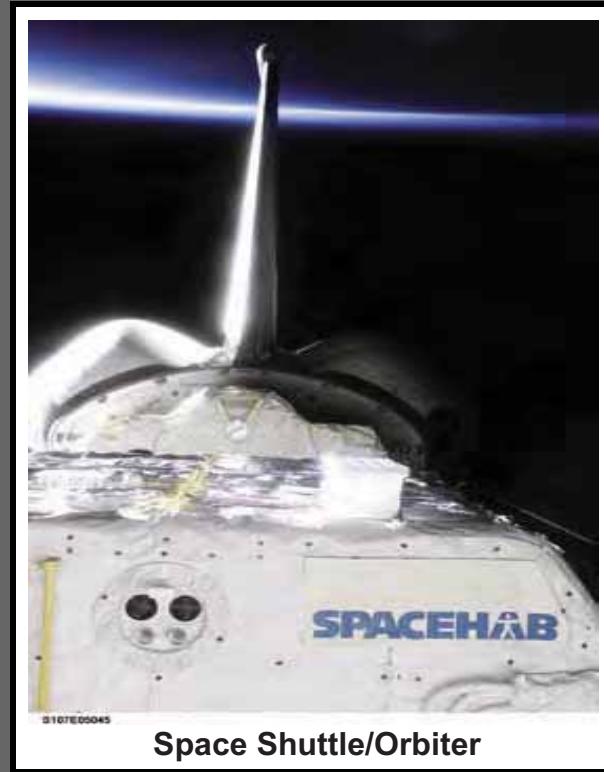
## BACKGROUND

## LIVING IN SPACE



Associated with US space station planning was a “Logistics Vehicle” (which became the Space Shuttle) and a design team headed by Max Faget originated the vehicle concept:

- The Space Station Orbiter is a small, short-term laboratory supporting missions of one week or less:
  - Two cabin levels provide a total of 2,525 cu. ft. (about 10 times as much as Apollo Command Modules).
  - The Orbiter sometimes carries a European Space Laboratory in the cargo bay to provide additional habitable volume for life science and other experiments.
  - It also sometimes carries a “SpaceHab” module for microgravity space processing and other experiments.
  - Since missions are short, crews are willing to accept cramped quarters with little privacy.
- Since the early 1980's, NASA has led an effort involving Russian, European, Japanese and Canadian partners to create an International Space Station (ISS):
  - The ISS supports microgravity and life sciences.
  - Originally planned crew accommodations have been scaled back due to Space Shuttle and budget problems.



**Space Shuttle/Orbiter**

## BACKGROUND

## LIVING IN SPACE

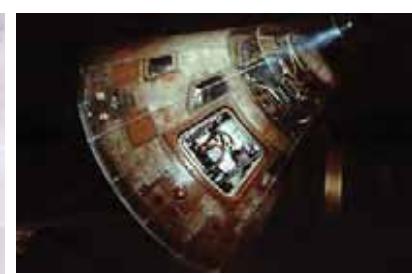


Aboard future space outposts there will be new ways of living, working, and perhaps even thinking.

- 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

## BACKGROUND

## LIVING IN SPACE



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.



## BACKGROUND

## THE HUMAN FACTOR



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

## BACKGROUND

## THE HUMAN FACTOR



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: <ul style="list-style-type: none"><li>• Influences of weightlessness on design/ adaptation.</li><li>• Artificial-g design options/ considerations.</li><li>• Partial-g lunar/ planetary surface environments.</li></ul>	Psycho-Social Factors: <ul style="list-style-type: none"><li>• Mission influences on crew support requirements.</li><li>• Isolation/ confinement issues.</li><li>• Operational factors influencing morale.</li></ul>
Habitat Volume/ Configuration: <ul style="list-style-type: none"><li>• Launch vehicle &amp; landing constraints.</li><li>• Fixed and expandable module options.</li><li>• Accommodations for evolutionary growth.</li></ul>	Functional Areas/ Accommodations: <ul style="list-style-type: none"><li>• Crew support facilities/ systems.</li><li>• Work stations &amp; support equipment.</li><li>• Flight mission operations &amp; maintenance support.</li></ul>
Space Radiation Hazards: <ul style="list-style-type: none"><li>• Primary sources &amp; characteristics.</li><li>• Allowable crew dose exposures.</li><li>• Shielding options/ requirements.</li></ul>	Extra-Vehicular Activities: <ul style="list-style-type: none"><li>• Mission-driven EVA requirements.</li><li>• EVA airlocks, suits &amp; equipment devices.</li><li>• Telerobotic support systems/ operations.</li></ul>

### General Organization of Lecture Topics

## BACKGROUND

## THE HUMAN FACTOR



Additional information relevant to this section can be found in Part I, sections A,B,C and E and Part III, Section A of this SICSA Space Architecture Seminar Lecture Series, along with other publications listed below :

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## BACKGROUND

## REFERENCES AND OTHER SOURCES



B-1

## SECTION B: INFLUENCES OF WEIGHTLESSNESS ON DESIGN AND ADAPTATION

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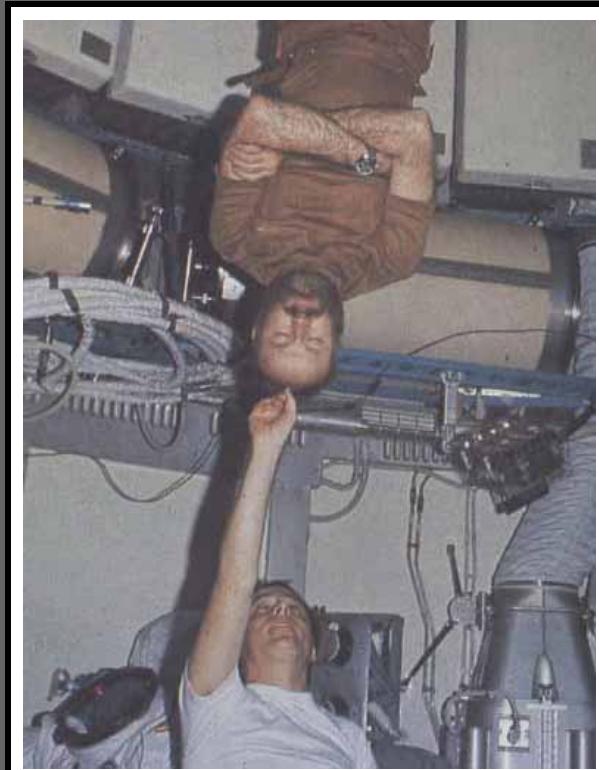




Weightless conditions in space have many important influences on habitat design and operations:

- 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



Operational Influences

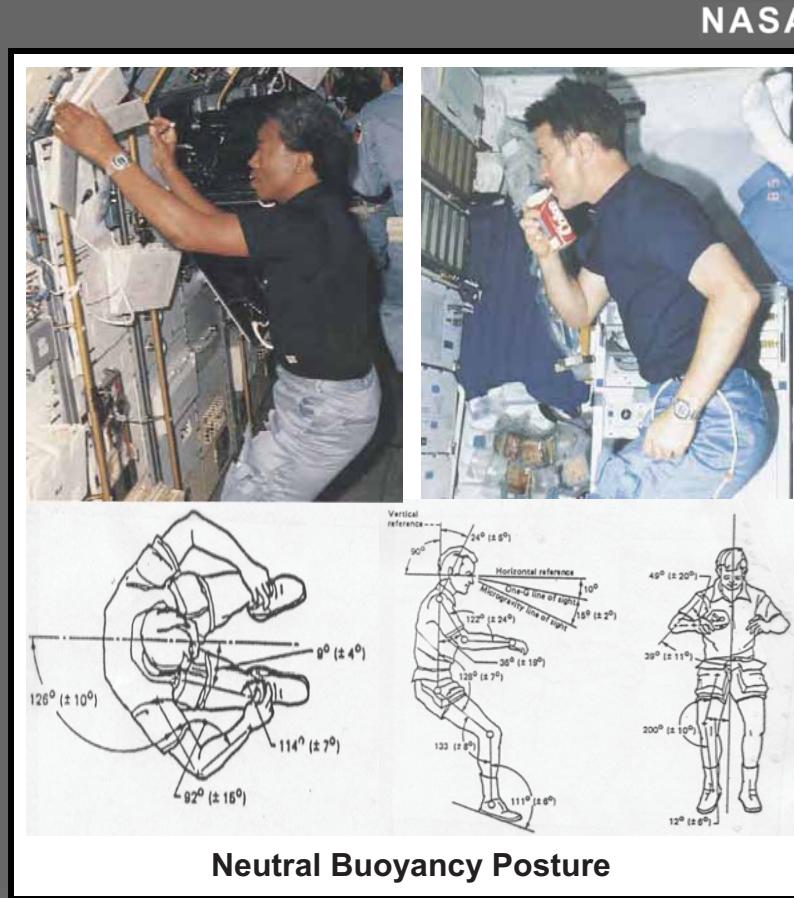
## WEIGHTLESS CONDITIONS

## DESIGN CONSIDERATIONS



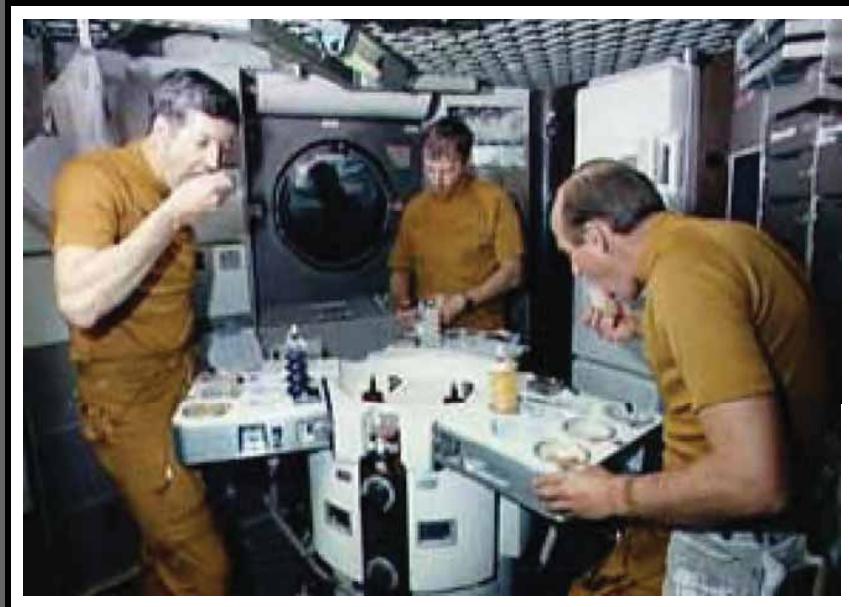
Body posture is altered significantly under weightless conditions:

- 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).



## WEIGHTLESS CONDITIONS

## DESIGN CONSIDERATIONS



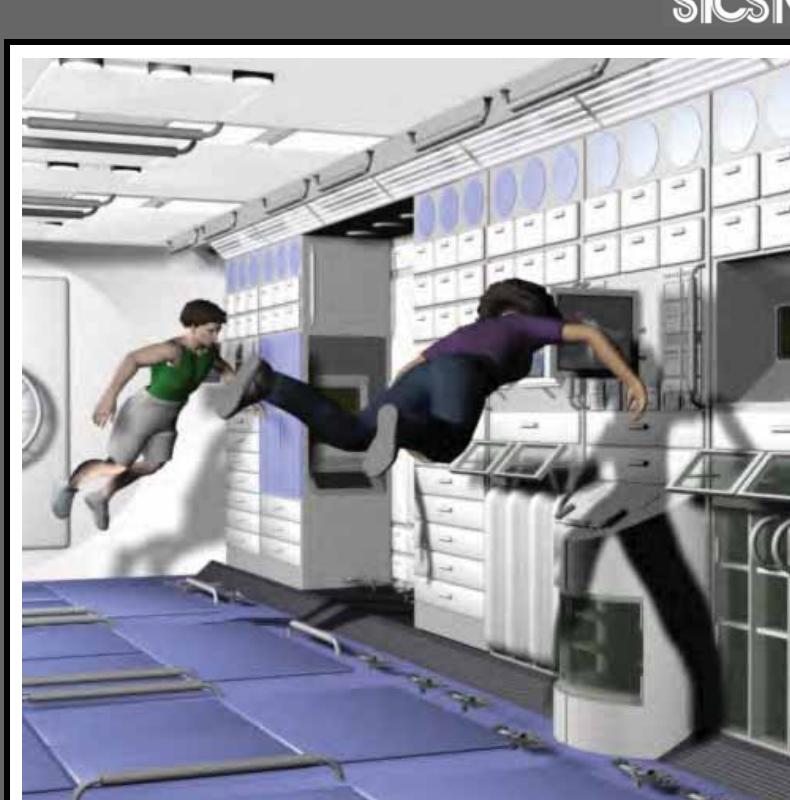
## WEIGHTLESS CONDITIONS

Neutral Buoyancy Posture

## DESIGN CONSIDERATIONS

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 CONDITIONS

## DESIGN CONSIDERATIONS

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.

NASA



Meal Time Mixed with play in Space



Health Maintenance in Space

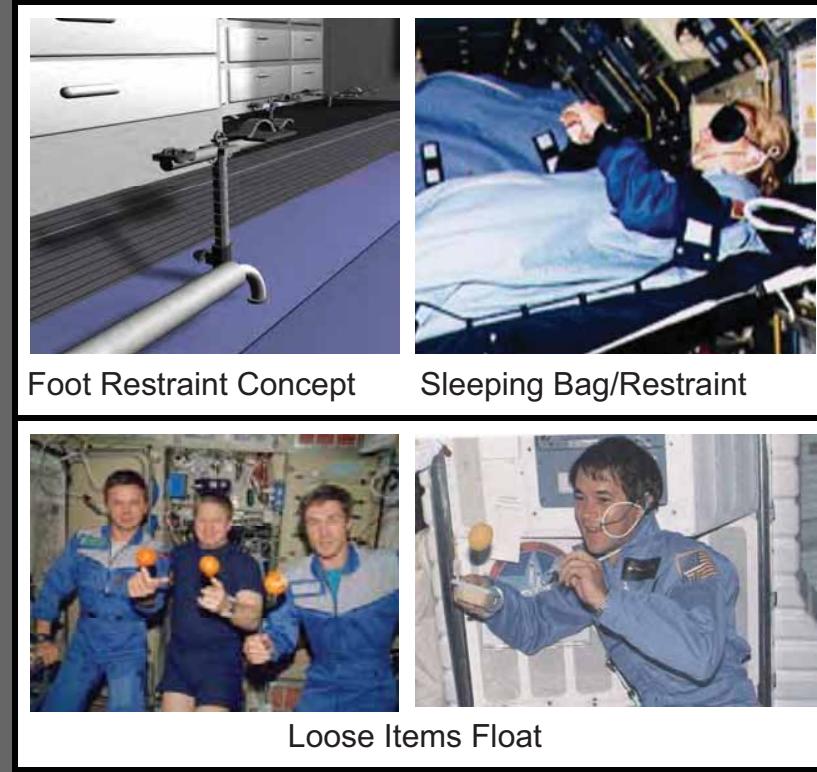
## Crew Adaptation and Safety

### WEIGHTLESS CONDITIONS

### DESIGN CONSIDERATIONS

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.



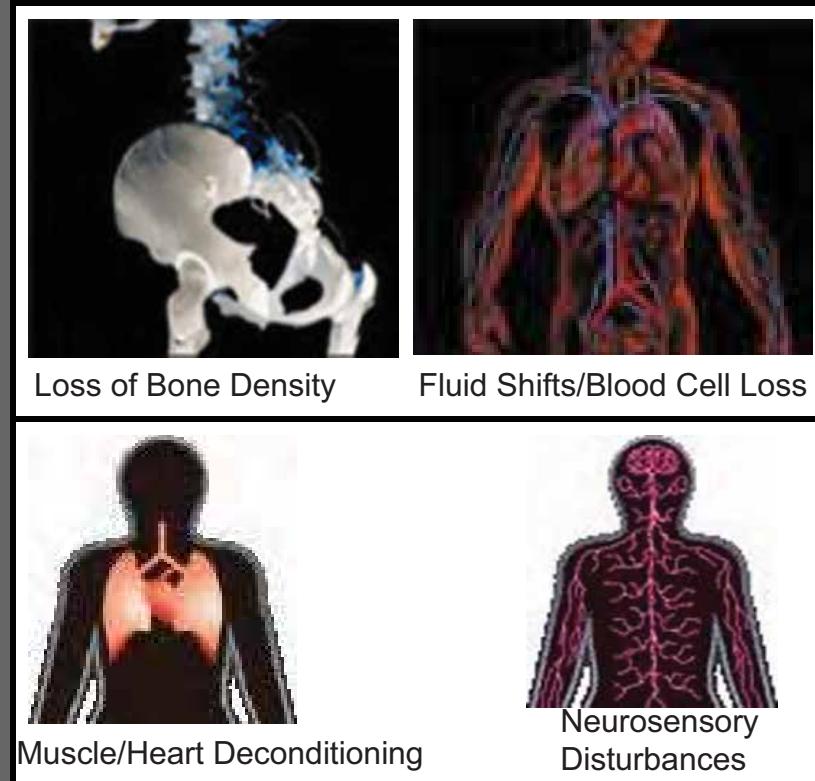
## Restraint Systems

## WEIGHTLESS CONDITIONS

## DESIGN CONSIDERATIONS

Long-term exposure to weightless conditions have important effects on the human body:

- Calcium loss from bones:  
 -Continues to occur throughout the flight.  
 -Bones can't repair themselves as they do in normal gravity, and become brittle.
- Muscular/ cardiovascular deconditioning:  
 -Reduced effort leads to loss of muscle mass and atrophy.  
 -Effects are influenced by flight length and the amount of exercise activity.
- Fluid shifts and blood loss:  
 -Body fluids move upward into chest and head areas causing bloating.  
 -The total quantity of fluids (including blood) is reduced, causing dehydration .
- Space adaptation (sickness) syndrome:  
 -Nausea can occur during first hours/ days (partly due to otolith canals in inner ears).  
 -Affects about half of all people who go to space.



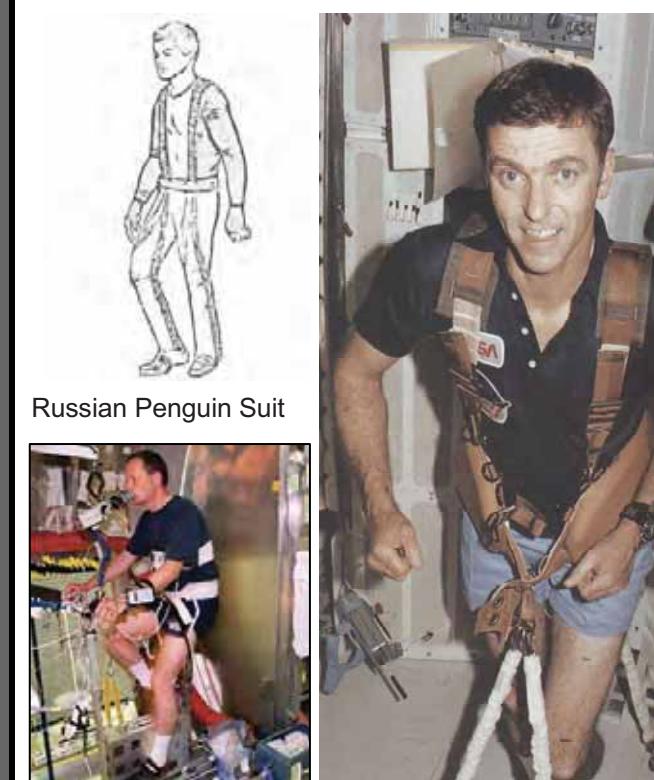
**Physiological Influences**

## WEIGHTLESS CONDITIONS

## DESIGN CONSIDERATIONS

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 ergometers 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

## Importance of Exercise

## WEIGHTLESS CONDITIONS

## DESIGN CONSIDERATIONS



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 otolith 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

## WEIGHTLESS CONDITIONS

## DESIGN CONSIDERATIONS



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 Requirements

### WEIGHTLESS CONDITIONS

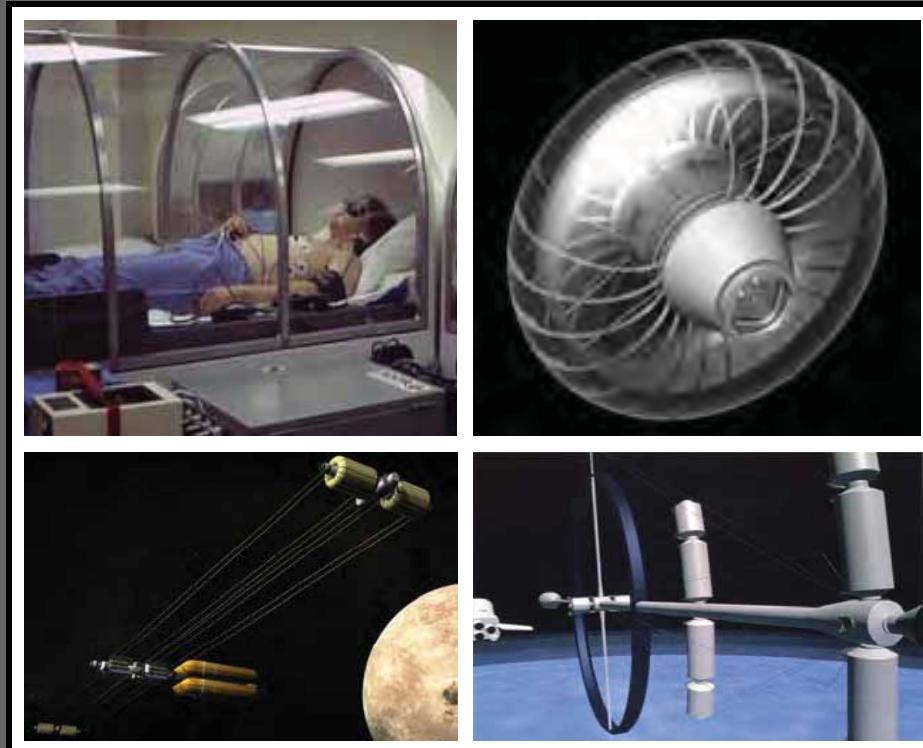
### DESIGN CONSIDERATIONS



C-1

## SECTION C: ARTIFICIAL-G SPACECRAFT CONCEPTS & CONSIDERATIONS

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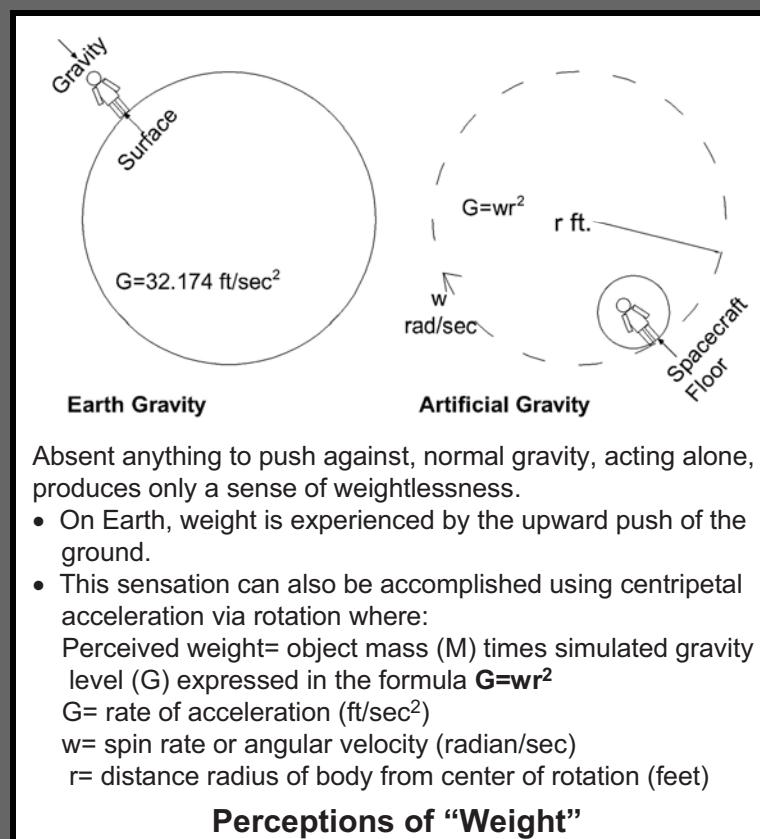


Artificial gravity (AG) space vehicles and centrifuge devices are often proposed as countermeasures against detrimental health and performance effects of prolonged weightlessness during missions to Mars and back, including:

- Loss of bone mineral density and associated increases of renal stone risk.
- Muscle atrophy.
- Cardiovascular deconditioning including fluid shifts and blood cell losses.
- Sensory/ neurovestibular alterations including balance and perceptual illusions.

A-g might also provide other benefits:

- Reducing levels of particulate matter suspended in the atmosphere (including microbial and toxic).
- Ergonomic advantages such as materials handling, surgery and excretory functions.



## ARTIFICIAL-G CONSIDERATIONS

## KEY ISSUES AND QUESTIONS



Life under A-g conditions will be different than often depicted in science fiction movies and publications.

- Illustrations show travelers passing between A-g and weightlessness unaffected by Coriolis forces or A-g induced illness responses.
- Rotating vehicles often have short radii which would be unacceptable for human comfort, adaptation and performance.
- Long connecting tunnels between central hubs and A-g areas do not consider gravity gradients or the massive pressurized structures that would have to be constructed.
- Disorientations and dizziness caused by cross-coupled angular accelerations aren't in evidence.



A-g Conditions Depicted in Movies

## ARTIFICIAL-G CONSIDERATIONS

## KEY ISSUES AND QUESTIONS

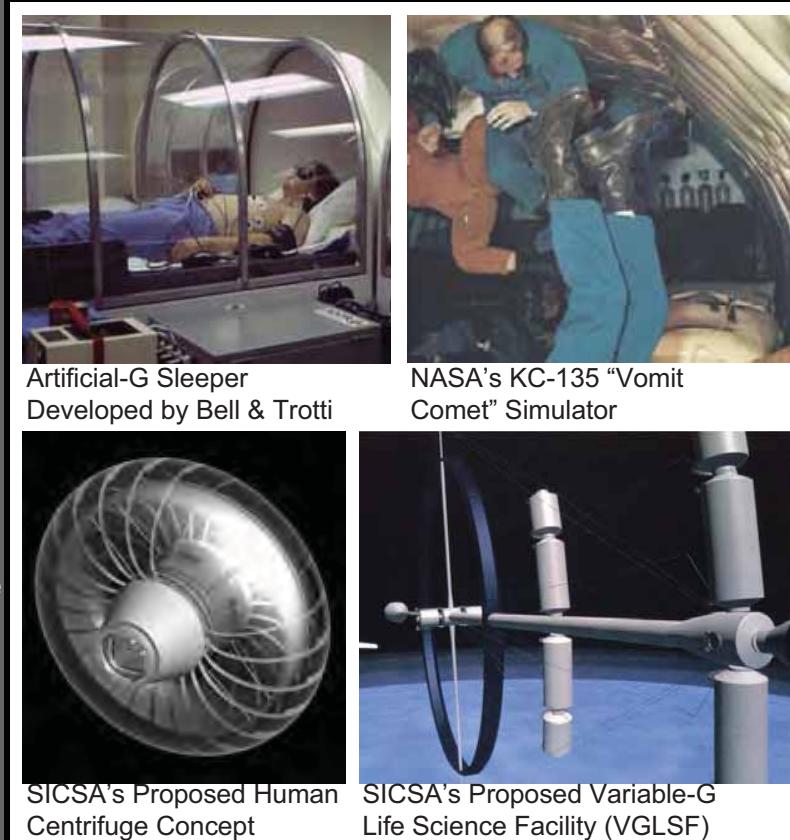


Our current understanding of A-g affects upon crew health, adaptation and performance is based upon problematic and incomplete Earth studies:

- Human centrifuge experiments are limited by inabilities to cancel out effects of Earth gravity and restrictions upon the range of simulated tasks that can be conducted .
- Flight experiences using aircraft on parabolic maneuvers are very brief .
- Future space A-g experiments might be conducted using a separate human centrifuge module attached to the ISS.
- Development of rotating research spacecraft is possible, but will be very costly due to complex technical and construction requirements.



BELL & TROTTI, INC



Artificial Gravity Experiments

## ARTIFICIAL-G CONSIDERATIONS

## KEY ISSUES AND QUESTIONS



Most A-g research addresses human survivability and adaptation, not optimizing comfort and habitability:

- Fractional A-g levels necessary to support mental and physical health during long-duration exploration missions are unclear.
- The minimum-g threshold at which A-g induced sickness can be avoided is also uncertain.
- Abilities of people to adapt movements and activities to A-g conditions so that they become normal and routine is unproven.
- Possible nauseaogenic responses produced by transitions between weightlessness to A-g and back must be determined.

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

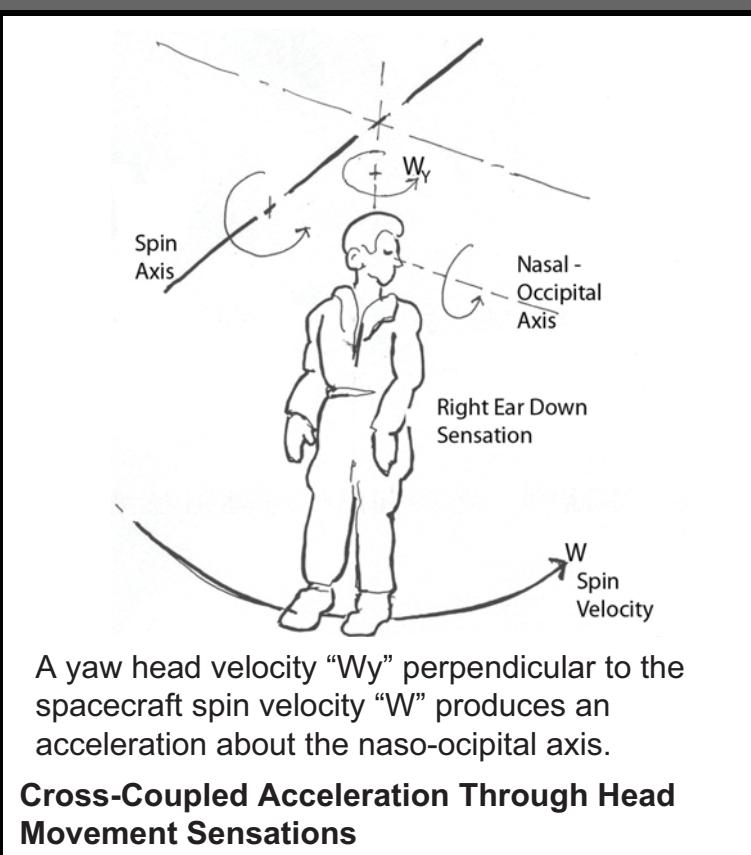
#### Unresolved Research Issues

## ARTIFICIAL-G CONSIDERATIONS

## KEY ISSUES AND QUESTIONS

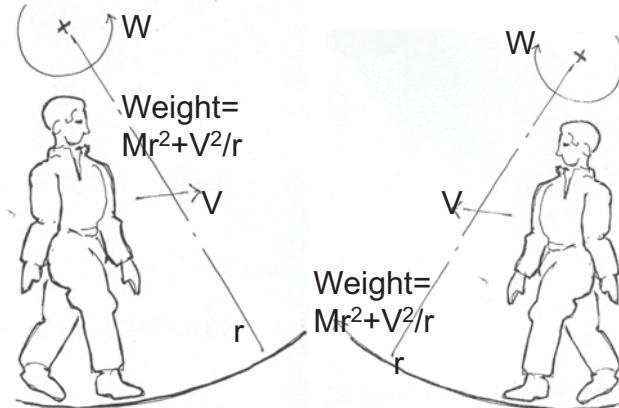
Despite experimental research limitations, some physiological consequences of rotational A-g are well documented through ground-based research:

- Head movements made out-of-plane with the rotation vector cause people to experience nauseogenic cross-coupled vestibular stimulation (an illusion of tumbling).
- The magnitude of nausea-producing effects depends upon which way a person is facing relative to the direction of the rotation.
- Coriolis forces deflect a person's limbs in a consistent/ predictable direction depending upon the rotation vector reference.
- Adaptation to these phenomena, particularly when people are moving and changing orientations, may require several days with sea sickness-like discomfort.
- Reentry back to normal-g will require a similar readjustment period.



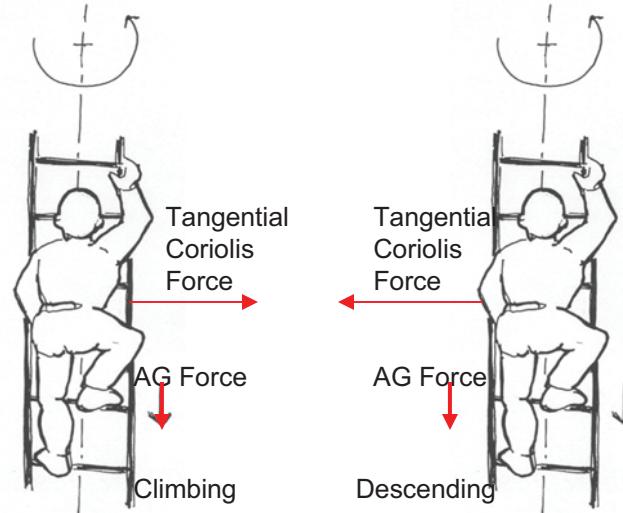
## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES



Walkers will be pushed towards or away from the center of rotation, depending upon the direction of locomotion. They will feel heavier moving in the spin vector due to their increased angular momentum.

### Radial Coriolis Forces

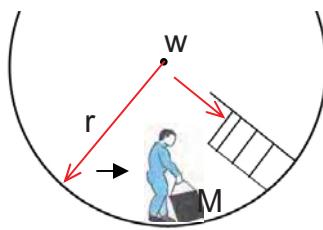


These forces push objects towards or away from the central hub perpendicular to the g force. This will push a climber or descender towards or away from a ladder, depending upon which way they are moving.

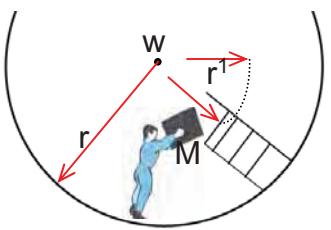
### Tangential Coriolis Forces

## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES



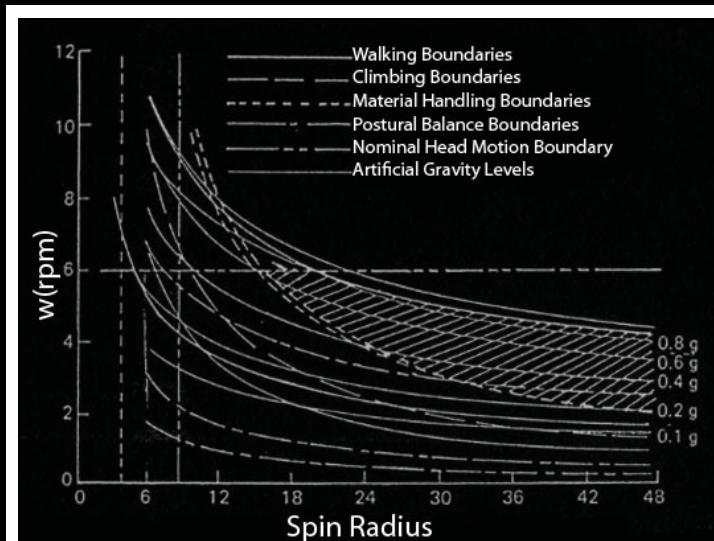
An object of Mass M "weighs"  $Mrw^2$  on the spacecraft surface



An object of Mass M "weighs"  $Mrw^2$  at radius  $r'$

People moving away from the center of rotation (near weightlessness) become heavier as their radii positions increase. They will experience a 50% gravity gradient at half-way points, and 100% at their destinations.

### Gravity Gradient Influences



While study projections vary, many researchers predict that most people can tolerate rotation rates up to 6 rpm, and will be comfortable up to 1 rpm.

### Projected Human Performance Boundaries

## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES

**Reference:**

*Emanuel Schnitzer/ Paul R. Hill, NASA Langley Research Centers 40 ft. Rotating Space Simulator (1962):*

A cable system supported test subjects, allowing them to walk around the simulator surface which rotated between .05-0.75 g and “climb” a ladder to a “higher” deck. A comfort zone was determined to be:

- Centripetal acceleration between 0.035-1 g, and angular velocity less than 4rpm.
- Rim speed (floor tangential velocity) greater than 20 ft./sec.

**Reference:**

*Robert Gilruth, Proceedings of a “Manned Laboratory in Space” symposium at the NASA Johnson Space Center (1968):*

Based upon results from the KC-135 parabolic flight aircraft simulations established A-g comfort levels:

- Centripetal acceleration between 0.3-0.9 g.
- Angular velocity less than 2 rpm for “optimal comfort” and 0.3 g for “mobility limit” since most locomotion and fluid transfer problems are overcome at that level.

**Projected Comfort and Performance Ranges****ARTIFICIAL-G CONSIDERATIONS****GOVERNING PRINCIPLES**

**Reference:**

Theodore Gordon/ Robert Gervais, *McDonnell Douglas Astronautics, Proceedings of the NASA JSC Symposium* (1968).

Their paper at the same meeting hosted by NASA JSC Director Robert Gilruth presented different comfort zone conclusions:

- Centripetal acceleration between 0.2-1 g.
- Rim speed greater than 24 ft/sec.
- Angular velocity less than 6 rpm.
- Head-to-foot (6 ft. person) gravity gradients less than 15% (implying a radius greater than 40 ft).
- A lower boundary of 0.2 g for locomotion friction with minimum rim speed of 24 ft/sec to avoid weight variations (20% faster than Schnitzer and Hill).

**Reference:**

Bryant Kramer, *NASA Headquarters, Proceedings of NASA "Conference on Applications of Tethers in Space"* (1983).

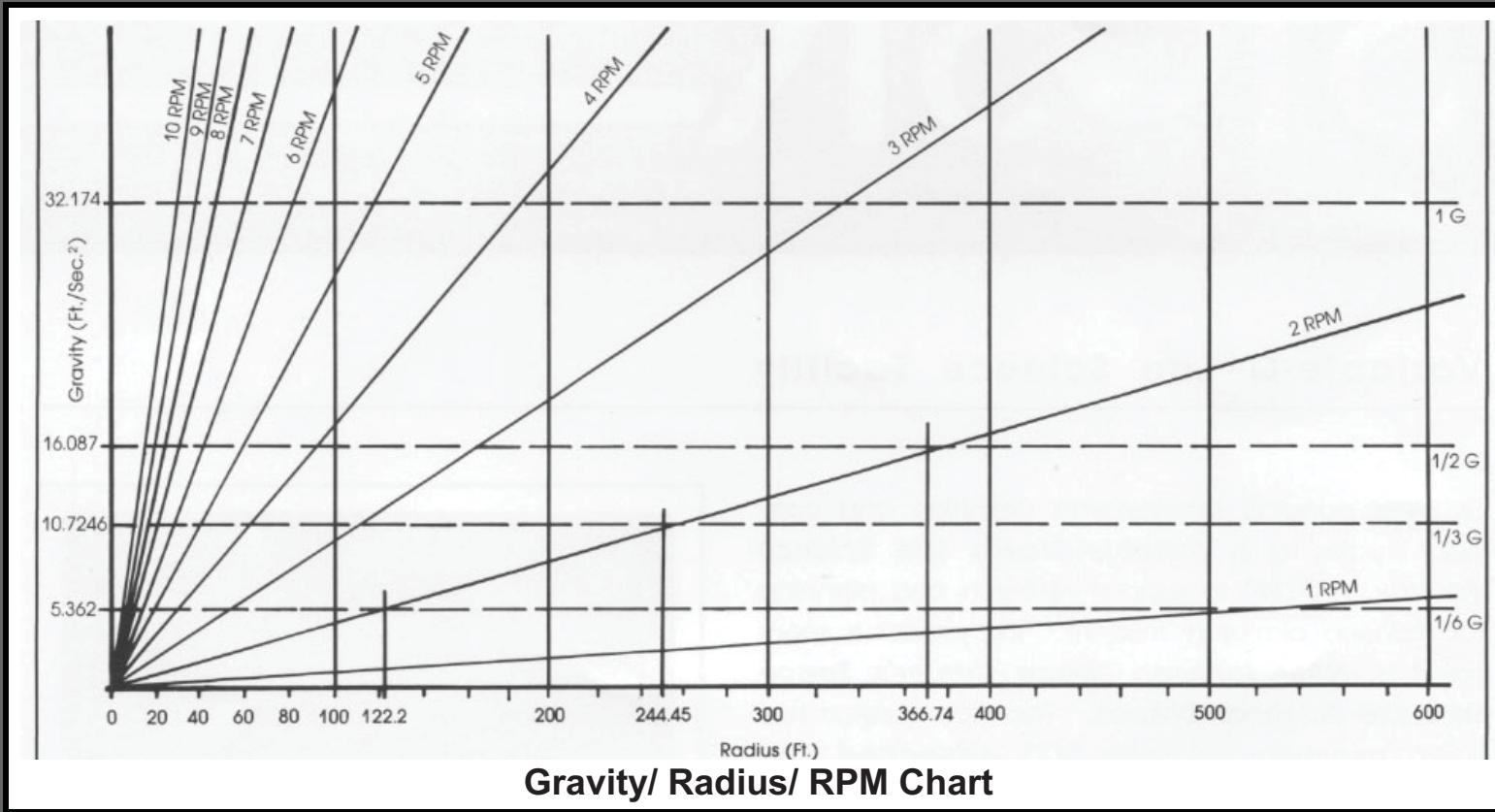
Kramer proposed the following criteria:

- Maximum centripetal acceleration of 1 g.
- Angular velocity less than 3 rpm to avoid motion sickness.
- Coriolis acceleration not to exceed 0.25 times centripetal acceleration for a velocity of 3 ft/sec in the radian direction.
- Gravity gradient should not exceed 0.01 g/ft in the radial direction (6% over 6 ft.).
- He indicated that a 100,000 lb cylindrical Kevlar tether could support a 100,000 lb module at 1 g (radius up to 20,000 ft with angular velocity 0.38 rpm).

## Projected Comfort and Performance Ranges

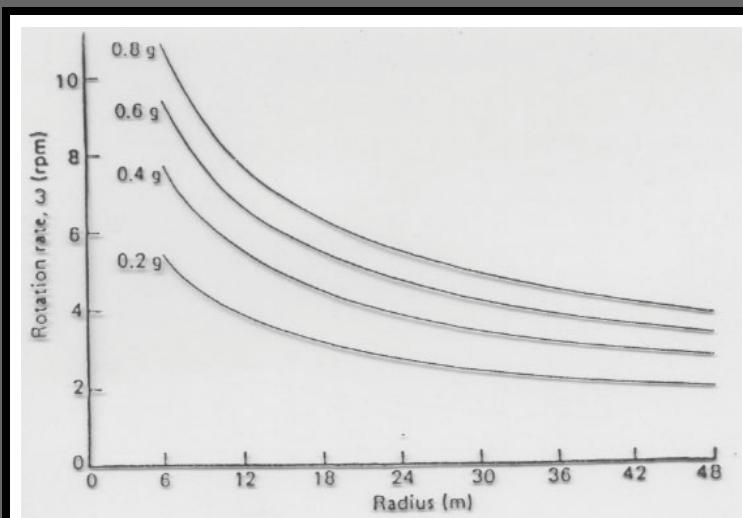
## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES

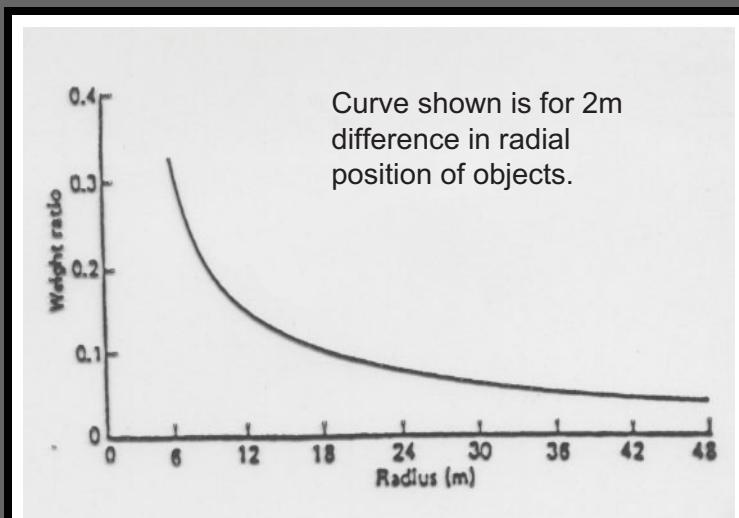


## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES



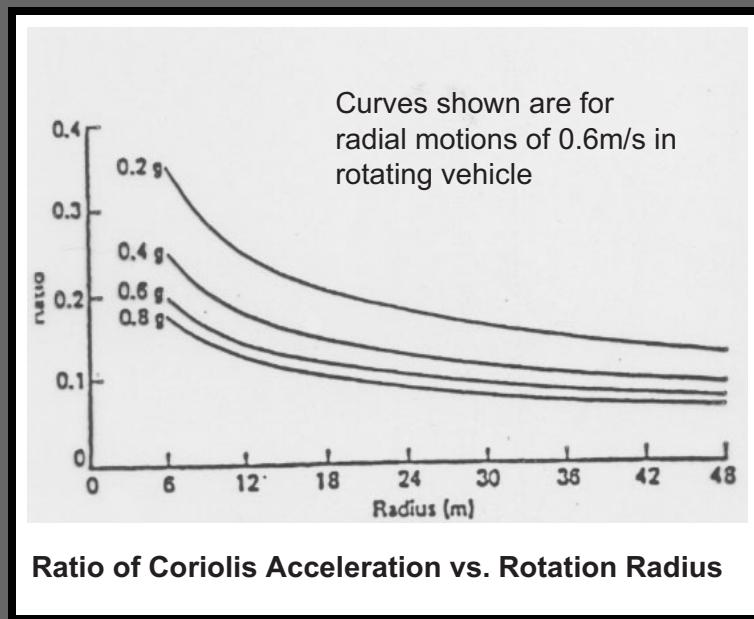
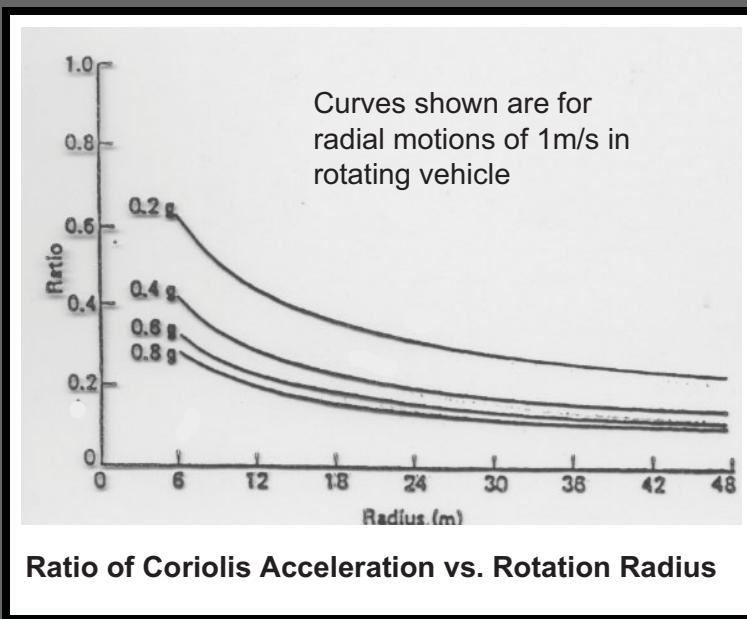
Rate of Rotation vs. Radius for Various AG levels



Artificial Weight Change vs. Rotation Radius

## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES



## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES



C-14

Provide internal visual references that provide clear and constant awareness of the spin direction for crew orientation using graphic symbols, colors, lighting and other devices.	Radial traffic should be kept to a minimum, and crew members should not be required to traverse through the spin axis unless the hub is non-rotating at the time.
Orient workstations so that the user's facial plane is parallel to the spin axis to minimize cross-coupled head rotations which can have adverse ear-down effects.	Living and work areas should be located as far as possible from the axis of rotation to maximize therapeutic physiological benefits (bone, muscle & cardiovascular fitness).
Design controls and displays so that left-right head rotations can be avoided and up-down arm motions are least necessary (to minimize Coriolis accelerations).	Means should be provided to facilitate crew transitions through gravity gradients as they pass from areas near the center of rotation to A-g destinations.
Orient crew compartments and equipment systems so that primary traffic paths are parallel to the spacecraft's spin axis to avoid locomotion and sensory conflicts.	Ladders oriented along vectors radial to the spin hub should enable one side to be used for ascent and the other for descent to compensate for tangential Coriolis forces.
<b>Interior Spacecraft Design Strategies</b>	

## ARTIFICIAL-G CONSIDERATIONS

## GOVERNING PRINCIPLES



Concepts for creating rotating spacecraft to produce A-g have been proposed over more than a century:

- Konstantin Tsiolkovsky, one of history's most renowned space visionaries introduced the idea in 1903, influencing the thinking of many others who followed.
- Sergi Korolev, the father of the Soviet Space Program had a technical team that designed a tethered flexible A-g system for the Voskhod manned mission in the early 1960s.
- Werner Von Braun, a great US space leader, proposed a 125 ft. diameter torus spinning at 3 rpm which offered a popular basis for many technical and science fiction visualizations.

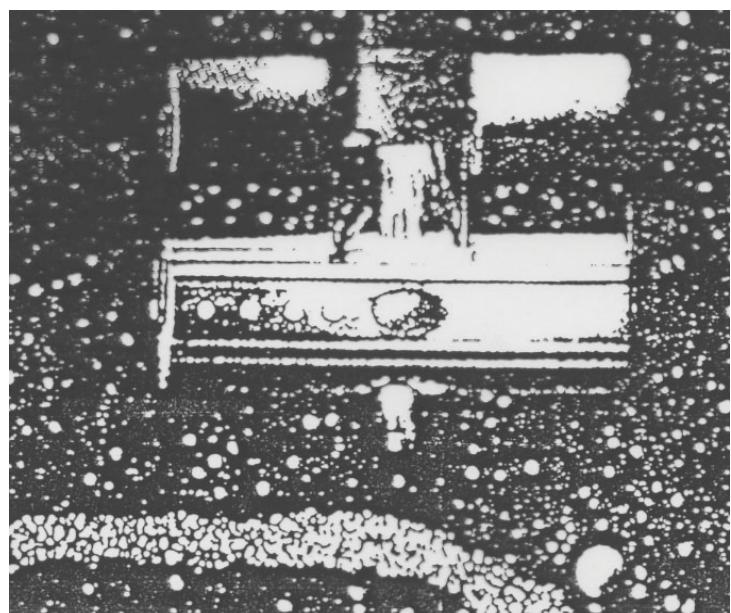
Most A-g spacecraft concepts that have been proposed are very preliminary in nature, and fail to address many problematic requirements:

- A-g capabilities will fundamentally drive all design, engineering and operational planning activities, establishing the framework and direction of all subsequent decisions.
- A-g will impose dramatic influences upon program complexity and cost, including fabrication; on-orbit assembly, orbital docking/ transfers, and solar power systems.
- Design for human safety, comfort and operations will present unique challenges, including adaptation to Coriolis forces, g-level transitions, and outside viewing.

### History and Issues

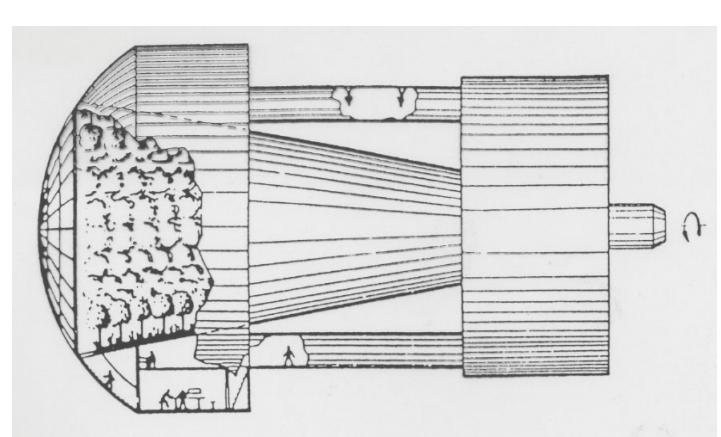
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



Ganswindt, circa 1890.

Willi Ley. *Rockets, Missiles, and Space Travel: Revised Edition*. Viking Press, 1957.

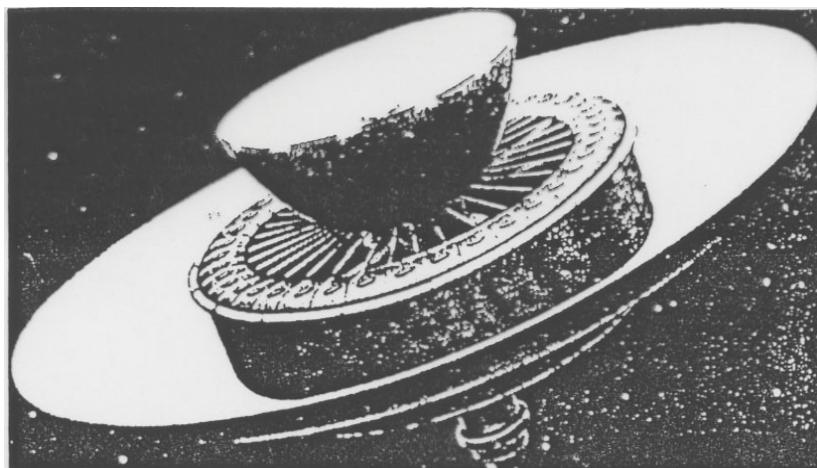


Tsiolkovsky, 1903.

John M. Logsdon and George Butler. "Space Station and Space Platform Concepts: A History Review." *Space Stations and Space Platforms-Concepts, Design, Infrastructure, and Uses*, pages 203-263. Edited by Ivan Bekey and Daniel Herman. American Institute of Aeronautics and Astronautics, 1985

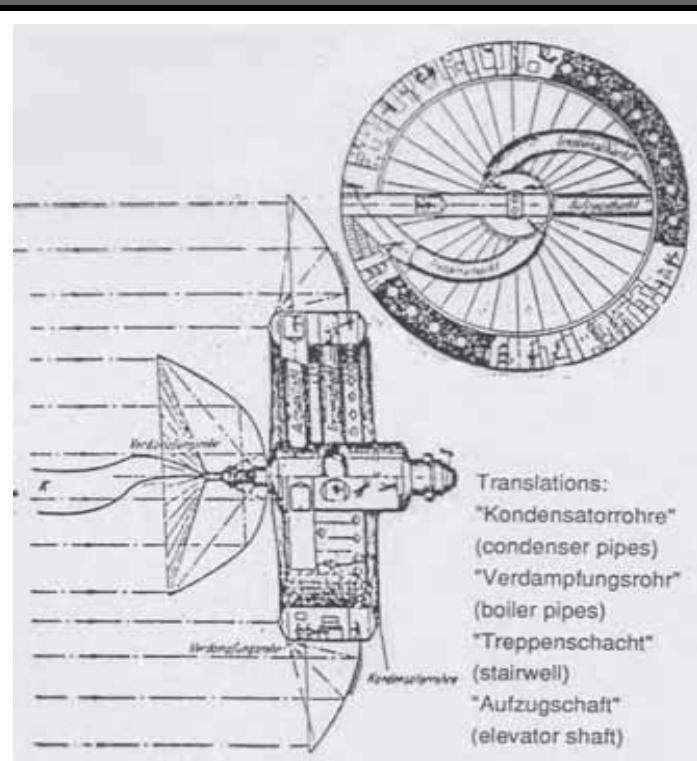
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



Noordung, "Wohnrad", 1928.

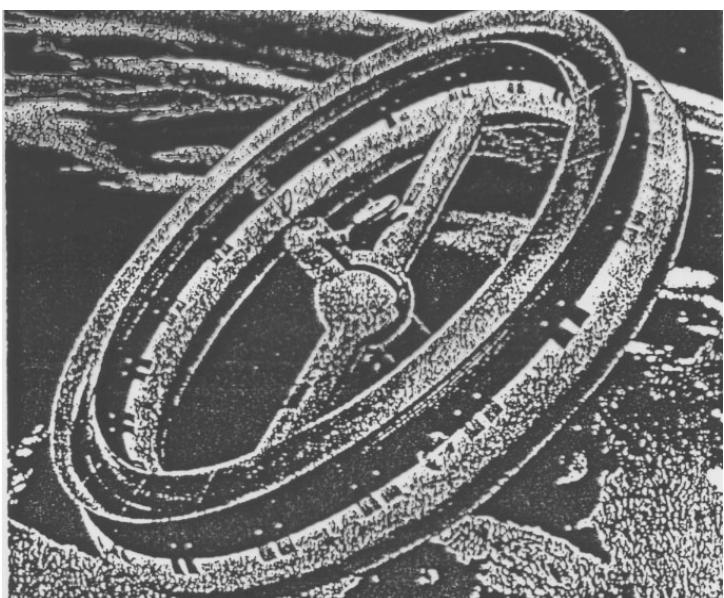
John M. Logsdon and George Butler. "Space Station and Space Platform Concepts: A History Review." *Space Stations and Space Platforms-Concepts, Design, Infrastructure, and Uses*, pages 203-263. Edited by Ivan Bekey and Daniel Herman. American Institute of Aeronautics and Astronautics, 1985.



Translations:  
"Kondensatorrohre"  
(condenser pipes)  
"Verdampfungsrohr"  
(boiler pipes)  
"Treppenschacht"  
(stairwell)  
"Aufzugschacht"  
(elevator shaft)

## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



**Von Braun, 1952.**

Werner von Braun. "Crossing the Last Frontier." *Collier's*, Vol. 129, no. 12, pages 24+, March 22, 1952. Crowell-Collier Publishing Company.



**Les Dorr. "The Future As it Was."**

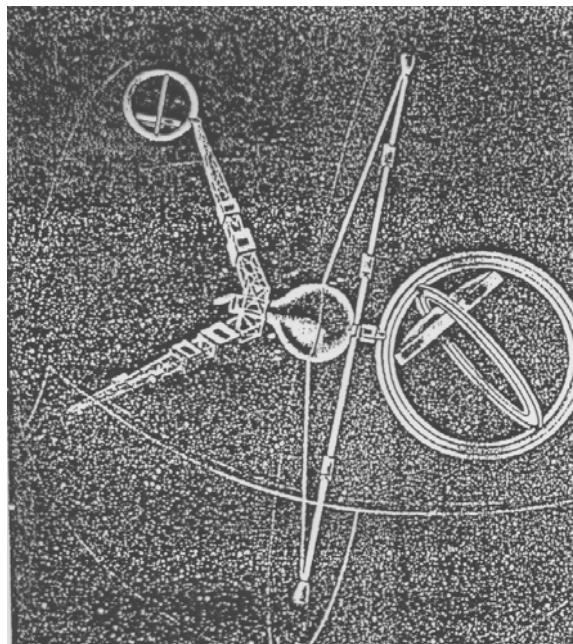
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## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS

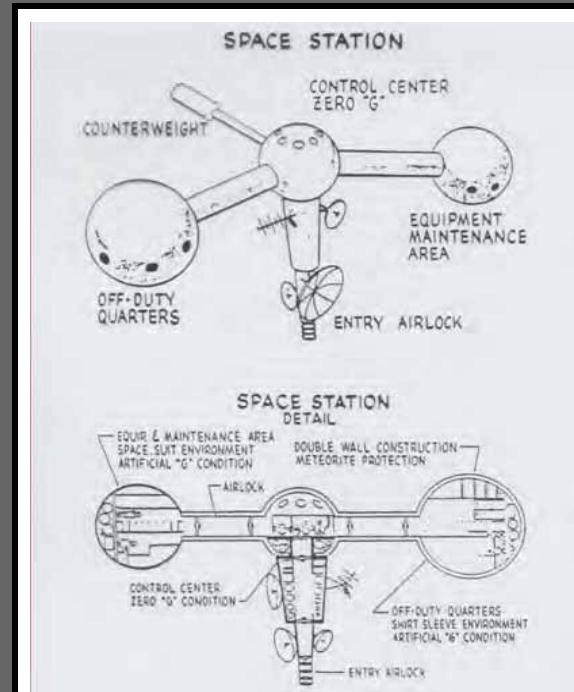


C-19



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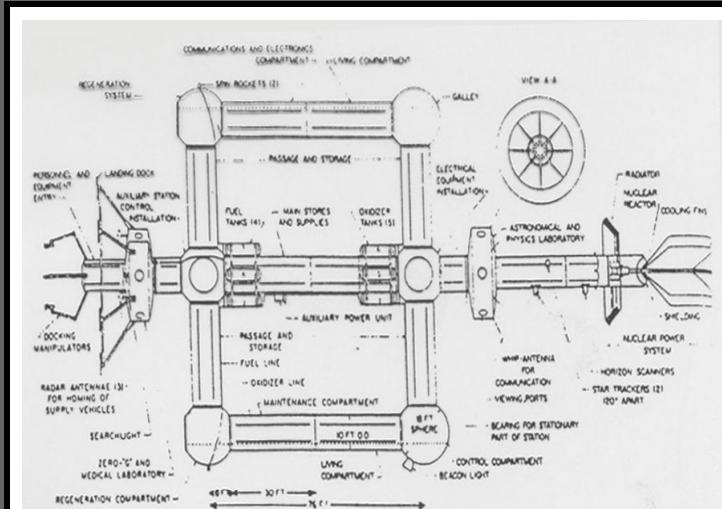
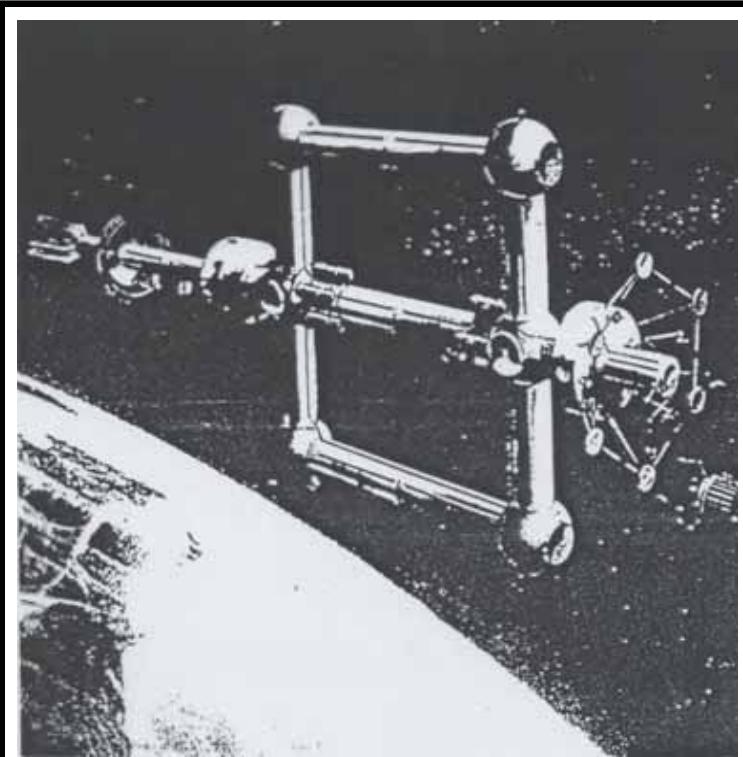


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## SPACECRAFT CONCEPTS

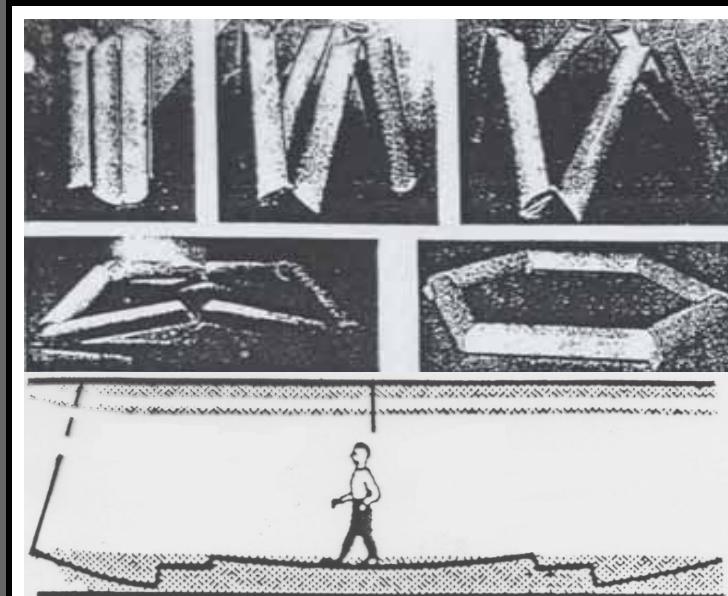
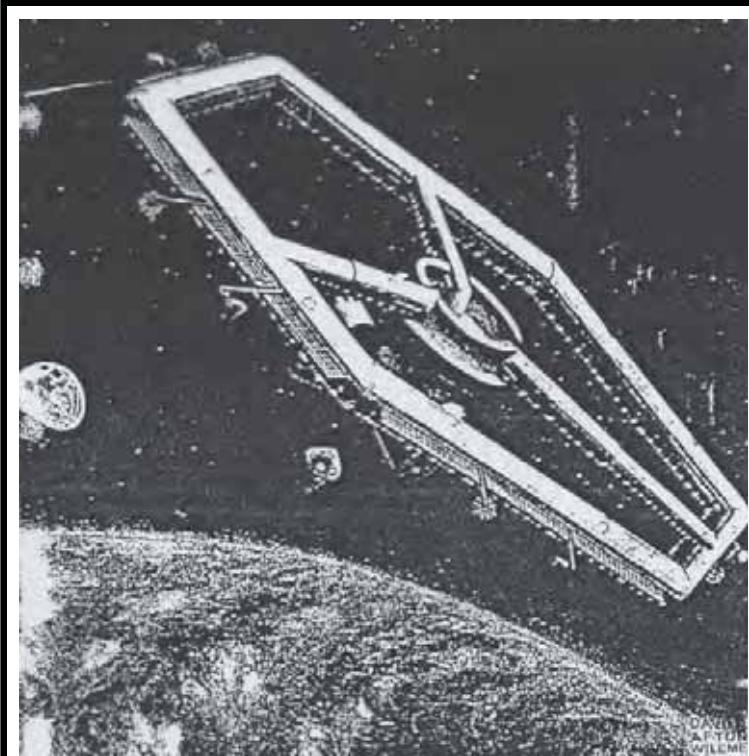


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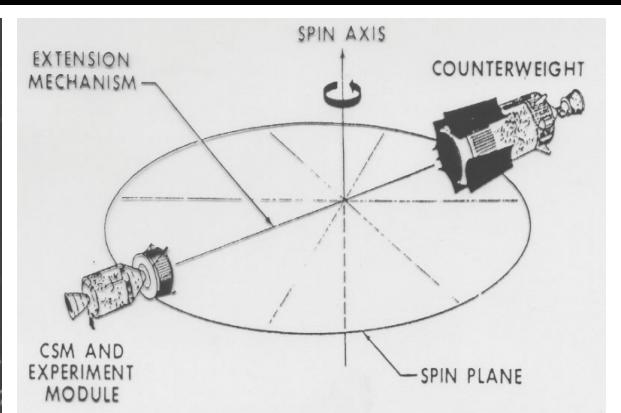
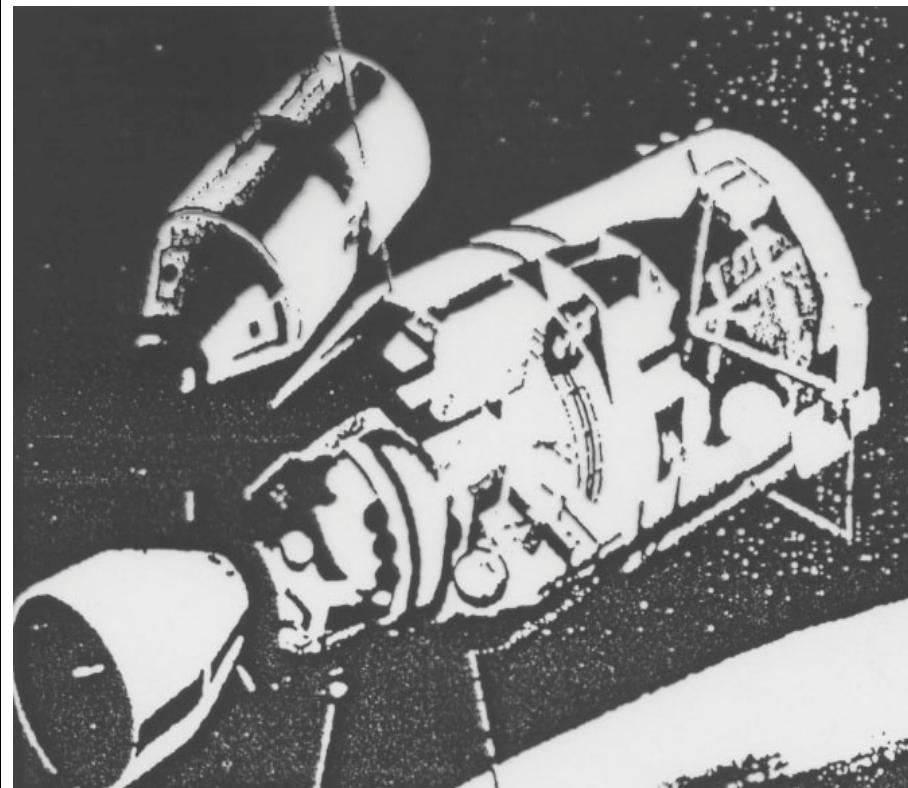
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## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS

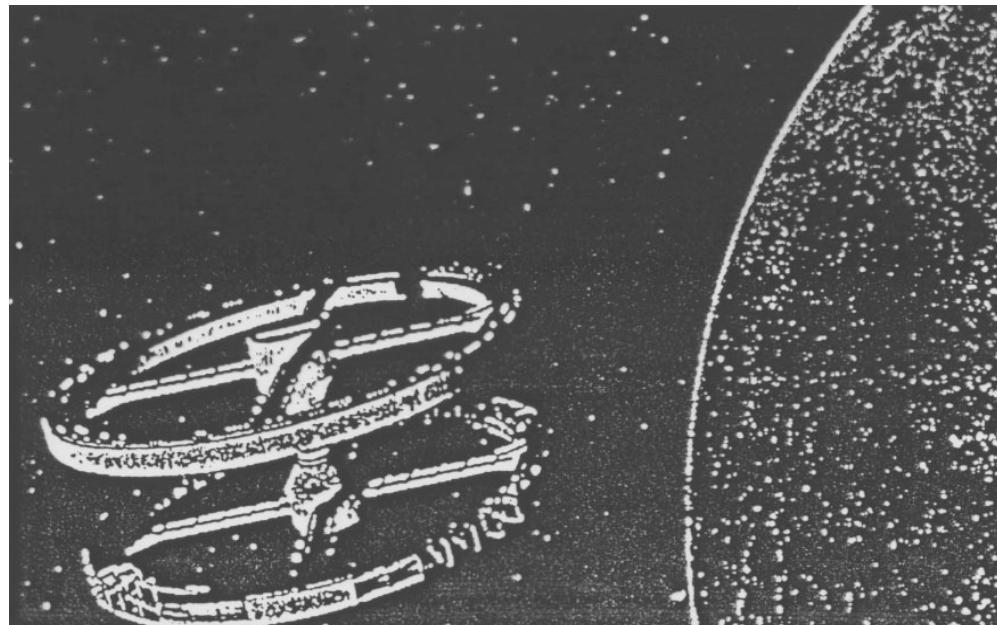


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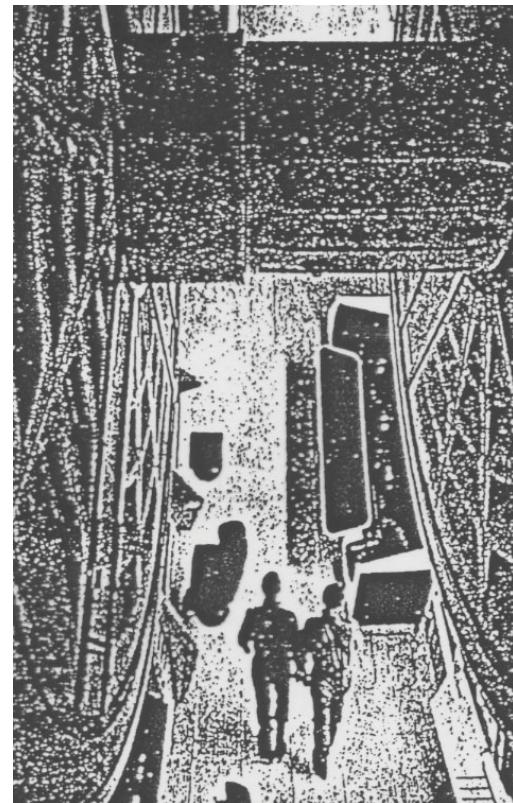
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



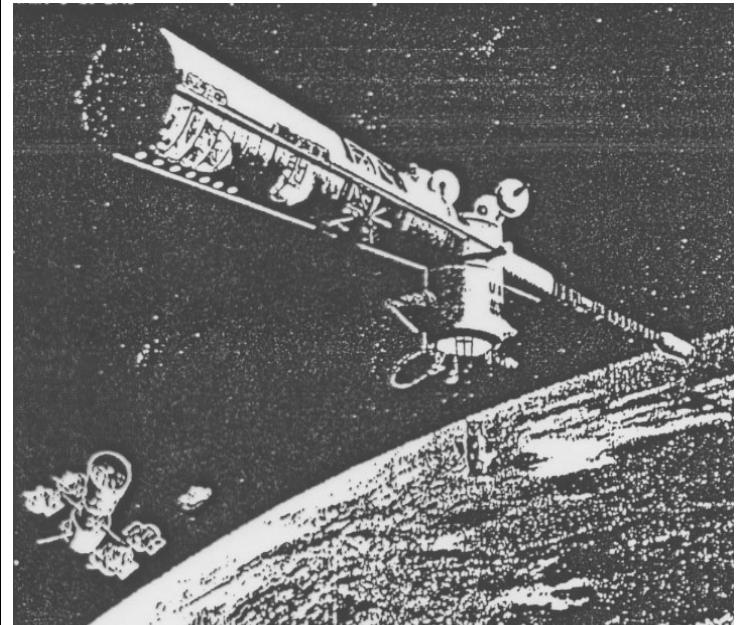
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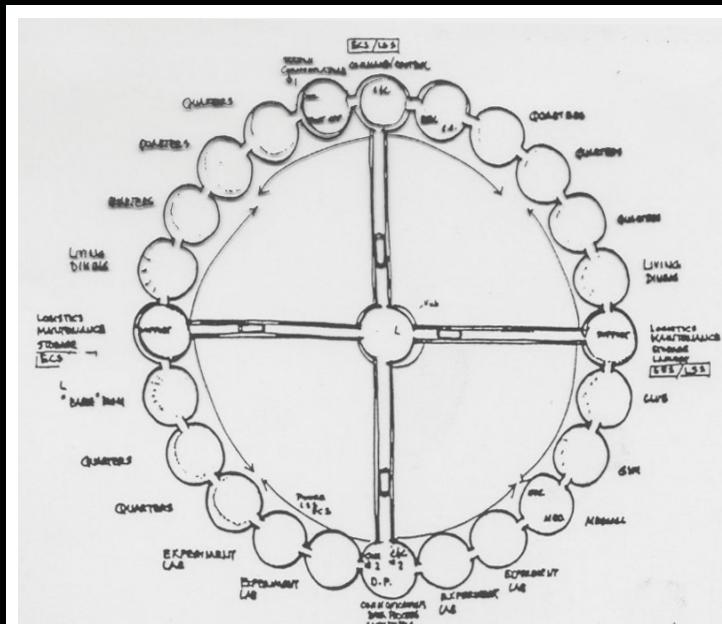
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



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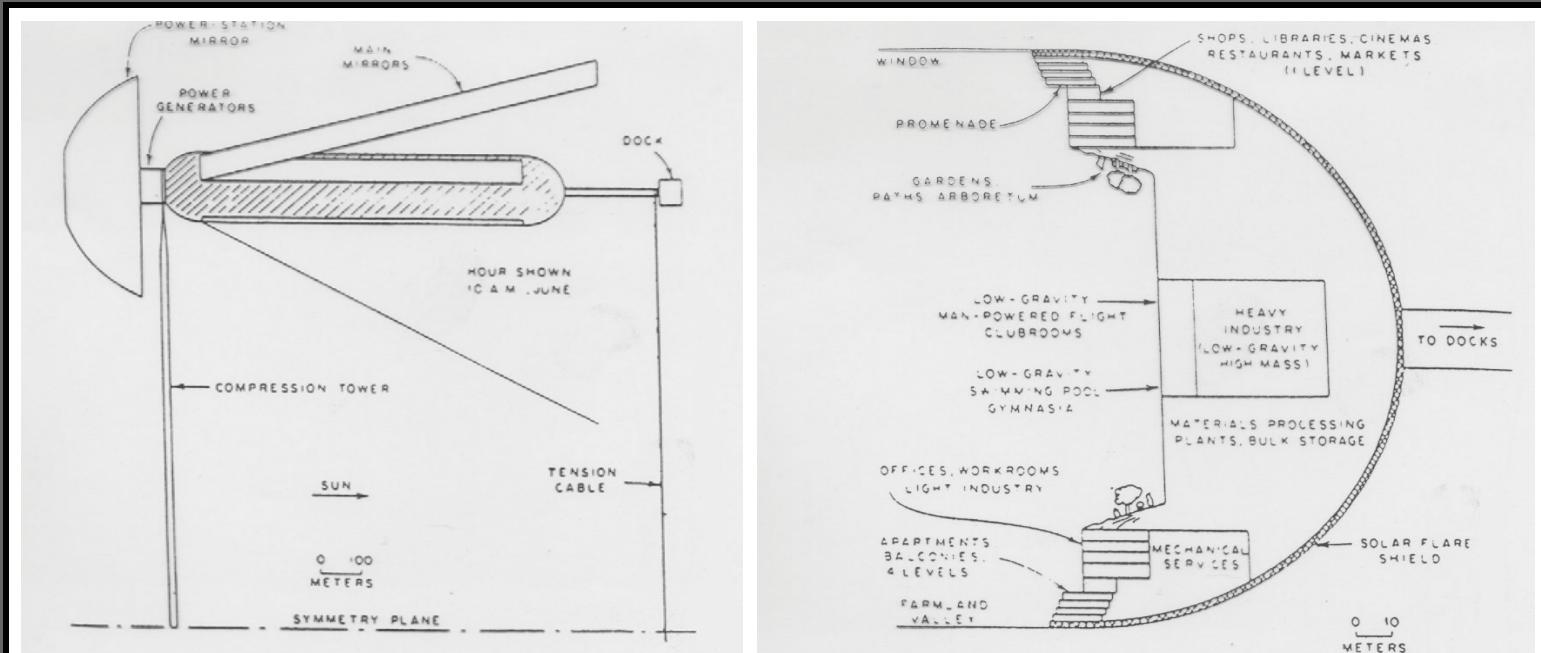
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## ARTIFICIAL-G CONSIDERATIONS

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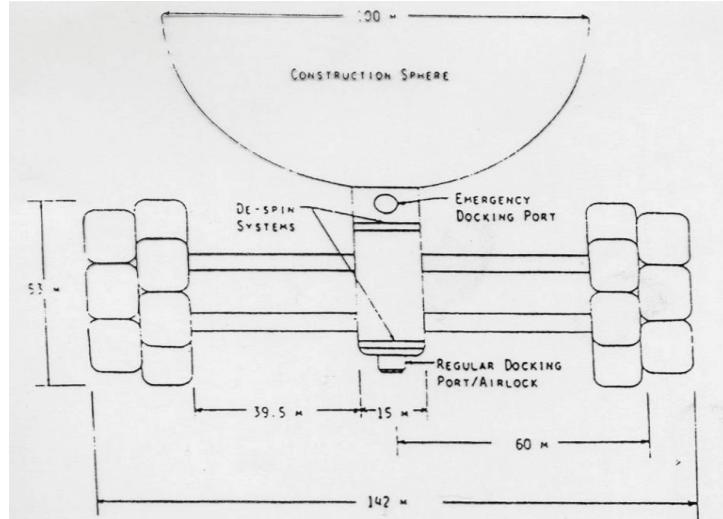


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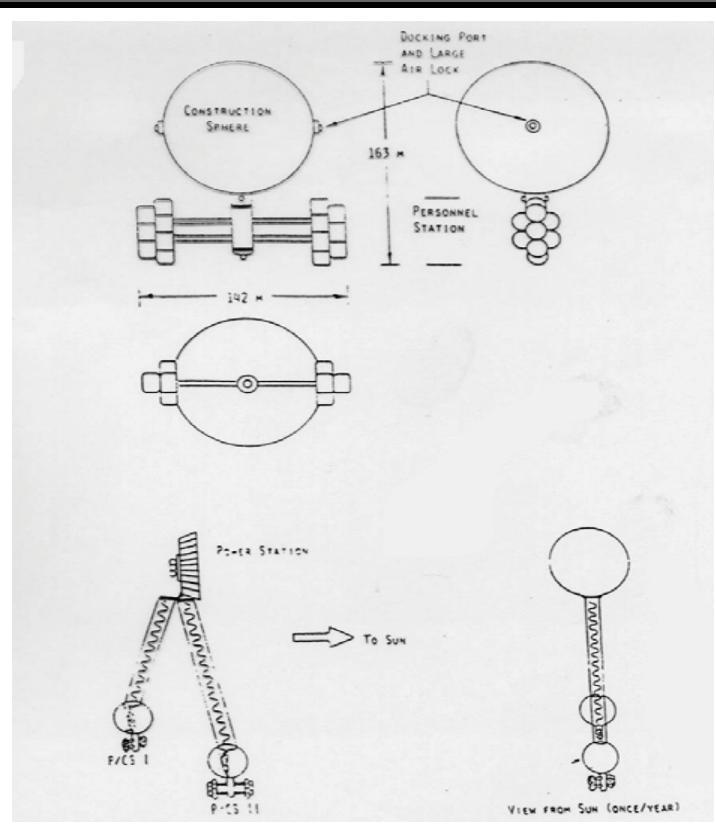
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



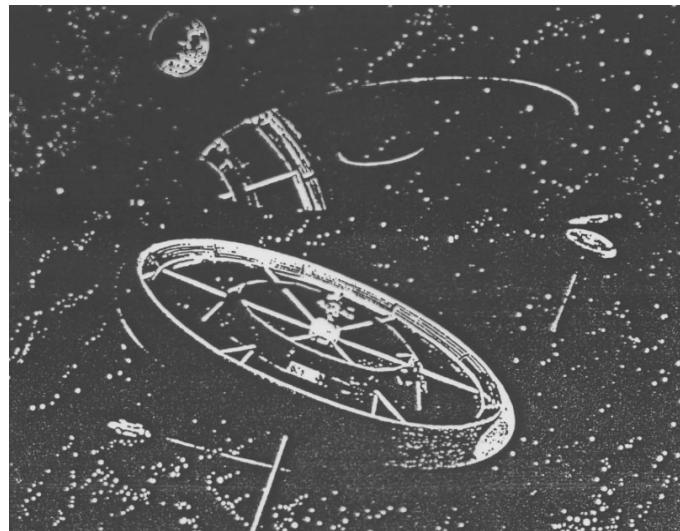
**Driggers, 1975. Construction sphere and habitat.**

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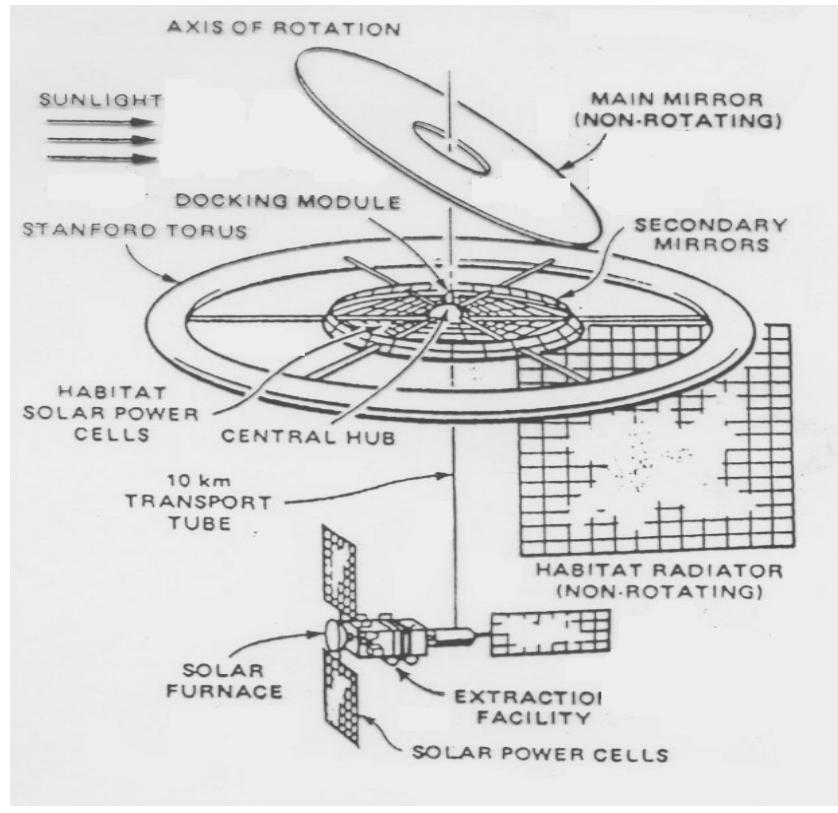
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



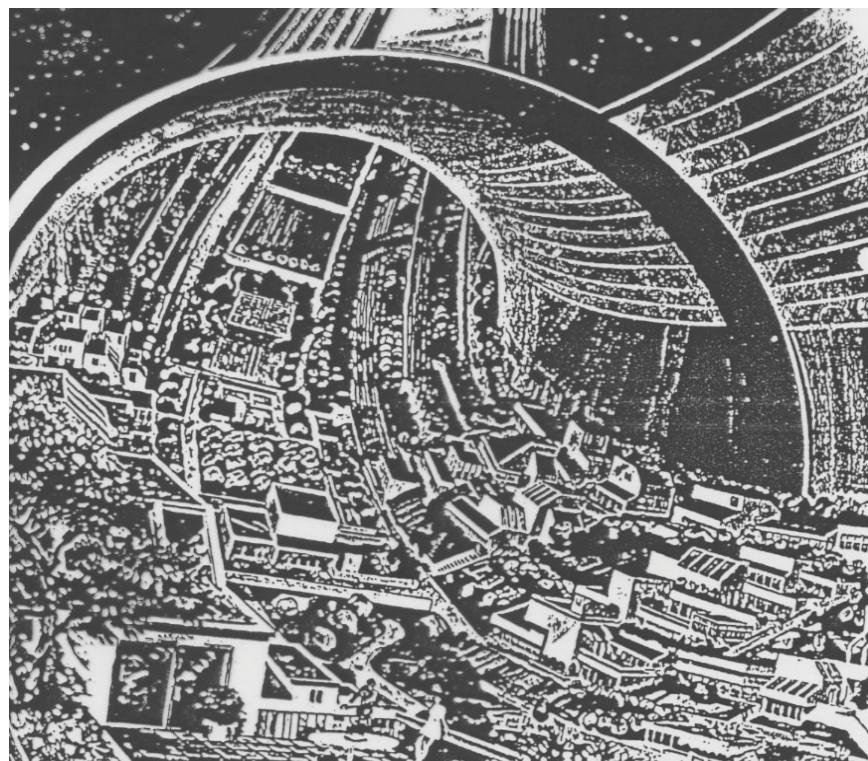
**Stanford Torus, 1975.**

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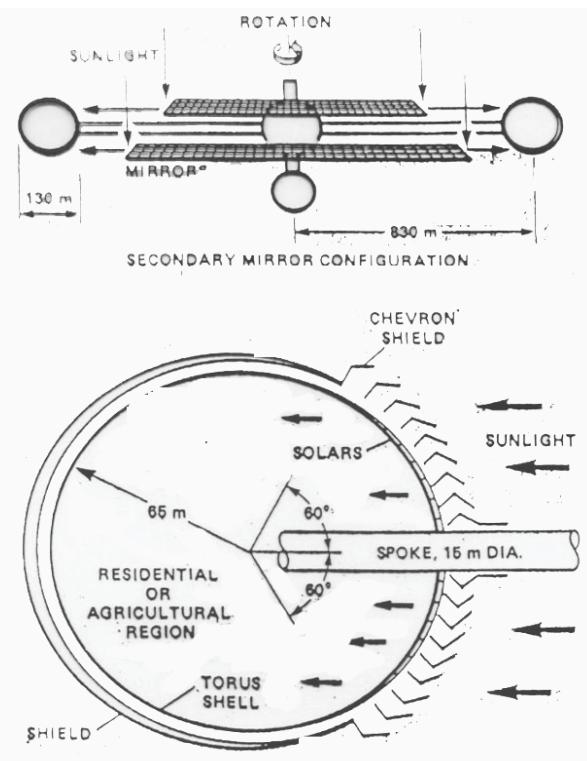


## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



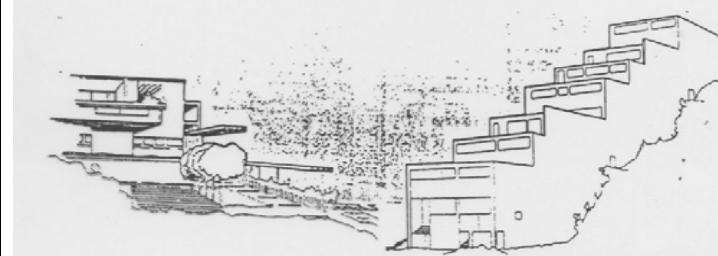
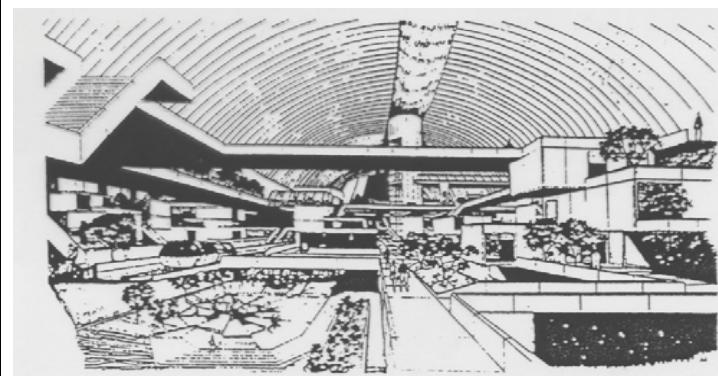
Stanford Torus, 1975.



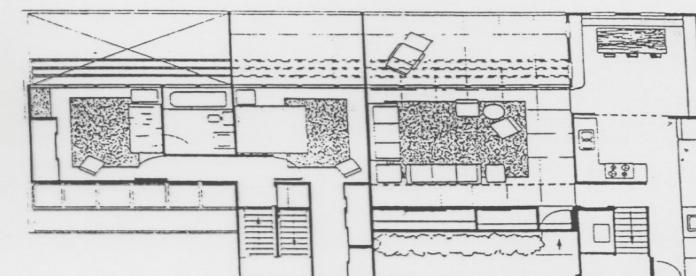
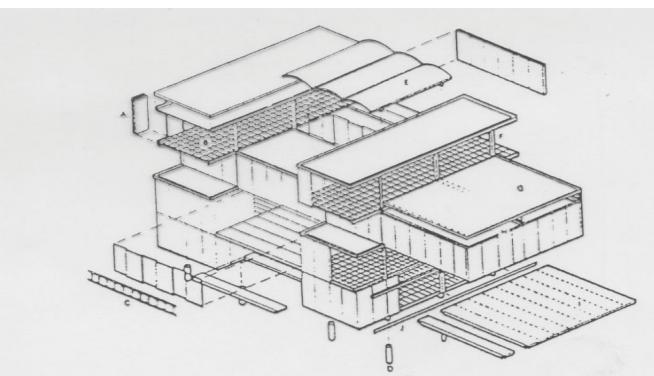
(b) SHIELD AND CHEVRON CONFIGURATION

## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



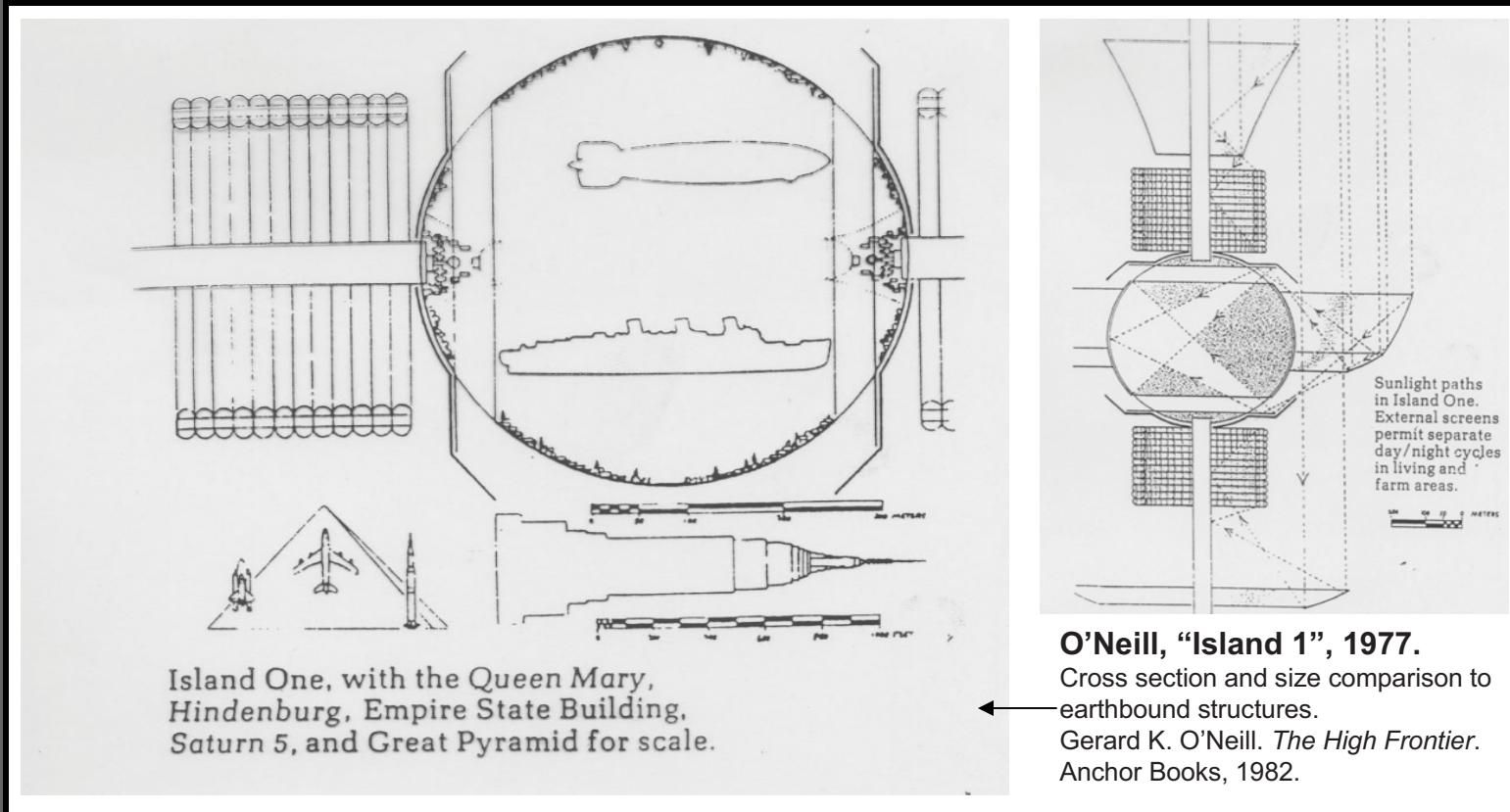
**Stanford Torus, 1975.** Interior views.



**Stanford Torus, 1975.** Modular construction system.

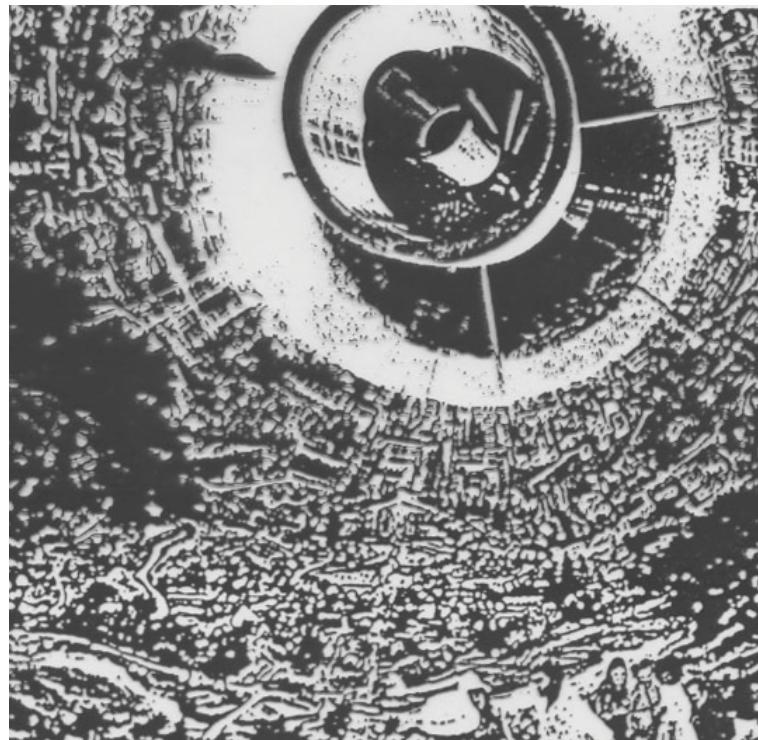
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS

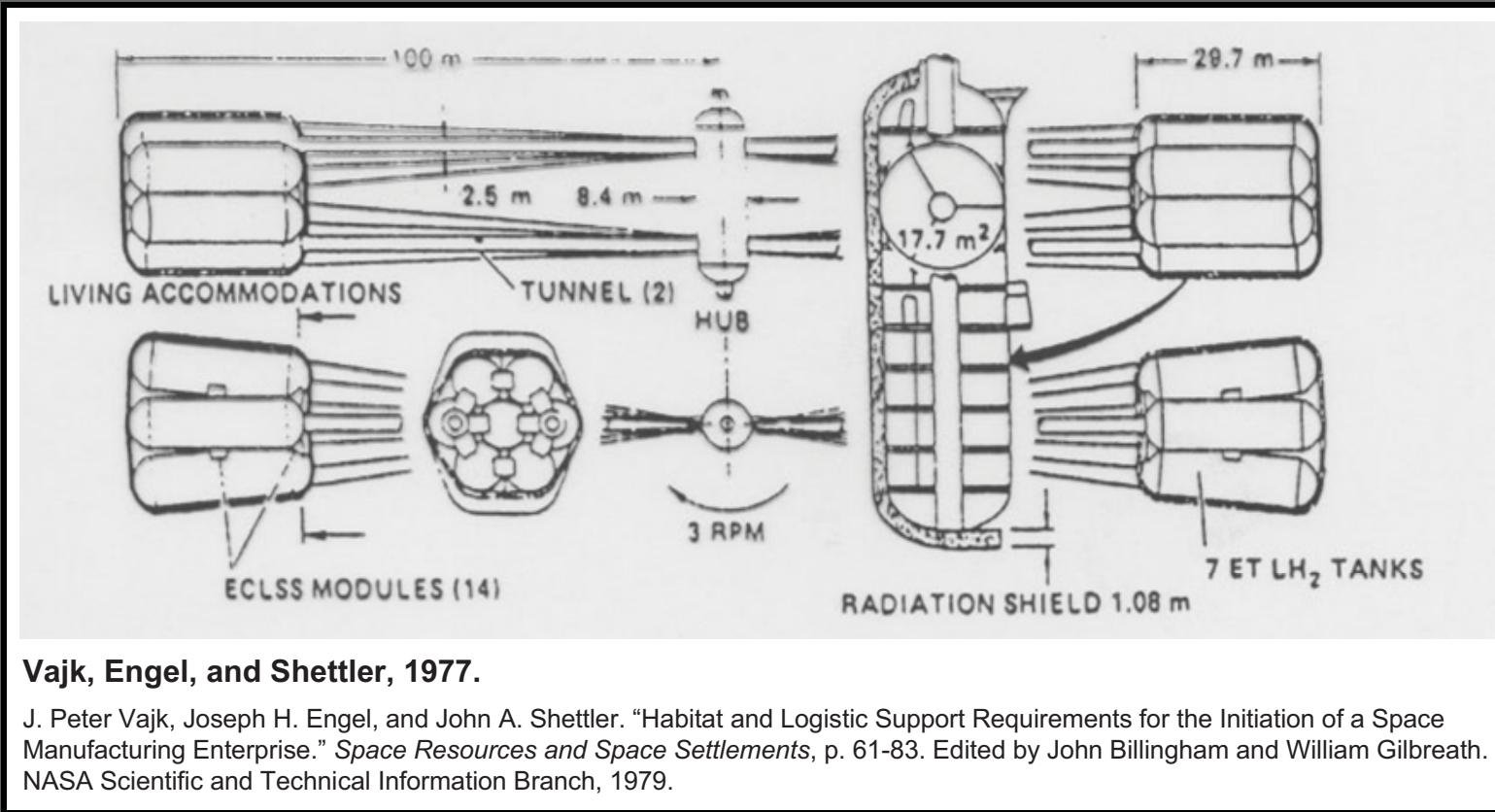


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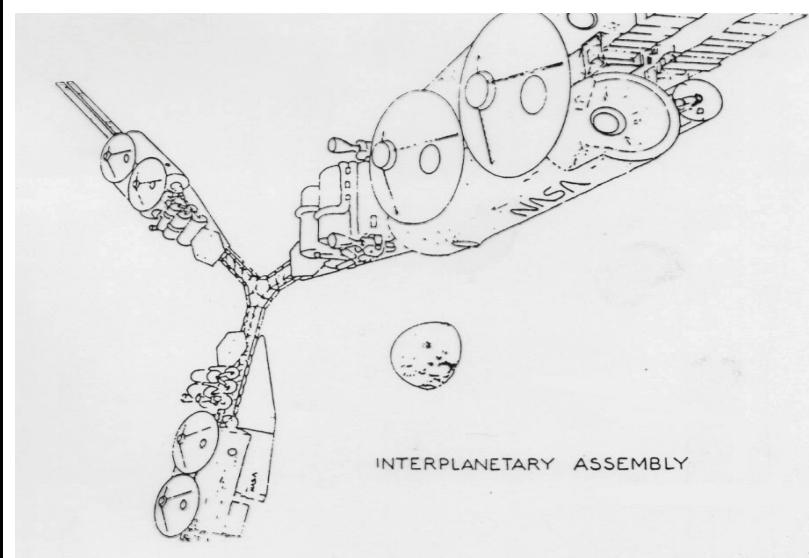
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



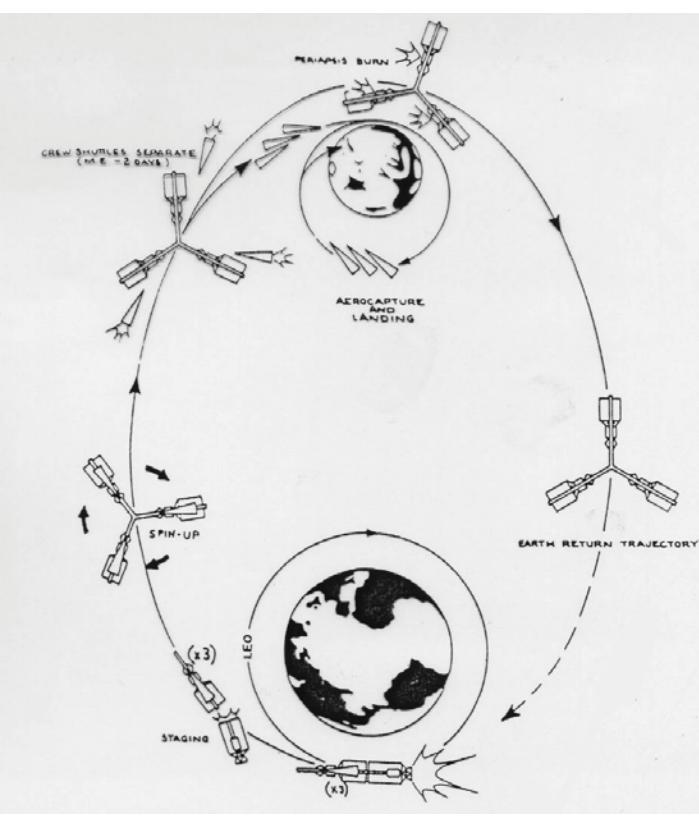
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



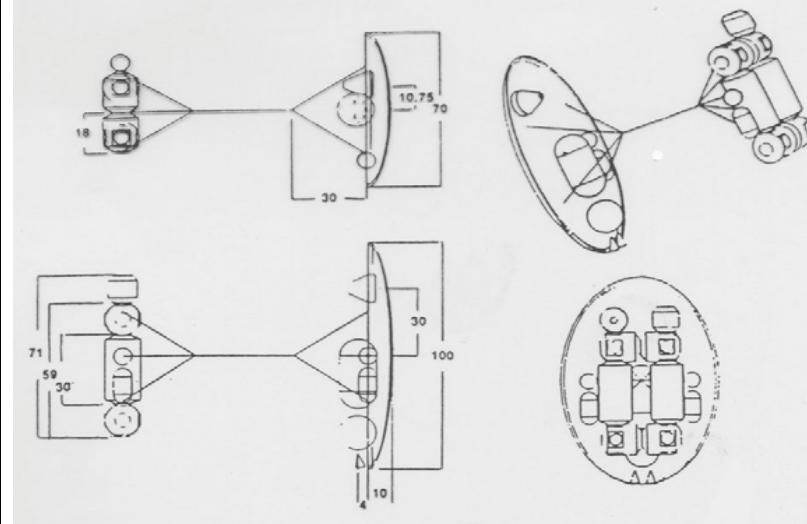
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## ARTIFICIAL-G CONSIDERATIONS

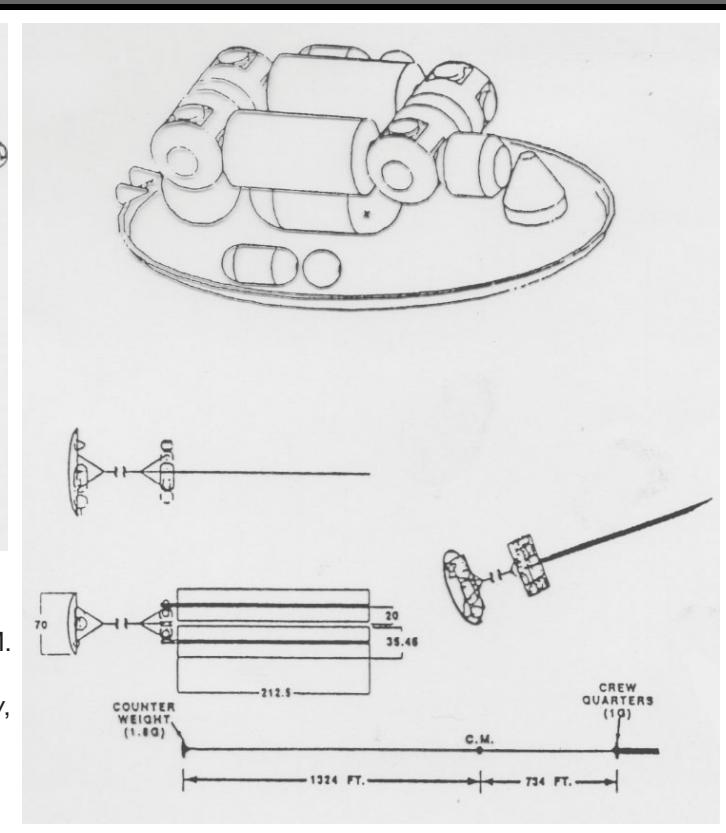
## SPACECRAFT CONCEPTS



**Schultz, Rupp, Hajos, and Butler, 1987.**

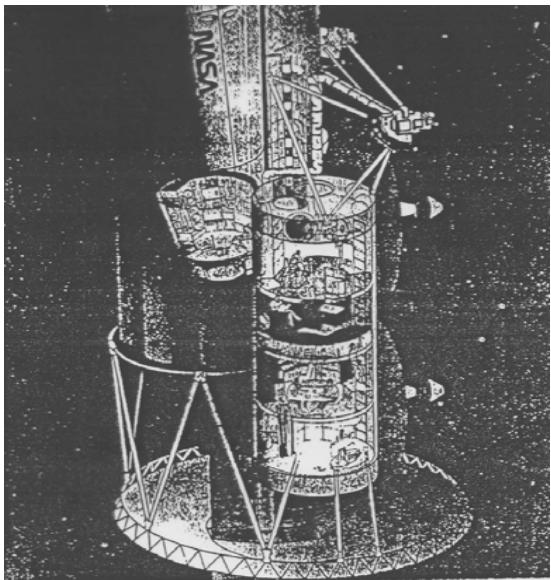
Manned Mars vehicle, retracted (top) and extended (bottom).

David N. Schultz, Charles C. Rupp, Gregory A. Hajos, and John M. Butler. "A Manned Mars Artificial Gravity Vehicle." *The Case for Mars III: Strategies for Exploration- General Interest and Overview*, pages 325-352. Edited by Carol Stoker. American Astronautical Society, 1989. Paper no. AAS-203. Volume 75 of the Science and Technology Series, Advances in the Astronautical Sciences.



## ARTIFICIAL-G CONSIDERATIONS

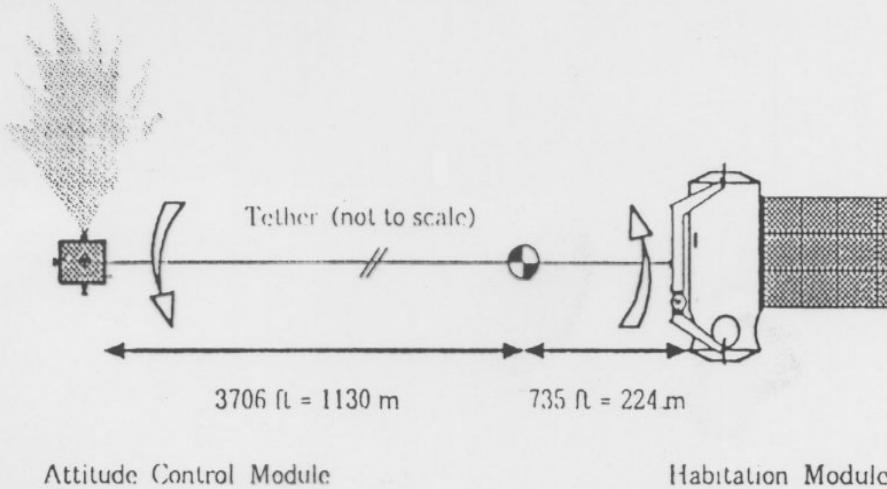
## SPACECRAFT CONCEPTS



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### Facility Diagram

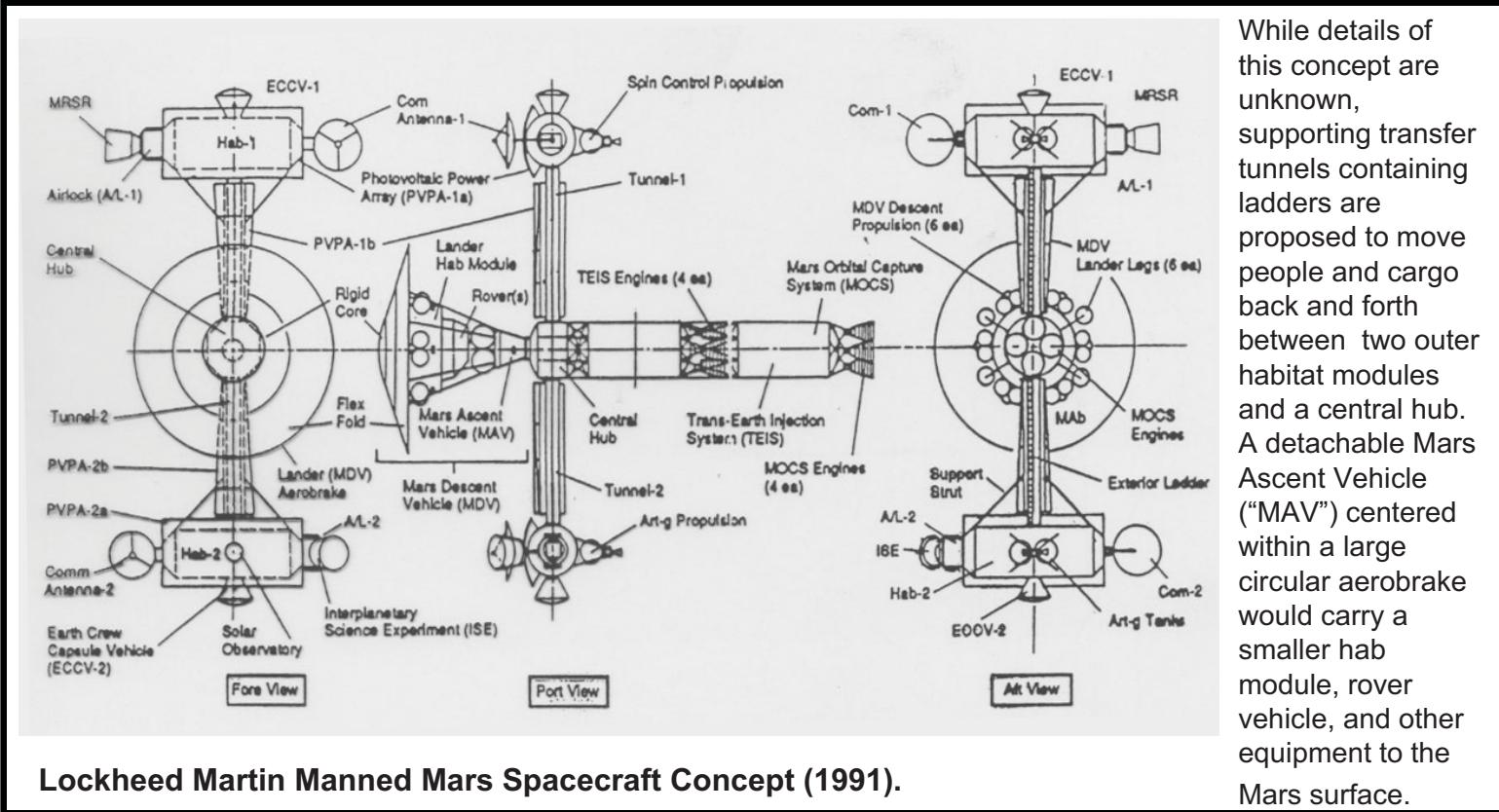


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## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



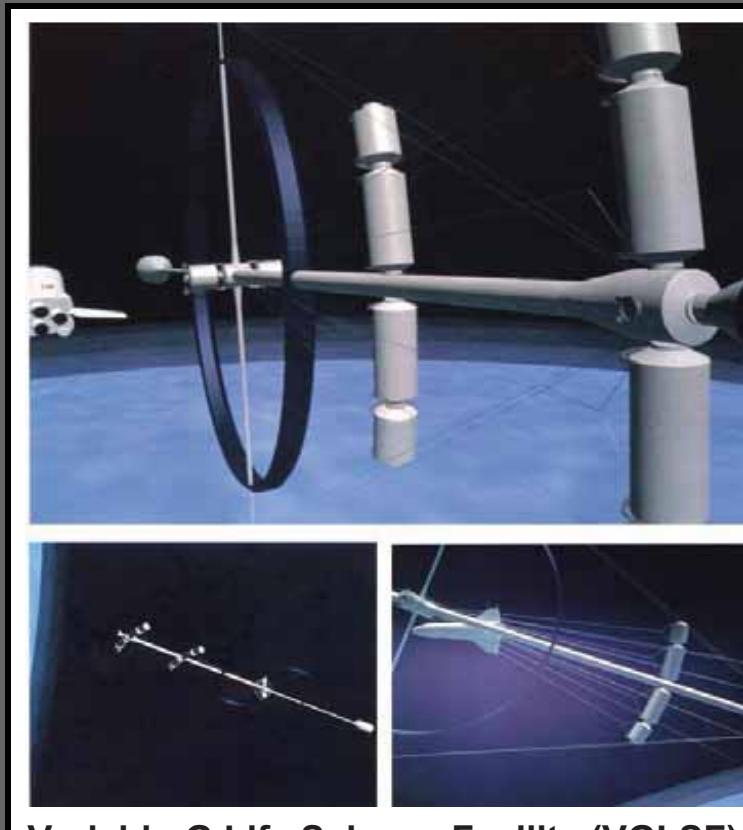
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



### Proposed by SICSA in 1987:

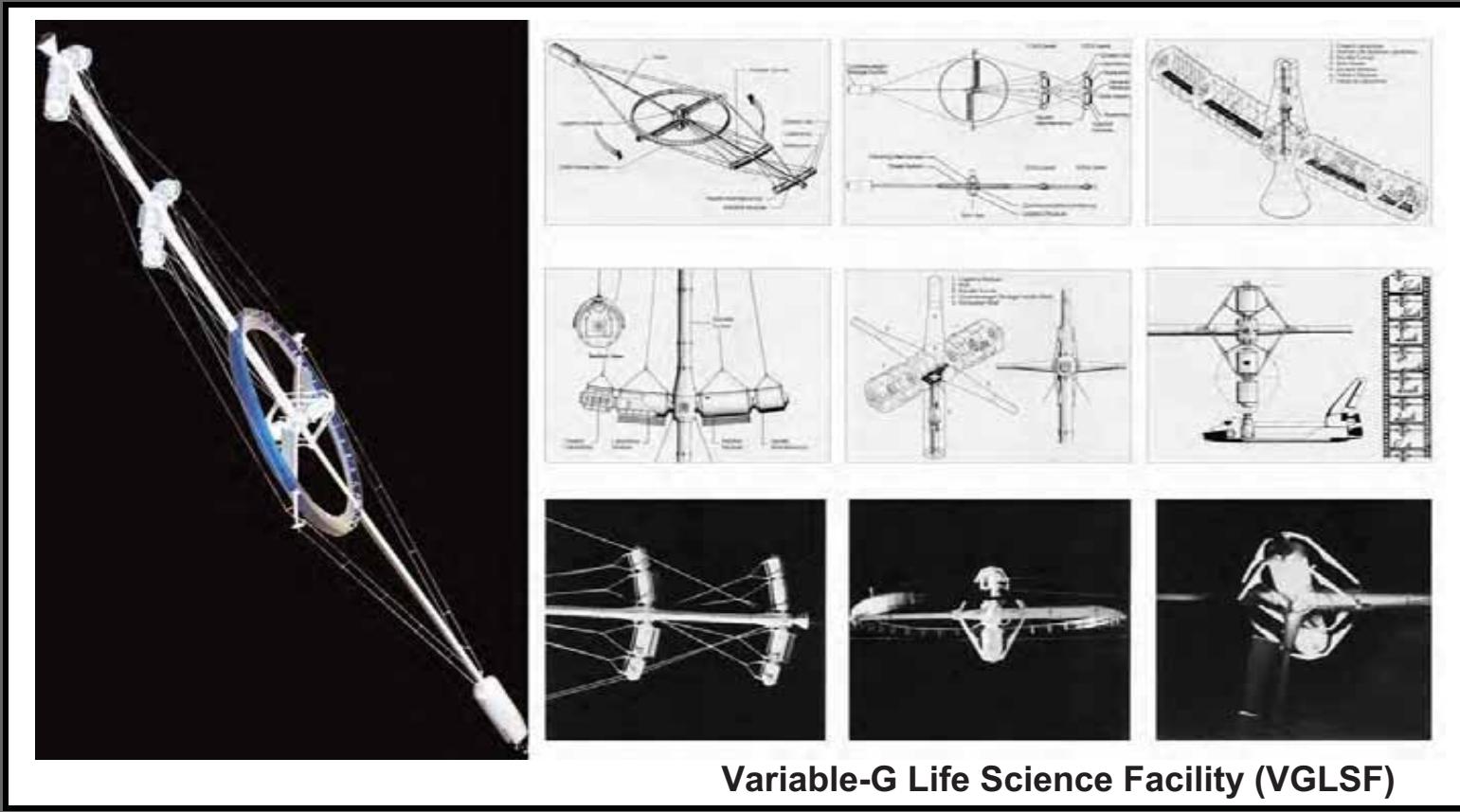
- A centripetally-induced artificial gravity research habitat to study human health/performance influences of lunar and Mars gravity levels:
  - The outer modules provide gravity levels comparable to Mars (1/3 gravity).
  - The inner modules provide gravity levels comparable to Moon (1/6 gravity).
  - G levels can be modified by changing facility spin rate.
- Special design features include:
  - A ring shaped photovoltaic power system.
  - A counter rotating “flip over” interface fixture for shuttle docking and crew/cargo transfers.



**Variable-G Life Science Facility (VGLSF)**

## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



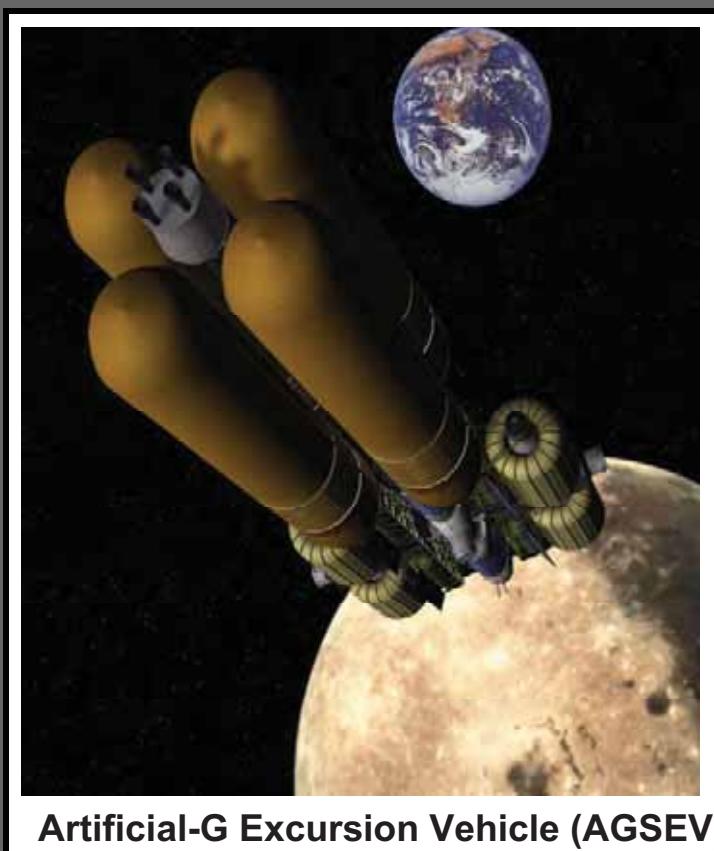
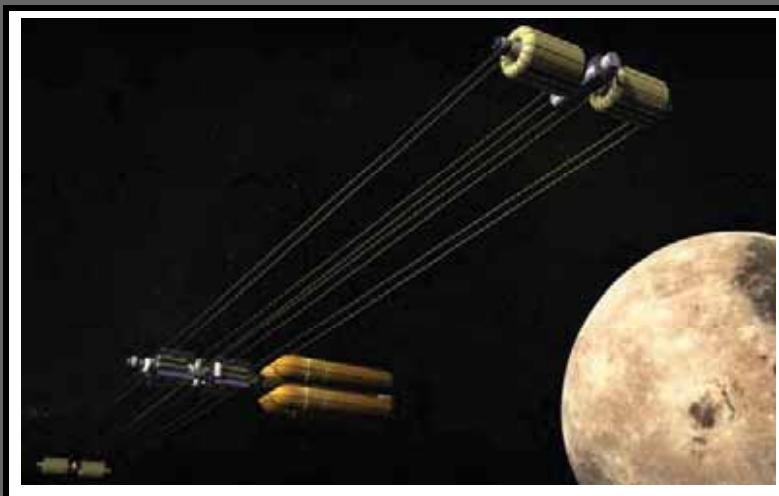
**ARTIFICIAL-G CONSIDERATIONS**

**SPACECRAFT CONCEPTS**



**Proposed by SICSA in 2001:**

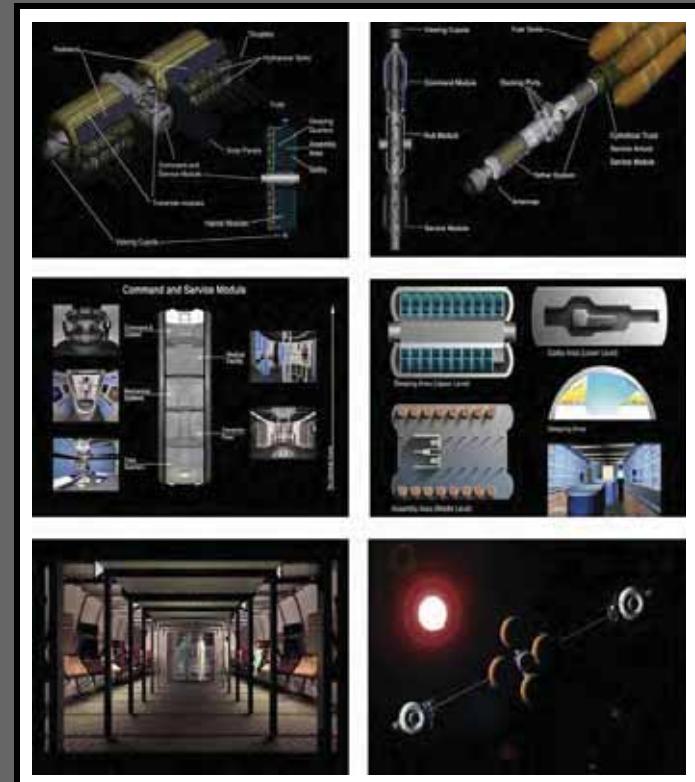
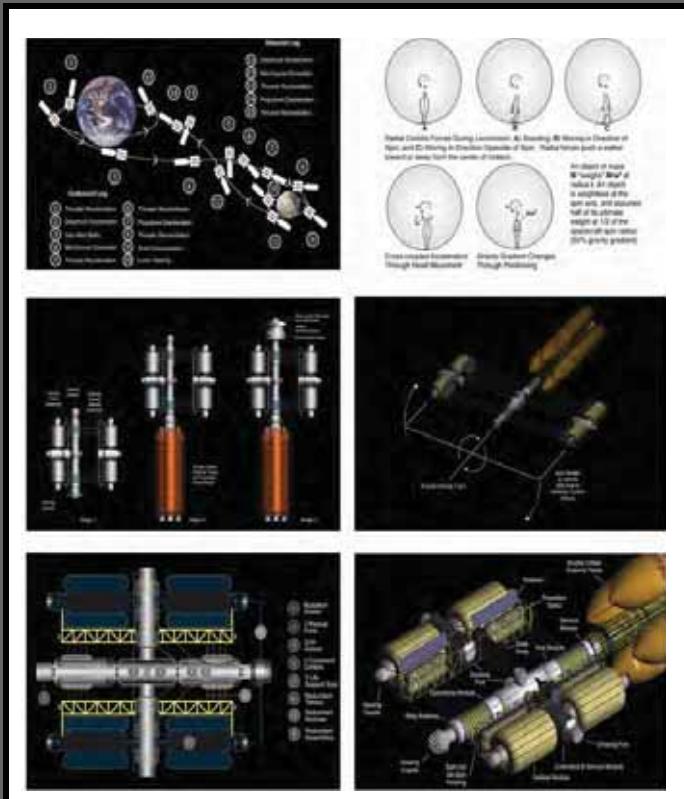
- A tethered space facility for long term Mars voyages:
  - Avoids large mass penalties of rigid tubular transfer vehicles.
  - Applies Shuttle external tanks and main engines for propulsion.



**Artificial-G Excursion Vehicle (AGSEV)**

**ARTIFICIAL-G CONSIDERATIONS**

**SPACECRAFT CONCEPTS**



**Artificial-G Excursion Vehicle (AGSEV)**

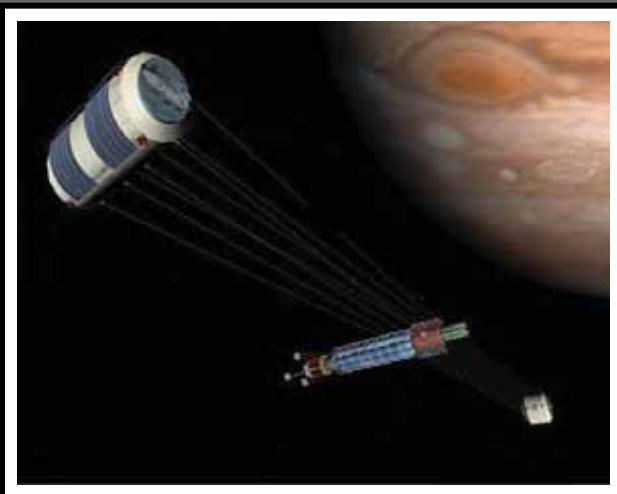
## ARTIFICIAL-G CONSIDERATIONS

## SPACECRAFT CONCEPTS



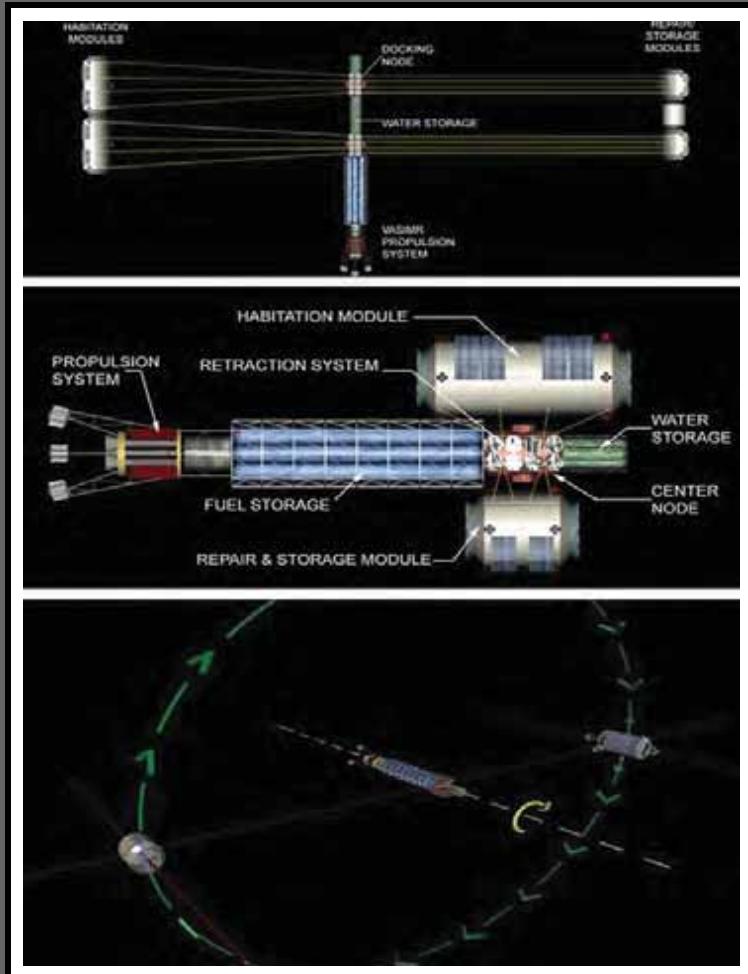
**Proposed by SICSA in 2003:**

- A tether vehicle for long term Space exploration voyages:
  - Applies elliptical cross section rigid modules.
  - Uses a low thrust ion propulsion system powered by a nuclear reactor.



SICSA

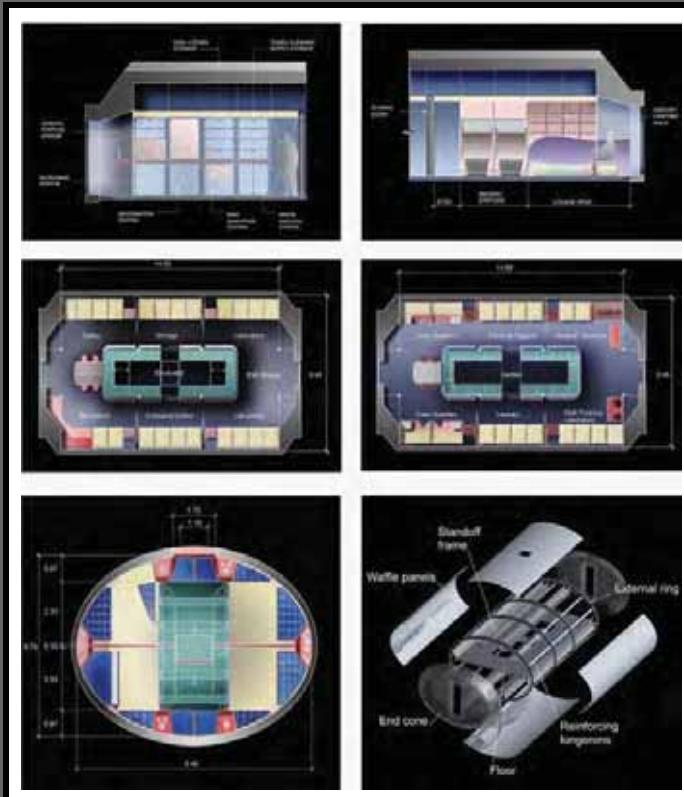
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**Rotationally-Induced Gravity (RING) Vehicle**

**ARTIFICIAL-G CONSIDERATIONS**

**SPACECRAFT CONCEPTS**



**Rotationally-Induced Gravity (RING) Vehicle**

## ARTIFICIAL-G CONSIDERATIONS

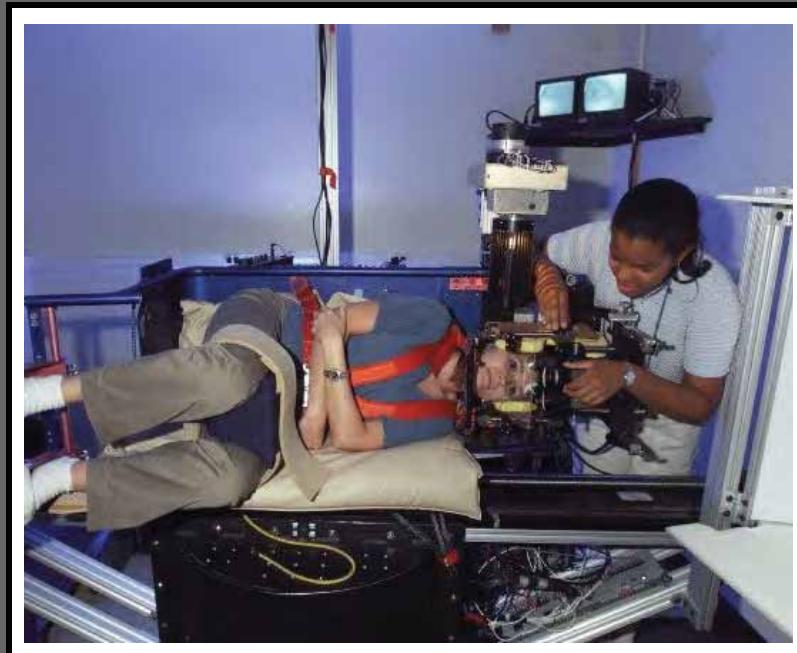
## SPACECRAFT CONCEPTS



Centrifuges are commonly used for A-g research using animals and human subjects, and have also been proposed as partial countermeasures against bone, muscle and cardiovascular deconditioning effects of extended weightless or reduced gravity conditions in space:

"Lazy Susan"- type centrifuges were first proposed and tested at MIT's Man Vehicle Lab during the mid-1980s, and have been used to evaluate human A-g influences and benefits for terrestrial and space applications:

- One or more subjects lie on a rotating support or turntable with heads near the spin axis where radius ( $r$ ) approaches 0.
- As the device spins, subjects experience approximately half of the resulting g-force at waists (50% gravity gradient) and the maximum at their feet.
- Some of these devices have been outfitted with means for exercise during tests, as well as sensors to monitor physiological functions and changes.



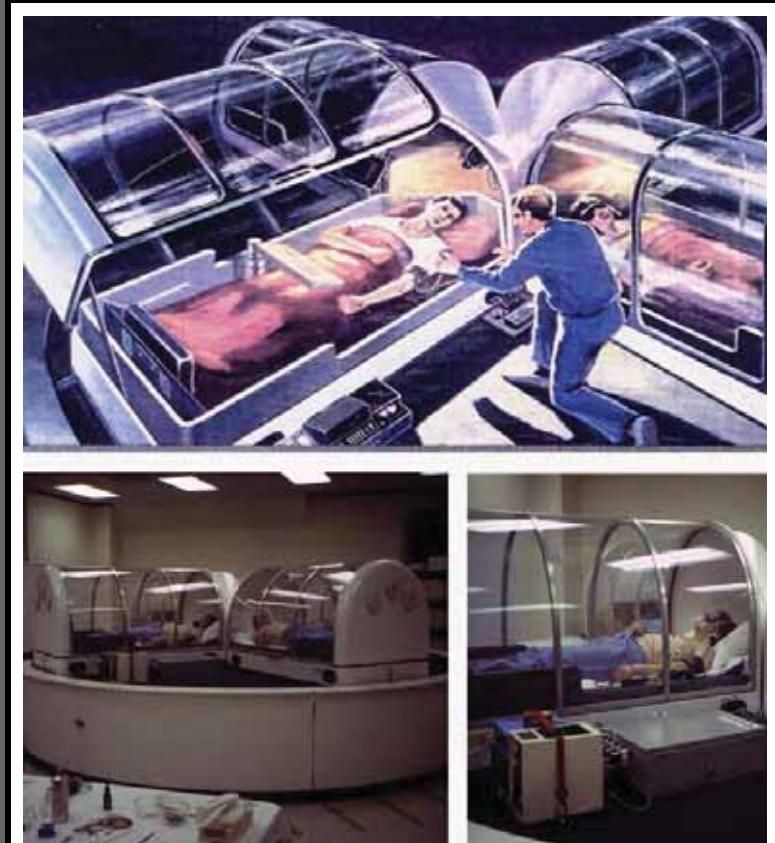
## ARTIFICIAL-G CONSIDERATIONS

## CENTRIFUGE DEVICES



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BELL & TROTTI, INC



**“Artificial Gravity Sleeper”**

### **Bell & Trott Development (1985):**

Bell & Trott, Inc. designed and built a “Lazy Susan”- type “Artificial Gravity Sleeper” based upon the MIT concept which was used for many years at the University of Texas Baylor College of Medicine facility in the Woodlands, Texas. The centrifuge was typically operated to create a 3-g force level at the subjects’ feet, and was instrumented to collect data on rapid eye movements (REMs), cardiovascular changes and other information over test periods lasting many hours or even days.

A key purpose of the experiments was to determine if A-g might be used to help long-term bed-confined patients reduce bone loss and fluid shift problems.

## **ARTIFICIAL-G CONSIDERATIONS**

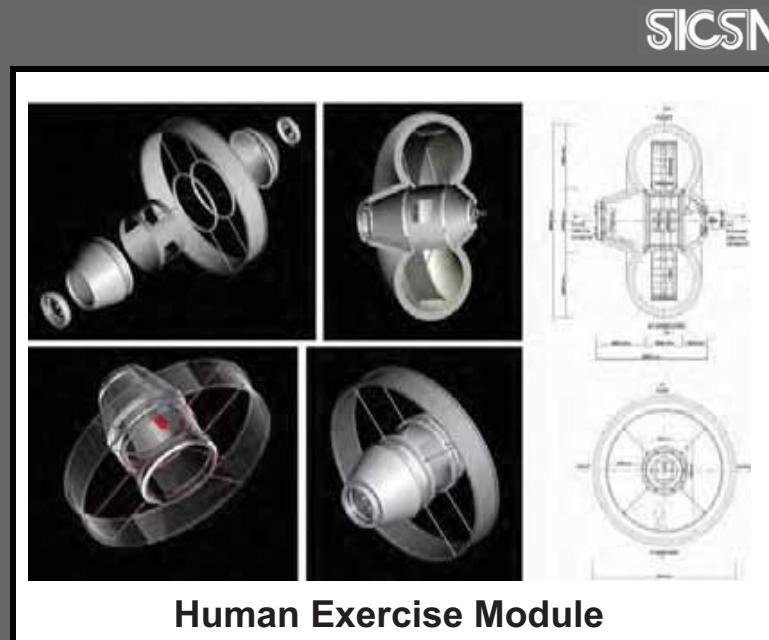
## **CENTRIFUGE DEVICES**



C-45

### SICSA Proposal (2003):

- A special module that can be attached to a LEO station or other long-term mission weightless facility:
  - Interior "track" structure rotates to provide centripetal force.
  - Serves as an exercise countermeasure to offset muscular/ cardiovascular deconditioning and bone density loss.
  - Connects to a standard berthing or docking port.
- Special design features include:
  - Incorporation of track into an inflatable ring structure.
  - Rotational energy supplied by air vanes.
  - End cone can incorporate a viewport or berthing interface.



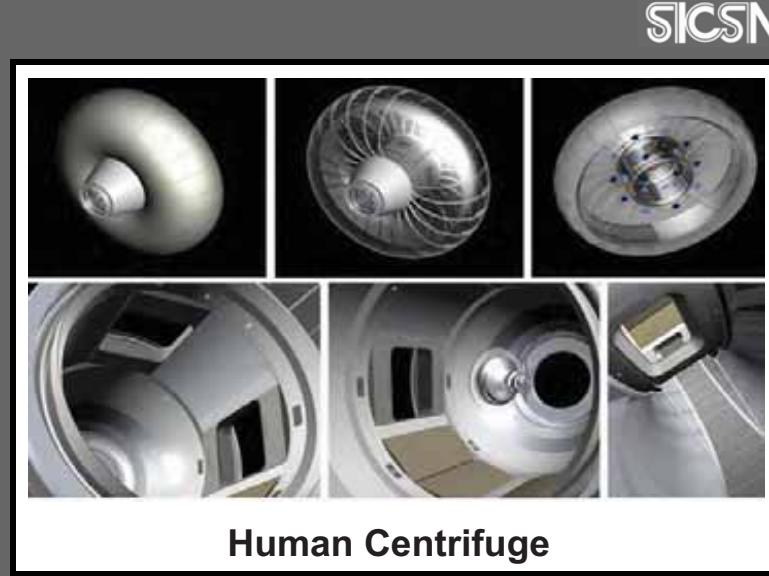
## ARTIFICIAL-G CONSIDERATIONS

## CENTRIFUGE DEVICES



Many organizations maintain and operate A-g centrifuges of varying types and sizes for terrestrial and space-related research experiments. All of these devices have limitations in answering comprehensive space adaptation questions:

- It is not possible by known means to cancel out Earth gravity influences upon Coriolis forces experienced by test subjects.
- Long-arm centrifuges are useful for calibrating human tolerances to angular velocities along with influences upon neurovestibular sensory disturbances, but restraints upon subject movement and activities limit adaptation/performance lessons.
- Subject suspended by tethers over large revolving drum surfaces are useful in assessing locomotion influences/ requirements, but pose activity adaptation limitations which are similar to other types.



## Space Research Approaches/Limitations

### ARTIFICIAL-G CONSIDERATIONS

### CENTRIFUGE DEVICES



Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
20 G Centrifuge	8.9	20.0	47	humans & other animals	hours
Man-Carrying Rotational Device (MCRD)	2.0 variable	4.5	48	humans, monkeys & rodents	weeks
Vestibular Research Facility	0.79	1.4	42	small monkeys & rodents	
24-Foot Diameter Centrifuge	3.7 variable	4.15	33	monkeys & rodents	months
52-Foot Diameter Centrifuge (2 Rotating Rooms)	8.0	3.0	20	humans, monkeys & rodents	months
8-Foot Diameter Centrifuge	1.25	10.0	89	rodents	months

#### NASA Ames Research Center

Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
Short-Arm Centrifuge	0.8	1.4	~33	1 human	hours
Artificial Gravity Simulator (AGS)	~2.55	2.0?	~28	4 humans	hours

#### NASA Johnson Space Center (JSC)

Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
Slow Rotation Room	3.4	4+	35	1-5 humans & other animals	weeks*
Centrifuge	1.0	2.5	50	humans	short

#### Brandeis University, Ashton Grabel Laboratory

### Research Equipment & Operations

## ARTIFICIAL-G CONSIDERATIONS

## CENTRIFUGE DEVICES



Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
Centrifuge Gondola	6.15	35	75	1-2 humans	hours
Centrifuge Equipment/Experiment Fixture	3.9	22	75	pigs, small primates, & other animals	days

**Brooks Air Force Base,  
USAF School of Aerospace Medicine**

Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
I, II	3.0	~4.5	~40	animals, ranging from chickens to rhesus monkeys (10K)	chronic
III Most similar to ISS Centrifuge	1.3	~3.5-4.0	~55	animals as large as squirrel monkeys	chronic
IV For profiles	~5	20.0	~62	animals as large as squirrel monkeys	short

**UC-Davis Chronic Acceleration Research Unit (CARU)**

Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
Multi-Axis Short-Arm Centrifuge	≤0.65 variable or 1 if fixed	1*	58.3	1 human	1 hour

\*dependant upon seat orientation

**Legacy Holladay Park Medical Center, Portland, Oregon**

Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
MIT Short-Arm Rotator	2.0	2.0	~31.0	1 human	10 hours
Defense & Civil Institute of Environmental Medicine (Toronto, Ontario)	6.1	15	48	1 human	hours

**Other North American Rotators**

**Research Equipment & Operations**

**ARTIFICIAL-G CONSIDERATIONS**

**CENTRIFUGE DEVICES**



Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
RAF Institute of Aviation Medicine, (Farnborough, UK)	9.14	5-10	30	2 humans & other animals	hours
Laboratoire De Medicine Aerospatiale (Bretigny, France)	6	15-40	80	1-2 humans & other animals	hours
TNO Institute for Perception (Netherlands)	~6.8	7.45	33	humans or other animals	hours
Tuebingen, Germany	1.5	16.5	33	1 human	hours
Konigsbruk, Germany	10	10	31	1-2 humans	hours
Royal Air Force of Sweden (Built by Wyle Labs)	~10	10	31	1-5 humans	hours

European Union

Device	Radius (m)	Maximum G Level	Maximum RPM	Passengers	Duration
Slow Rotation Room "Jupiter 2"	2.3	0.6	15	2 humans	7-10 days
Human Centrifuge "ASEA"	7.25	12	49.5	1 human	3 hours
Centrifuge "CF-4"	4	10	117	2 monkeys or other animals	1 hour
Centrifuge "CF-KB-365"	1.34	2	37.1	60 rats	3-6 weeks

Institute for Biomedical Problems, Moscow, Russia

## Research Equipment & Operations

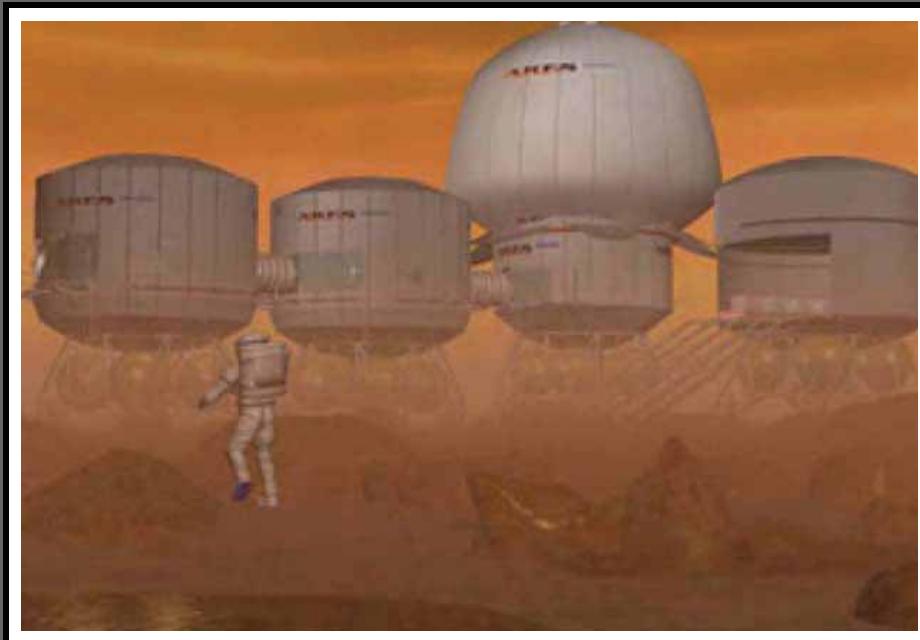
### ARTIFICIAL-G CONSIDERATIONS

### CENTRIFUGE DEVICES



D-1

## SECTION D : PARTIAL-G LUNAR/ PLANETARY ENVIRONMENTS





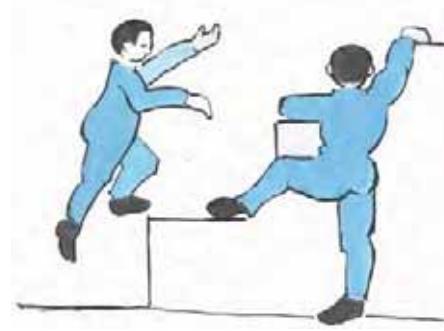
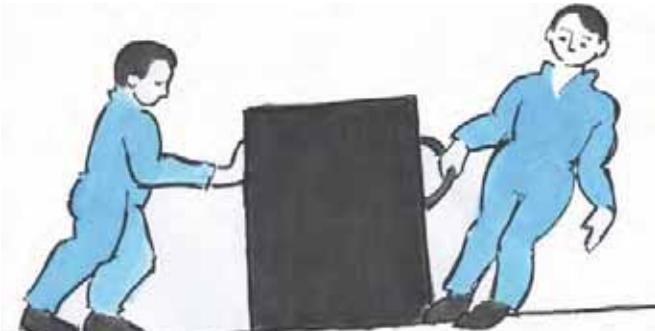
Partial-gravity conditions experienced on lunar/planetary surface missions will be more Earth-like than those associated with weightlessness or artificial-g.

- Astronauts will adopt 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

## PARTIAL-G CONSIDERATIONS

## HUMAN INFLUENCES

<p><b><u>Advantages:</u></b></p> <p>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.</p>	 <p>Lifting</p>	 <p>Jumping and Climbing</p>
<p><b><u>Disadvantages:</u></b></p> <p>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.</p>	 <p>Pushing and Pulling</p>	 <p>Torquing Down</p>

### Benefits and Limitations

## PARTIAL-G CONSIDERATIONS

## HUMAN INFLUENCES

Reduced gravity levels (0.16g Moon/0.38 g Mars) effect human locomotion by changing walking and running gaits, posture and traction:

Walking velocities partial-g are lower than on Earth:

- The speed at which walking changes to running is also slower, and the speed of running considerably slower than on Earth as well (6.04 m/sec under normal g vs. 3.99 m/sec on the Moon).
- According to 0.16g simulations, the most comfortable gait is “loping” at a speed of 3 m/sec, vs. 1.2 m/sec walking on Earth, an advantage afforded by reduced energy requirements for acceleration.



**Locomotion on Lunar Gravity**

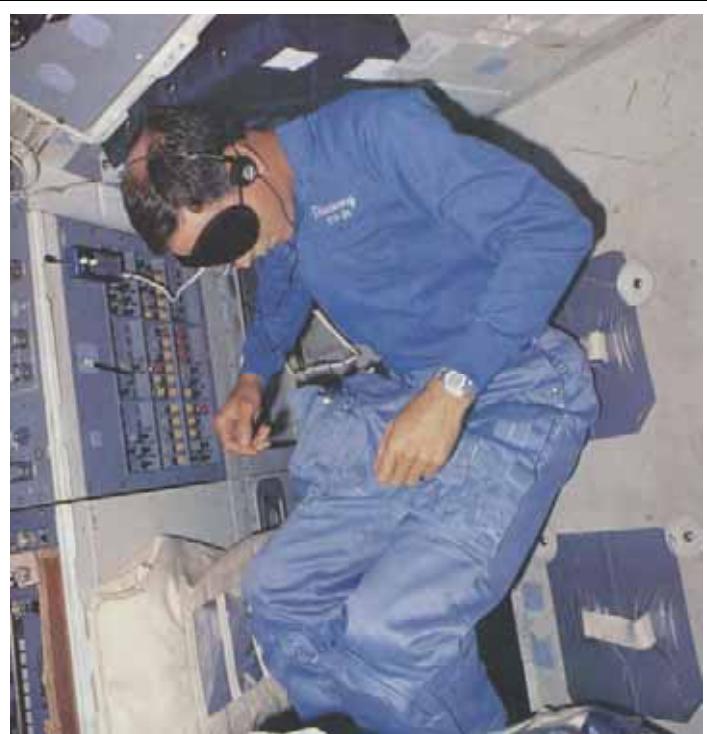
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## PARTIAL-G CONSIDERATIONS

## HUMAN INFLUENCES

Human posture during locomotion under partial-g conditions differs from posture during running on Earth:

- As speed is increased in lunar gravity, the angle of the forward body inclination becomes progressively larger. (The inclination of a sprinting gait on Earth is 10 degrees, while the loping gait on the Moon is 60 degrees.)
- Apollo Program experience indicates that a loping gate of about 3 m/sec is most comfortable with a forward body inclination of about 45 degrees.



**Body Posture in Reduced Gravity**

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## PARTIAL-G CONSIDERATIONS

## HUMAN INFLUENCES

Reduced traction under partial-g conditions influences human balance and locomotion:

- Limited friction between a person and the ground surface makes it more difficult to rapidly change positions to avoid moving or falling objects or to gain a surer foothold or handhold under hazardous circumstances.
- While the same inertial force is required to start moving from a complete stop, the ability of a person (or vehicle) to overcome that inertial force is reduced because of impaired surface traction.



**Surface Traction**

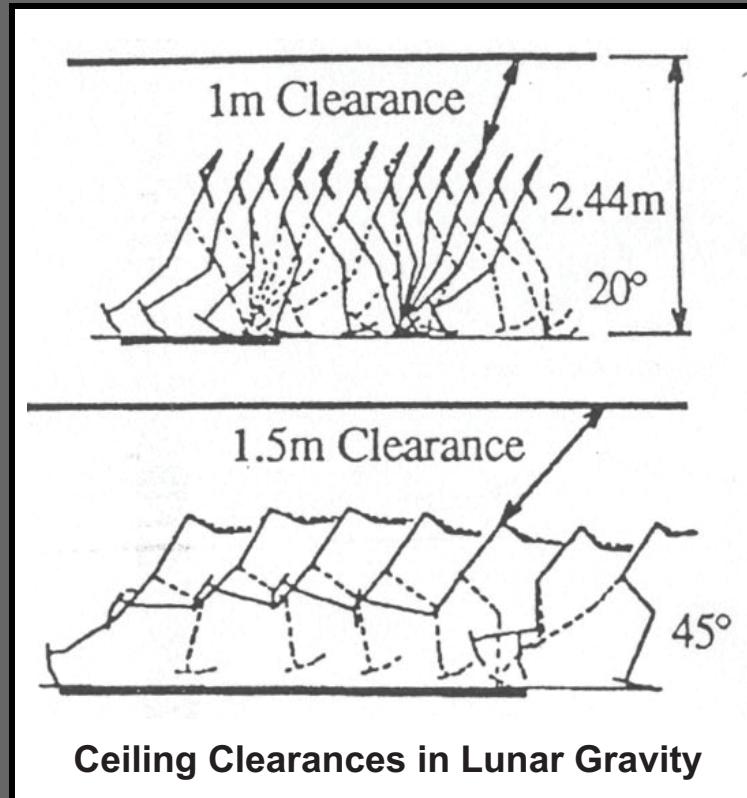
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## PARTIAL-G CONSIDERATIONS

## HUMAN INFLUENCES

People bounce higher when walking or running in reduced gravity, and although running within a space habitat would seem unlikely, some possible influences on ceiling heights might be considered:

- During normal walking in 0.16g (worst case between lunar and Martian applications), humans will probably bounce no higher than 2.44 m (standard Earth ceiling height) because their body inclination will be approximately 20 degrees.
- At a loping speed of 3 m/sec with a body inclination of 45 percent, a standard ceiling height would probably still be sufficient.

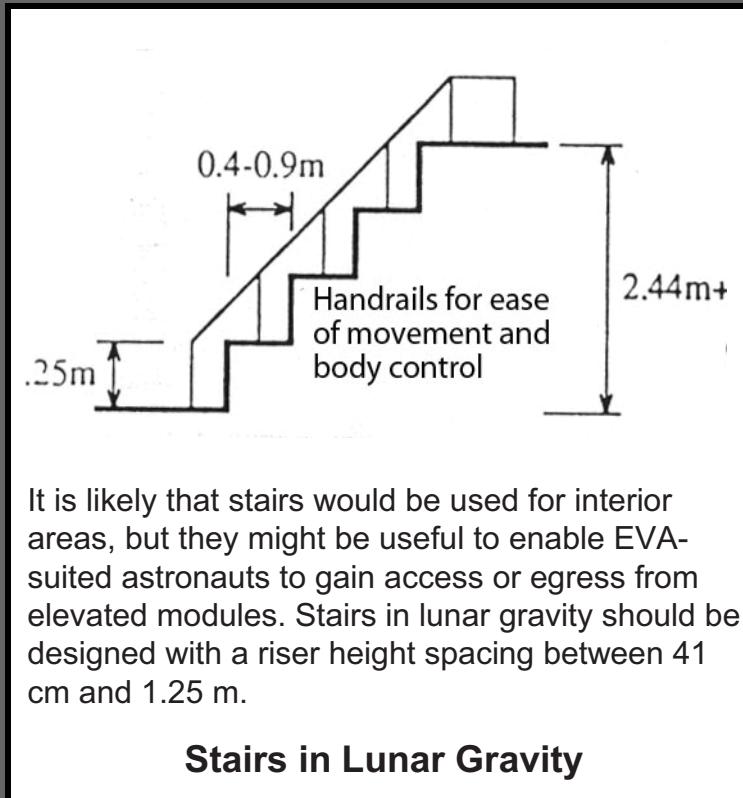


## PARTIAL-G CONSIDERATIONS

## DESIGN INFLUENCES

It should be no surprise that humans can jump higher under reduced gravity conditions:

- Tests have demonstrated that people can jump 3.7-4.3 m vertically in 0.16g when unencumbered by a spacesuit, while they can jump (rather than use stairs).
- Related tests show that the easiest way to access a landing height of 1.25m in 0.16g is simply to jump (rather than use stairs).
- Ladders are the most likely devices for vertical translation within small module habitats because they require very little space.



It is likely that stairs would be used for interior areas, but they might be useful to enable EVA-suited astronauts to gain access or egress from elevated modules. Stairs in lunar gravity should be designed with a riser height spacing between 41 cm and 1.25 m.

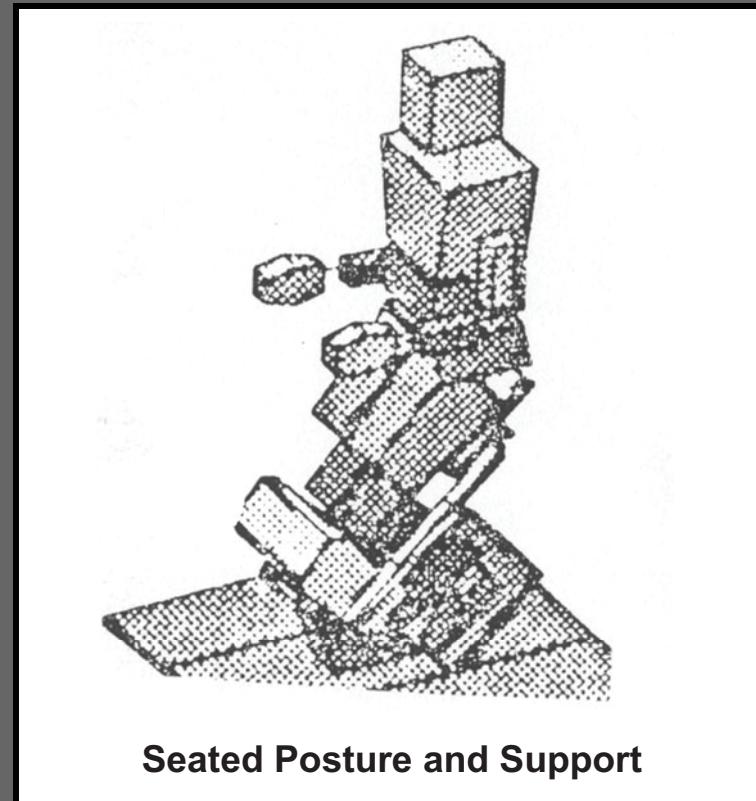
### Stairs in Lunar Gravity

## PARTIAL-G CONSIDERATIONS

## DESIGN INFLUENCES

In reduced gravity, a normal and comfortable sitting position will probably be different than on Earth:

- Earth gravity pulls the body into a nearly 90 degree normal and comfortable sitting position, and in microgravity the body assumes a "neutral buoyancy" posture. It is expected that reduced gravity will produce postures between these condition.
- It is theorized that seated body posture in 0.16g will be closer to the neutral buoyancy position, and could be accommodated by a system that supports the body only at the knees/thigh region.



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## PARTIAL-G CONSIDERATIONS

## DESIGN INFLUENCES



D-10

Reduced gravity conditions on the Moon and Mars will have important influences upon site planning, system engineering and operations:

**Disadvantages:**

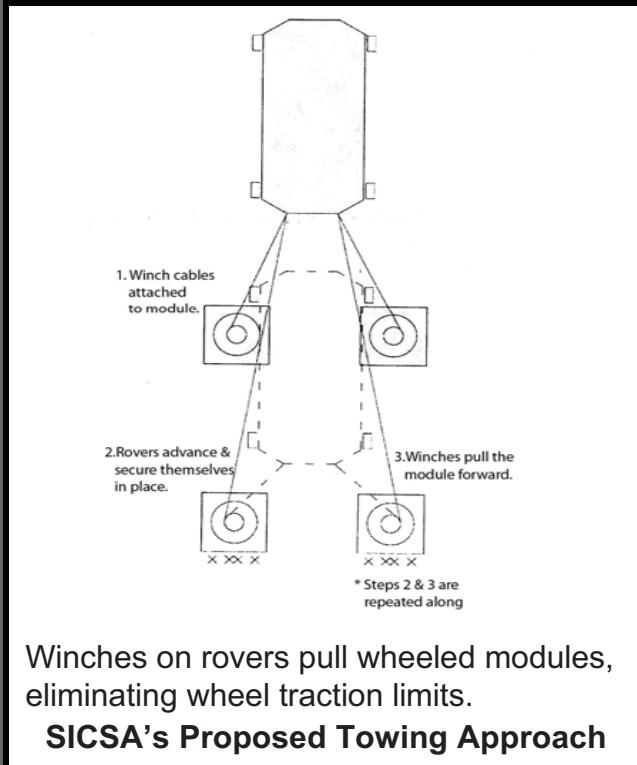
- Mobility vehicles and equipment used to tow, push or dig/drill into the surface will be handicapped with regard to wheel traction or mass to counteract mechanical forces.
- Landing/launch sites must be located at considerable distances from vulnerable/human facilities to minimize rocket thruster ejecta projectile hazards (reduced gravity and little or no atmosphere will extend ballistic ranges).

**Advantages:**

- As a benefit, people and equipment will be able to lift objects of much greater mass than they could on Earth, including structures, equipment and supplies.
- Enhanced abilities to lift will offer real advantages for crews who must transport/ relocate large equipment racks and, expendables and other elements without aid of cranes or other mechanisms.

**PARTIAL-G CONSIDERATIONS**

**SITE DEVELOPMENT/OPERATIONS**



Winches on rovers pull wheeled modules, eliminating wheel traction limits.



## Mobility and Support Systems

### PARTIAL-G CONSIDERATIONS

### SITE DEVELOPMENT/OPERATIONS



## Mobility and Support Systems

**PARTIAL-G CONSIDERATIONS**

**SITE DEVELOPMENT/OPERATIONS**



Mobile Power System:

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



Cargo Carrier:

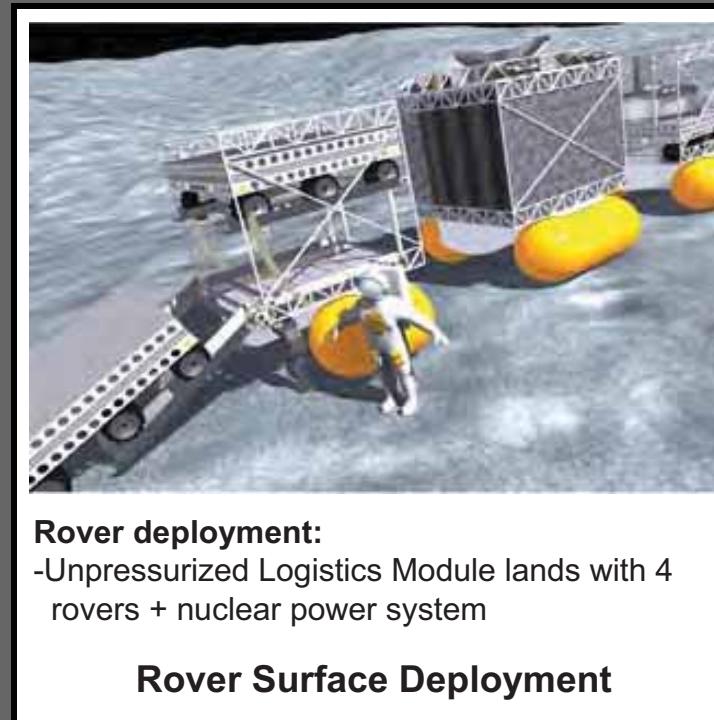
- flexible cargo area adapts to modular containers of varying size
- removeable guard rails secure payloads
- automatically controlled

### SICSA Rover System Adaptations

## Mobility and Support Systems

### PARTIAL-G CONSIDERATIONS

### SITE DEVELOPMENT/OPERATIONS



**SICSA**

## Mobility and Support Systems

### PARTIAL-G CONSIDERATIONS

### SITE DEVELOPMENT/OPERATIONS

CONSIDERATIONS	WEIGHTLESSNESS	ARTIFICIAL GRAVITY	PARTIAL GRAVITY
<b>Mobility and Operations</b>	Mobility aids and human/equipment restraint devices.	Interior and equipment layouts to minimize Coriolis influences.	Design/ operations to accommodate reduced traction/ leverage.
<b>Psychological Adaptation</b>	Appropriate visual orientation cues and information systems.	Approximate visual cues for orientations to spin the directions.	Apply some principles for good habitat design on Earth.
<b>Physical Adaptation</b>	Mobility aids/ restraint systems and exercise devices.	Design to accommodate tangential Coriolis forces and gravity gradients.	Exercise space and devices to compensate for reduced gravity levels.
<b>Engineering Design</b>	Design for equipment operations/ repair under zero-gravity.	Angular velocities/ gravity levels within performance boundaries.	Minimize structural and equipment mass for launch/ landing.
<b>Housekeeping And Maintenance</b>	Non-contaminating cleaning agents and easy-fix equipment.	Design for alternate artificial gravity and zero-gravity modes of operation.	Prevent EVA dust intrusion and avoid leverage constraints.

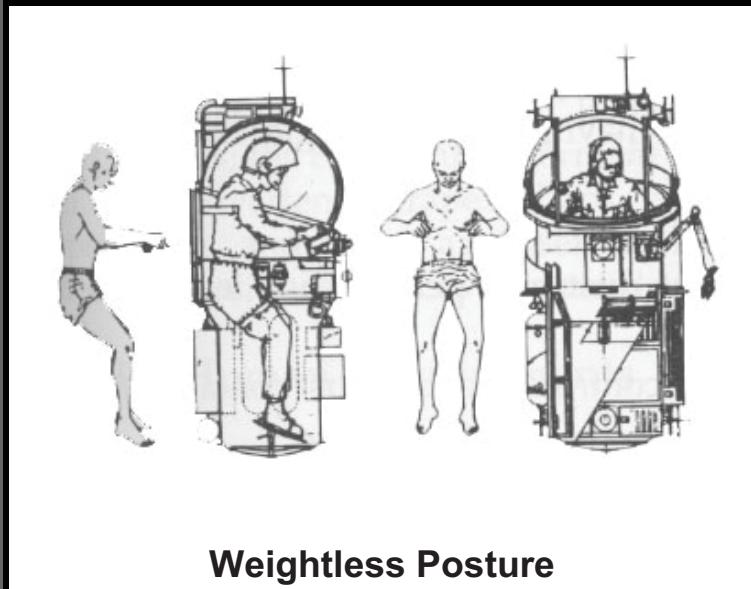
## Planning and Design Priorities

### PARTIAL-G CONSIDERATIONS

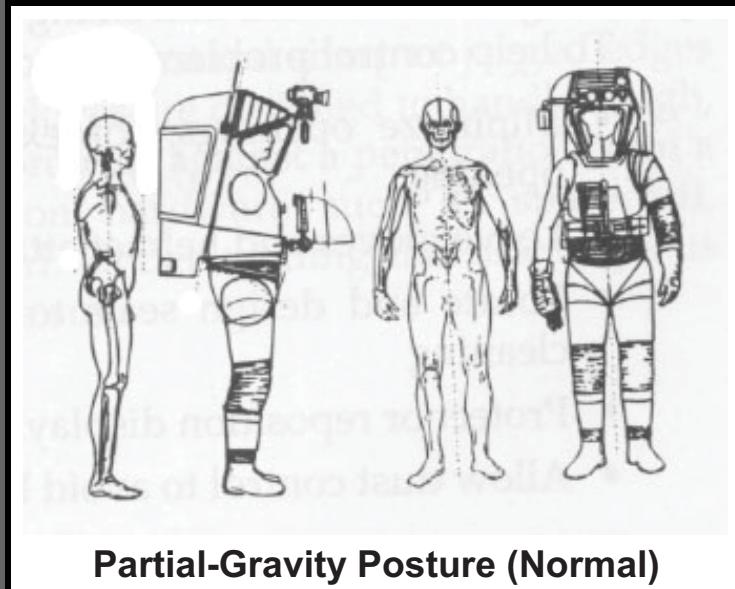
### SUMMARY COMPARISONS

## HUMAN SPACEFLIGHT

Changes in body posture under weightless and partial-gravity conditions must be considered in designing EVA systems and operations which are discussed in Section I.



**Weightless Posture**



**Partial-Gravity Posture (Normal)**

## Influences on EVA Design

### PARTIAL-G CONSIDERATIONS

### SUMMARY COMPARISONS



D-17

Additional information relevant to this section can be found in Part I, Section A (astrotectonics), C (habitat support systems) and E (robotic and mobility systems) of this SICSA Space Architecture Seminar Lecture Series, along with other publications listed below:

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## PARTIAL-G CONSIDERATIONS

## REFERENCES AND OTHER SOURCES



E-1

## SECTION E : PSYCHOLOGICAL & SOCIAL DESIGN CONSIDERATIONS FOR SPACE HABS



Prolonged space exploration missions will induce severe psychological and social stresses:

- Isolation and confinement:
  - Separation from loved ones, friends and community.
  - Lack of access to enjoyed places and activities.
  - Restricted volume, amenities and entertainment .
  - Interactions limited to a small group living and working in close quarters.
- Monotony and boredom:
  - Routine schedules dictated by mission requirements.
  - Altered day-night cycles without seasonal changes.
  - Tiresome tasks without access to "outside services".
  - Limited menu, clothing and environmental variety.

#### **Stress Inducements**

Psychological and social stresses can impair crew morale, performance and interpersonal relationships:

- Influences upon the individual:
  - Anxiety and depression leading to wide mood shifts.
  - Motivational impairments upon work performance.
  - Sleep patterns change causing fatigue and reduced alertness.
  - Antisocial actions that harm relationships and safety.
- Influences upon group behaviors:
  - Crew member and ground personnel conflicts.
  - Difficulties in working as a cooperative team .
  - Intolerances to small personality and action irritants.
  - Depression/paranoia impairing mission performance.

#### **Stress Reactions**

## **PSYCHO-SOCIAL CONSIDERATIONS**

## **GENERAL INFLUENCES**



Influences effecting psychological and social stressors include:

- Personal space infringements associated with crowding and limited volume, comfort and privacy.
- Demanding activities and schedules (stimulus overload and deprivations).
- Lack of personal choices (inabilities to exercise control over decision and behavior options).
- Complexities/ difficulties of tasks (and limitations upon people/ tools for these tasks).
- Isolation from outside contacts (limited window views and communications with loved ones).
- Constrained variety (food menu, internal furnishings, clothing and other choices).
- Character of the sensory environment (aesthetics, lighting systems, colors and materials).

#### Environmental and Operational Influences

Mission success and safety depends upon the mental health and stability of each individual:

- The uncontrollable actions of one person can jeopardize the entire crew.
- Unlike life on Earth, one cannot leave the problem by getting out of the environment.
- Fatigue and physiological deconditioning will impair abilities to cope with frustrations over time.
- Individuals must be prepared to "fill in" for others who become ill or incapacitated.
- Accidents, mechanical emergencies and other unscheduled problems will demand teamwork.
- Future mission crews may be more technically trained, but have less "right stuff" spirit.
- Small interpersonal disagreements can lead to serious conflicts without opportunities to "cool off".

#### Special Behavioral Implications

### Stress factors and impacts

## PSYCHO-SOCIAL CONSIDERATIONS

## GENERAL INFLUENCES

Attitudes and performance on long missions will be influenced by:

- Professional and cultural backgrounds of individual crew members.
- Personal background, maturity, competence and personalities.
- Who they are confined with and the organizational, decision-making/ leadership structure.
- The nature and length of preflight training that the crew has experienced together.
- The crew mix (personalities, language/ culture, age, gender and professional backgrounds).

#### Crew Backgrounds and Mix



Docking of Apollo and Soyuz

### Stress Responses and Changes

## PSYCHO-SOCIAL CONSIDERATIONS

## GENERAL INFLUENCES



Various people react differently to the same surrounding conditions and stimuli:

- Some can adapt more readily to close living contact and crowding than others.
- Attitudes and expectations regarding privacy can be influenced by cultural backgrounds.
- Individuals respond differently to stress and abilities to work under pressure.
- Extroverted vs. introverted tendencies, humor and communication skills influence interpersonal relations.
- Aesthetic preferences and responses to particular foods, smells and music tend to be personal.

#### Personal Differences

Behavioral and mood changes often occur over the period of a long mission:

- Crew morale is typically highest at the beginning of the experience.
- Individual and team spirit often bottoms out after the middle of the stay.
- Morale can be elevated by special events and communications (mail drops/ supply ships).
- Unscheduled emergencies, task schedule slippages and interpersonal conflicts can cause depression.
- Crew bonding is often most apparent near a missions end.

#### Mission Time/Event Influences

### Individual Differences and Responses

## PSYCHO-SOCIAL CONSIDERATIONS

## GENERAL INFLUENCES



Good space mission planning must consider appropriate human-machine roles and relationships:

**What humans do best:**

- Pursue a diverse range of tasks, including many that require mobility and dexterity.
- Respond to unplanned opportunities and problems with innovative solutions.
- Recognize, interpret and respond appropriately to complex patterns of sound.
- Reason inductively to exercise judgment with limited and incomplete data.
- Store experiential information and recall relevant facts at appropriate times.

**What machines do best:**

- Respond rapidly to control signals and handle numerous complex tasks simultaneously.
- Perform routine/ exacting tasks reliably without fatigue.
- Store/ process large amounts of complex data using deductive methods.
- Apply great force smoothly and precisely with or without human control.
- Handle hazardous tasks under extreme environmental conditions.

**Human vs. Machines**

**PSYCHO-SOCIAL CONSIDERATIONS**

**GENERAL INFLUENCES**



**Experiences on US and Russian spacecraft, polar stations and underwater vessels have revealed a variety of common issues:**

- Cut off from “the outside”, crews must learn to be resourceful, and to depend upon one another:
  - They must work to help crewmates deal with mental and physical stresses.
  - They are required to adapt to a lack of familiar comfort and recreational amenities.
  - They must be prepared for fatiguing work overloads and stimuli deprivations.
  - They must be prepared to address equipment malfunctions that can jeopardize activities and lives.
- Common types of constraints place severe requirements and restrictions on habitat design and operations:
  - Limitations on internal volumes that can be delivered to support human activities.
  - Limitations on equipment, labor and processes for structure assembly/deployment.
  - Limitations on maintenance and repairs (people, tools/ spares and methods).
  - Safety and operations under harsh environmental conditions and demanding mission schedules.

### Common Extreme Environment Issues

#### PSYCHO-SOCIAL CONSIDERATIONS

#### ANALOG EXPERIENCES



Small Antarctic research stations, such as the 20-person US South Pole facility, present conditions which are similar in many respects to those that will be encountered on future lunar and planetary surface missions:

- Teams of highly motivated and trained personnel must learn to live and work together under remote, dark and hazardous conditions.
- Monitoring of crew adaptation and performance influences under analogous circumstances can yield important lessons.



**Small Antarctic Stations as Analogs**

## PSYCHO-SOCIAL CONSIDERATIONS

## ANALOG EXPERIENCES



Confinement on submarines can also provide behavioral data that can be informative for planning prolonged space missions:

- A large quantity of psychological data has been collected since 1953 about human adaptation and performance under adverse and stressful conditions.
- Crew populations on modern US ballistic missile submarines are relatively large, typically about 140 officers and enlisted personnel, creating cramped living conditions.
- Crews however, are primarily young single men, who are likely to be more homogenous than future space voyagers.



Nuclear Submarines as Analogs

## PSYCHO-SOCIAL CONSIDERATIONS

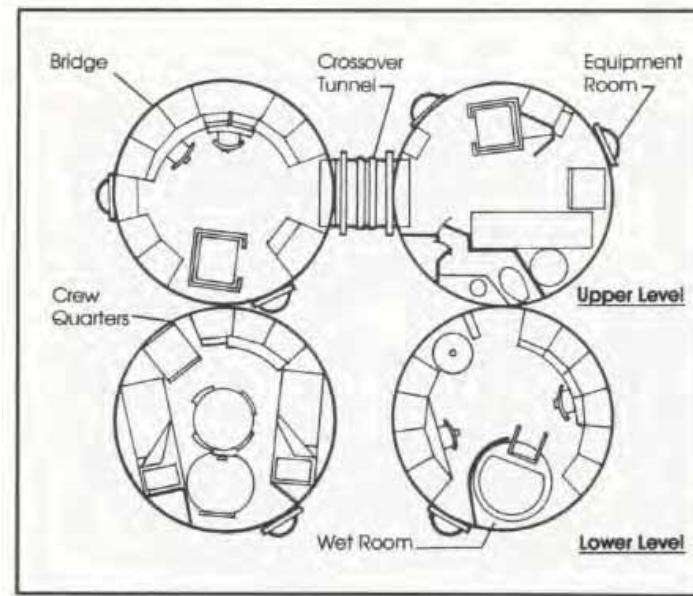
## ANALOG EXPERIENCES

### **Manned Life Support System Tests (1968-71):**

McDonnell Douglas conducted 60 day (1968) and 90 day (1971) tests in which crews of four were enclosed in sealed cabins to test regenerative life support systems. Abilities of crews to maintain physiological and psychological health were evaluated.

### **Tektite (1969-1970):**

The US Office of Naval Research sponsored an experiment in which four crewmembers were housed in an undersea habitat for 60 days. A key purpose was to study small group behavior and effectiveness under stressful, isolated conditions.



**Underwater Tektite I and II Habitat**

### **Controlled Isolation Experiments**

## **PSYCHO-SOCIAL CONSIDERATIONS**

## **ANALOG EXPERIENCES**

Confined conditions on spacecraft, at small polar stations and in nuclear ballistic submarines challenge crews to adjust expectations and lifestyles:

- Privacy, personal belongings and recreation options are severely limited by interior volume constraints.
- Meals take on special importance as times to talk and as events to structure daily schedules.
- Simple activities such as outside viewing through windows are often highly valued (Periscope viewing is regarded as a treat on submarines).



**Mealtime in Space**

### Crew Lifestyle Adjustments

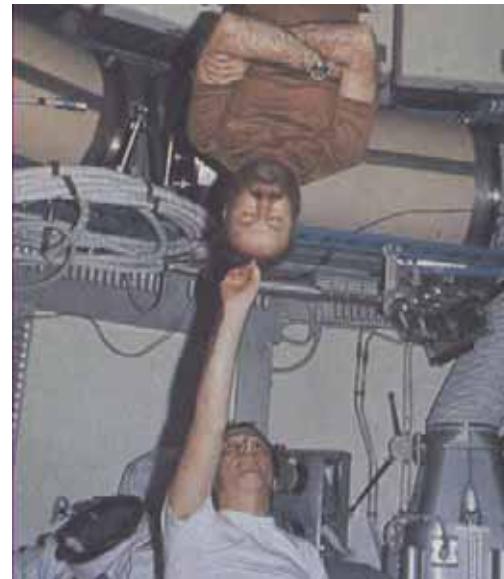
## PSYCHO-SOCIAL CONSIDERATIONS

## HUMAN FACTORS

NASA

Much remains to be learned about prolonged altered gravity effects upon humans in space:

- While US *Skylab* and Soviet space station missions have yielded substantial data about physiological effects of weightless conditions over periods up to a year, possible weightless effects during longer future exploration voyages remain unknown .
- Also not understood is how long humans can remain healthy in the reduced gravity of the Moon and Mars (about 1/6 and 1/3 Earth gravity, respectively).



Weightlessness Onboard Skylab

## Adaptation to Reduced Gravity

### PSYCHO-SOCIAL CONSIDERATIONS

### HUMAN FACTORS

NASA

Planning and accommodations should provide means to prevent and respond to crew health problems:

- Special concerns include airborne infections; toxic substance and radiation exposures; chemical and electrical burns and shocks; lacerations and fractures; and “bends” occurrences following extravehicular activities.
- Surgery and other radical procedures may be precluded by limited equipment, expertise and unsanitary conditions.
- Crewmembers will require training to perform tooth extractions and other paramedical procedures on each other.



Health Care Onboard Skylab

## Preventive and Emergency Health Care

**PSYCHO-SOCIAL CONSIDERATIONS**

**HUMAN FACTORS**

Minimizing perceived and real safety risks is essential to crew morale and wellbeing:

- Limited spare parts, tools and repair specialty skills on long missions will demand high levels of system reliability.
- Crews must be cross-trained to undertake critical functions previously performed by an incapacitated or deceased team member.
- All maintenance and repair operations must be planned to be as simple as possible, using standardized parts and tools.
- Comprehensive instructions must be available to cover all contingencies in event of lost communication with ground support.



**Maintenance Operation in Microgravity**

## **Maintenance and Safety**

## **PSYCHO-SOCIAL CONSIDERATIONS**

## **HUMAN FACTORS**

**Environmental Systems and Features:**

- **Air quality and comfort:** Control of breathing atmosphere, temperature and humidity is important for crew health and comfort.
- **Noise control:** Objectionable sounds from fans, motors and other equipment can interrupt sleep and task performance concentration.
- **Lighting systems:** Highest illumination levels are required for hygiene and workstation activities. (Psychologically, Russian cosmonauts increasingly desired more light as time passed.)
- **Color and décor:** Some crewmembers criticized the drab, monotonous colors on *Skylab*, demonstrating that aesthetics and variety are important considerations.

The Interior Environment

**Crew Living Accommodations:**

- **Privacy and leisure:** *Skylab* demonstrated the importance of individual sleep areas to provide privacy from fellow crew and ground monitoring.
- **Dining/ menu selection:** Meals onboard *Skylab* were important social periods and broke up the day. Food variety is important, and taste preferences change in space.
- **Exercise:** In space it is vital to health, but becomes boring. The favorite *Skylab* recreation was window viewing of the Earth.
- **Toilet and hygiene:** Commode malfunctions in space can have serious consequences. Personal hygiene is laborious, but vital to health and morale.

Interior Accommodations

**Habitability Lessons**

**PSYCHO-SOCIAL CONSIDERATIONS**

**HUMAN FACTORS**

Lighting, color and music can offer needed variety and influence positive moods:

- Soviet space experience indicates that a desire for brighter illumination increases with mission length. (Higher lighting levels appear to help counteract fatigue and decreased visual and mental acuity over time).
- Some Skylab astronauts emphasized the importance of having good adjustable task lighting and color variety to offset monotony.
- Antarctic crews and Soviet cosmonauts have emphasized the importance of music on long missions. (Russians often programmed music to complement activities).



**Cosmonauts During Leisure Time**

### **Lighting, Color and Music**

## **PSYCHO-SOCIAL CONSIDERATIONS**

## **HUMAN FACTORS**

**Anthropometric and ergonomic factors:**

- Influences on design and dimensioning of equipment and work surface heights.
- Influences on reach envelopes and general task procedures/ performance.
- Influences on force requirements and leverage constraints for various tasks.

**Internal equipment layouts and designs:**

- Optimum utilization of walls, floors and ceilings with local vertical 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.

**Restraints and mobility aids:**

- Hand-holds, foot restraints and body leverage devices for various tasks.
- Means to secure diverse items while stored and in use.

**Micro and Reduced Gravity Conditions**

**Habitat and equipment layout:**

- Avoidance of traffic obstacles and circulation bottlenecks.
- Separation of living and work areas, quiet and noisy areas, and private areas.
- Rapid and easy crew emergency egress and critical equipment repair access.
- Convenient arrangements of related functions and equipment.
- Ample volumes for group gatherings and maintenance operations.

**Equipment operability and servicing:**

- Standardization of monitors and controls to optimize coherence and familiarity.
- Adequate lighting, contrast and controls for precise and critical tasks.
- Simplicity of operations with clear and complete instructions.
- System/ subsystem accessibility with quick and easy disconnects.
- Adequate spares, tools and instructions.

**General Space Conditions**

**Human Engineering Influences**

**PSYCHO-SOCIAL CONSIDERATIONS**

**HUMAN FACTORS**

Attitudes and performance on long-duration missions are influenced by the crew mix:

- Their individual professional and cultural backgrounds; their maturity, competence and personalities; the way they and others perceive their roles; and the leadership structure with which they must comply.
- Heterogeneous crew mixes present challenges. Soviet experiences have revealed that language and cultural differences within multinational crews can present significant interpersonal problems.
- Conflict potentials increase with time due to fatigue and the limited outlets for emotional relief which strain tolerance levels.



STS-104 ISS Crew

## Crew Composition and Relationships

### PSYCHO-SOCIAL CONSIDERATIONS

### HUMAN FACTORS



### Cosmonaut Selection Considerations:

Since the beginning of their space program, the Russians have applied rigorous psychological testing and training prior to flight. Important cosmonaut selection criteria include:

- A low general anxiety level.
- An emotionally well-balanced outlook.
- An extrovert personality.
- High-level intellectual/ perceptive abilities.
- Steady voluntary attention spans.
- Good attention separability/ changeability.
- Good memory for details.
- A capability to control personal reactions.

### Crew Organization and Schedules:

- **Size and composition:** Small crews often have high levels of interdependency. The mix of skills, cultural/ professional backgrounds and personalities is important.
- **Sex and role identity:** Crews must avoid stereotypic views and behavior. They must be versatile to adapt to changing circumstances and needs as required.
- **Leadership and motivation:** Teams can be organized around democratic or authoritarian models. Mutual respect and confidence must be common to both.
- **Activity schedules:** All experience demonstrates that good crew morale and performance requires a proper balance between work and leisure.

## Crew Selection and Activities

### PSYCHO-SOCIAL CONSIDERATIONS

### HUMAN FACTORS

Soviet training programs subject cosmonauts to survival challenges aimed at building self confidence and discipline:

- Early training involves more than 100 parachute jumps, many requiring cosmonauts to complete check lists or other tasks during free fall periods.
- Later tests abandon trainees in remote, environmentally-hostile locations where they suffer extreme temperatures, loneliness, hunger and thirst for days.
- Training also includes intensive self-programming courses to prepare them for interpersonal pressures and performance of any necessary task without hesitation.



Cosmonaut Underwater Training

### Psychological Testing for Crews

## PSYCHO-SOCIAL CONSIDERATIONS

## HUMAN FACTORS



E-21

Additional information relevant to this section can be found in Part I, Section B (space structures and applications) and Part III, Section D, (crew selection and requirements) of this SICSA Space Architecture Seminar Lecture Series, along with other publications listed below:

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## PSYCHO-SOCIAL CONSIDERATIONS

## REFERENCES AND OTHER SOURCES



F-1

## SECTION F : FUNCTIONAL AREAS AND SUPPORT ACCOMMODATIONS



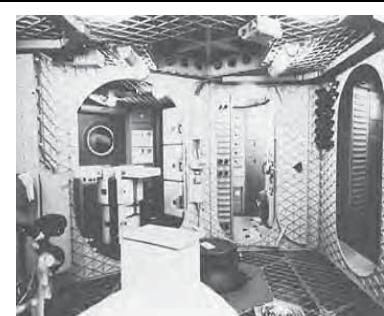


Human roles and accommodations have advanced significantly during the short history of space flight:

- Mercury astronauts, functioning primarily as passive passengers, endured 40 cu. ft. capsules.
- Gemini capsules which enabled astronauts to pilot their spacecraft carried 2 people (60 cu. ft.).
- Apollo Command Modules provided about 240 cu. ft. for 3-person crews.
- Skylab offered about 9,950 cu. ft. of volume, nearly 45 times the space available for Apollo missions.
- Skylab's Orbital Workshop was divided into 2 levels, with ample volumes for living, exercise and work.
- While Space Shuttle Orbiter crews accept cramped quarters without privacy or amenities, the missions are short.
- International Space Station (ISS) modules are much smaller than Skylab, but missions are also quite short.
- Large volume inflatable modules are being developed for expanded orbital populations and extended exploration missions.



Gemini Capsule



Skylab Interior



Shuttle Orbiter Interior



Bigelow Aerospace Module

## Crew Accommodations

### FUNCTIONAL AREAS/ACCOMMODATIONS

### BACKGROUND



“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

### FUNCTIONAL AREAS/ACCOMMODATIONS

### BACKGROUND



F-4

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

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Functional Unit

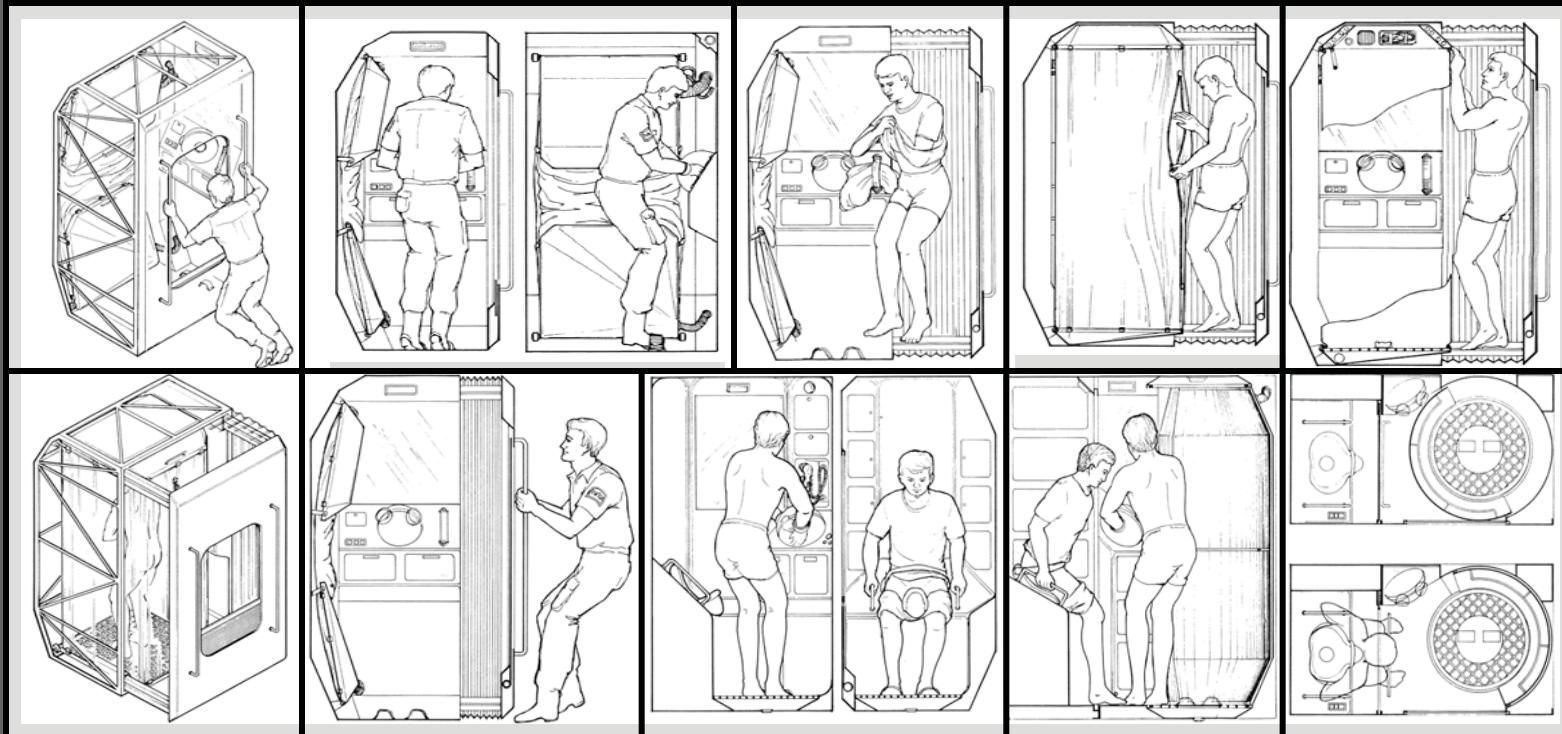
Rack

Modular Enclosure Approach

FUNCTIONAL AREAS/ACCOMMODATIONS

BACKGROUND

**BELL & TROTTI, INC**



**Bell & Trottini, Inc. Functional Unit Concepts**

**FUNCTIONAL AREAS/ACCOMMODATIONS**

**BACKGROUND**

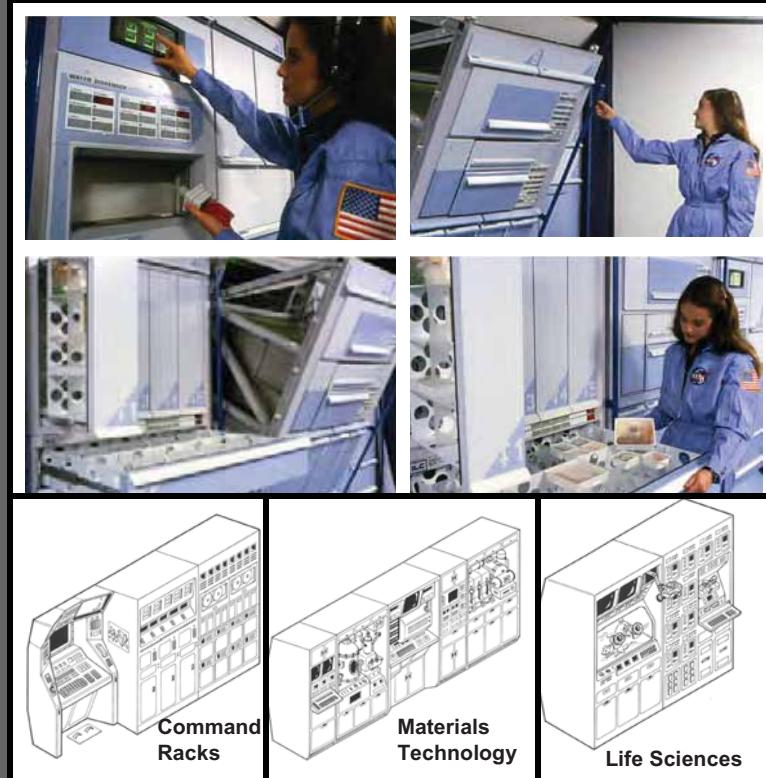


F-6

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 & Trottini, Inc. Rack Concepts

FUNCTIONAL AREAS/ACCOMMODATIONS

BACKGROUND

### 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 utensil 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.

### Crew Support Areas & Elements

## FUNCTIONAL AREAS/ACCOMMODATIONS

## FACILITIES



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

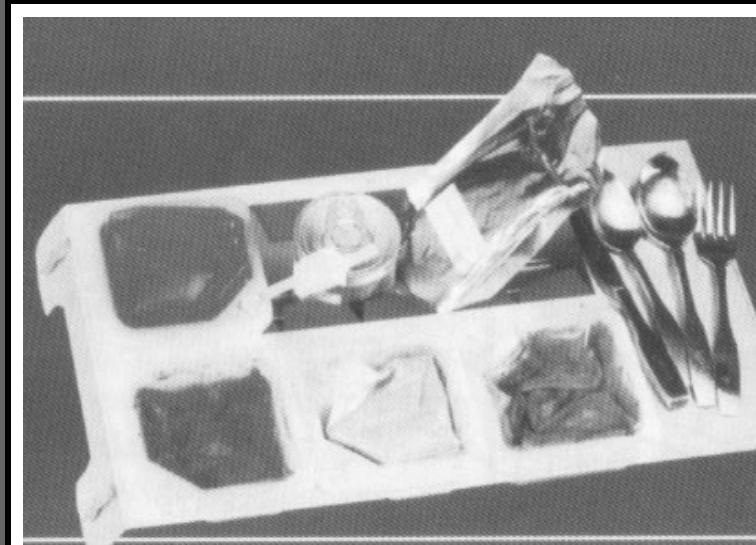
## FUNCTIONAL AREAS/ACCOMMODATIONS

## FACILITIES

## INTRODUCTION TO SPACE

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 be 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

## FUNCTIONAL AREAS/ACCOMMODATIONS

## FACILITIES

## SPACECRAFT SYSTEMS DESIGN & OPERATIONS

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.

### Special Galley Considerations

## FUNCTIONAL AREAS/ACCOMMODATIONS

## FACILITIES



F-11

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 by 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 .

### SPACECRAFT SYSTEMS DESIGN & OPERATIONS



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

## FUNCTIONAL AREAS/ACCOMMODATIONS

## FACILITIES

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.



## Exercise & Recreation

### FUNCTIONAL AREAS/ACCOMMODATIONS

### FACILITIES



F-13

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



## Special Exercise Considerations

### FUNCTIONAL AREAS/ACCOMMODATIONS

### FACILITIES

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

### FUNCTIONAL AREAS/ACCOMMODATIONS

### FACILITIES



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)

## SPACECRAFT SYSTEMS DESIGN & OPERATIONS

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, intravenous administration, and intravenous "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**

## Special Health Maintenance Considerations

### FUNCTIONAL AREAS/ACCOMMODATIONS

### FACILITIES

**SPACECRAFT SYSTEMS  
DESIGN & OPERATIONS**



Trauma Subpack



Airway Subpack



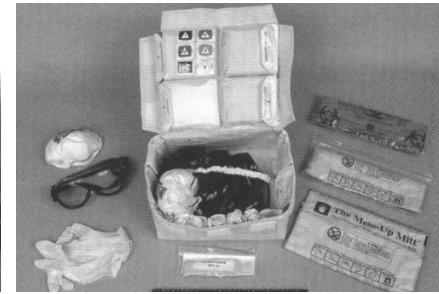
Defibrillator



Advanced Life Support Pack



Respirator Support Pack



Containment Cleanup Kit

**Special Health Maintenance Considerations**

**FUNCTIONAL AREAS/ACCOMMODATIONS**

**FACILITIES**



F-17

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.

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Bell & Trottini, Inc. Concept/Mockup

Personal Hygiene

FUNCTIONAL AREAS/ACCOMMODATIONS

FACILITIES



F-18

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.)

NASA



Shower in Skylab

## Special Hygiene Considerations

### FUNCTIONAL AREAS/ACCOMMODATIONS

### FACILITIES



F-19

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.

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Bell & Trottini, Inc. Concept/Mockup

Waste Management

FUNCTIONAL AREAS/ACCOMMODATIONS

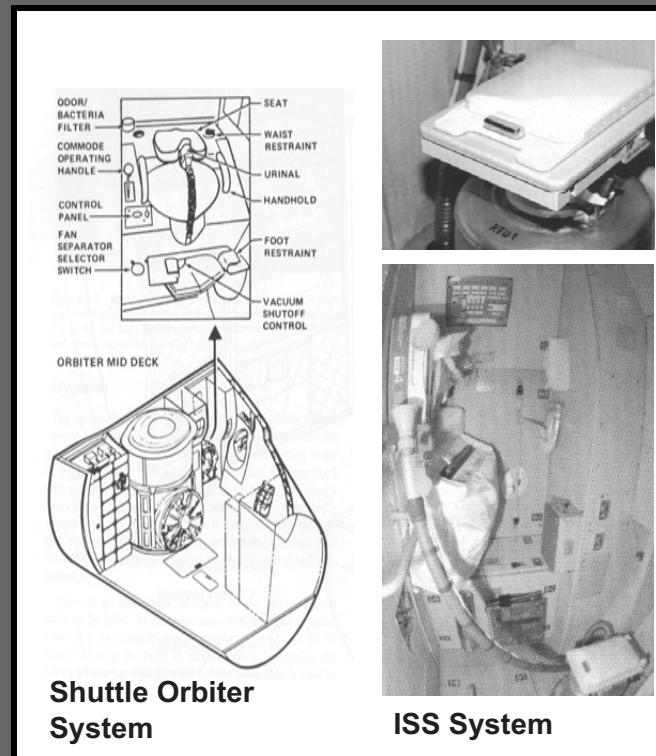
FACILITIES

## INTRODUCTION TO SPACE

### SPACECRAFT SYSTEMS DESIGN & OPERATIONS

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.



## Special Waste Management Considerations

### FUNCTIONAL AREAS/ACCOMMODATIONS

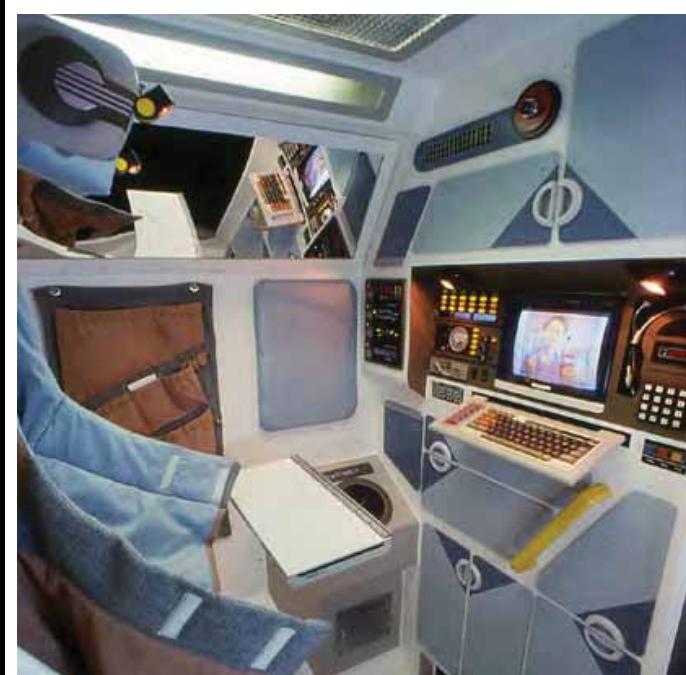
### FACILITIES



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.

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**Bell & Trottini, Inc. Concept/Mockup**

## Microgravity Sleeping Quarters

### FUNCTIONAL AREAS/ACCOMMODATIONS

### FACILITIES



F-22

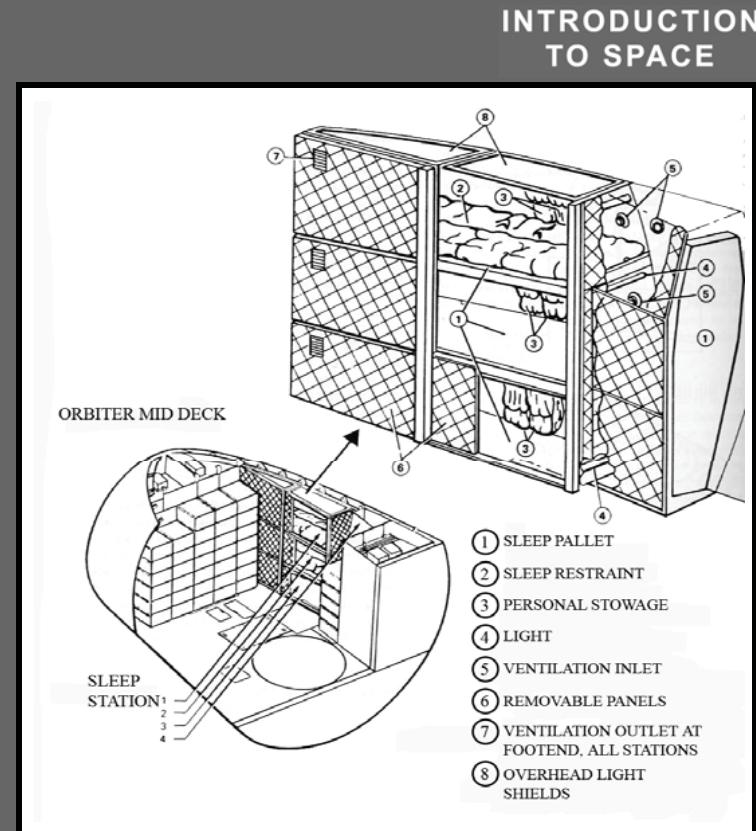
Under weightless conditions, astronauts need not lie "down" to sleep, and some have slept while simply floating around the spacecraft:

- 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

### FUNCTIONAL AREAS/ACCOMMODATIONS

### FACILITIES



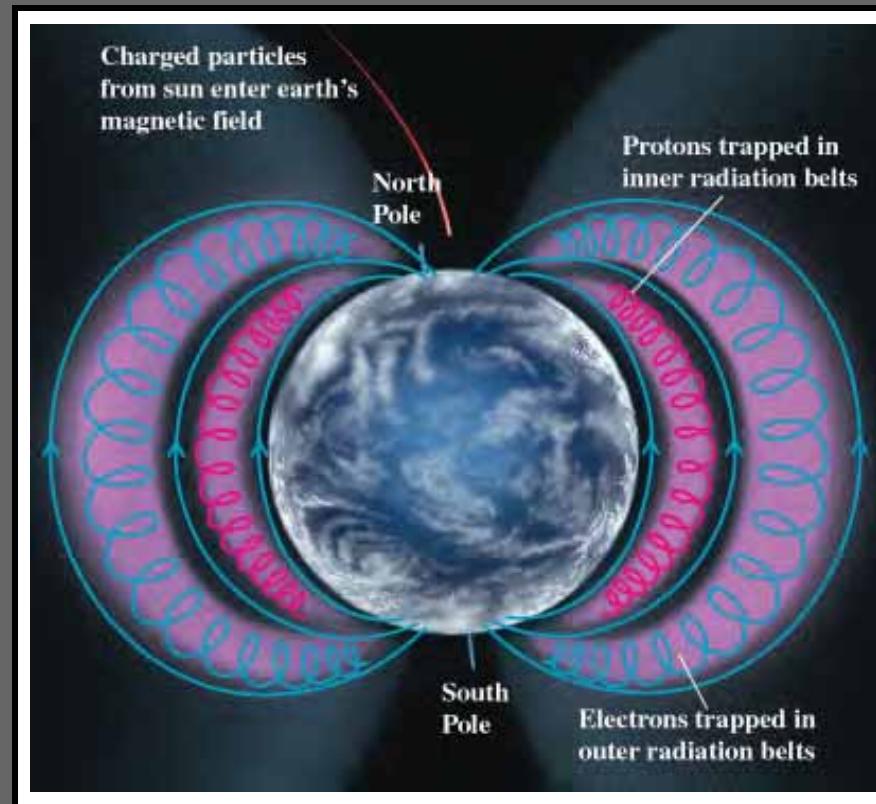
Additional information relevant to this section can be found in Part I, Sections B (space structures) and C (habitat support systems) of this SICSA Space Architecture Seminar Lecture Series, along with other publications listed below:

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## FUNCTIONAL AREAS/ACCOMMODATIONS

## REFERENCES AND OTHER SOURCES

## SECTION G : SPACE RADIATION EFFECTS AND SAFEGUARDS





The Sun is a medium-sized star composed primarily of hydrogen:

- The Sun is located 152 million km from Earth:
  - It contains one million times Earth's volume.
  - Its diameter is 110 times larger than Earth's.
- Nuclear fusion of hydrogen at enormous pressure produces helium at 300 million degrees:
  - Hydrogen fusion causes emission of charged particles, radiation, meteoroids, cosmic rays and electromagnetic waves.
  - The Sun is responsible for Earth's weather, but only 2 billionth of the sun's total energy reaches our planet.
- Solar proton storms extend far beyond Earth, presenting radiation hazards to exposed astronauts and spacecraft equipment:
  - The Earth's magnetosphere and atmosphere provide substantial shielding on the surface.
  - Operations in LEO receive benefits from Earth's magnetosphere to reduce hazards.
  - The Van Allen Belts that surround Earth trap radiation, creating a very hazardous zone.



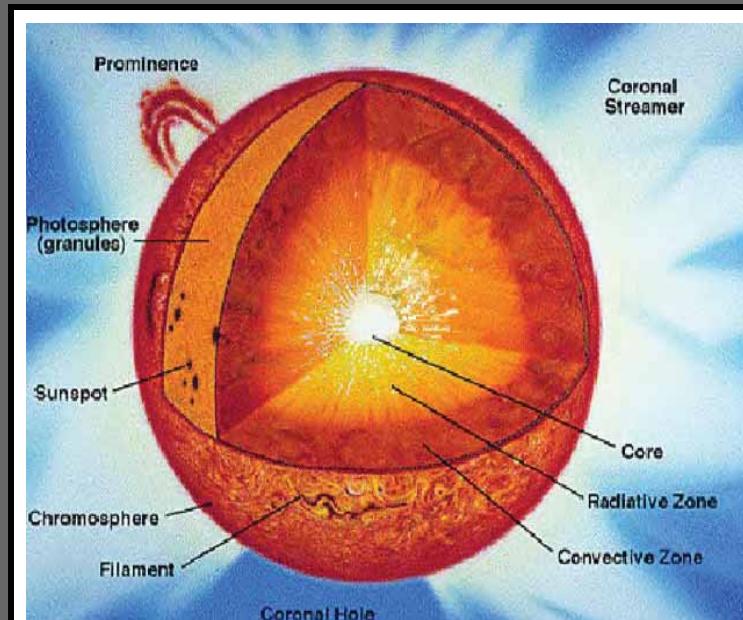
## The Sun's Influences

### SPACE RADIATION

### BACKGROUND

The Sun's structure is comprised of a core, a photosphere, a chromosphere and a corona:

- The core is the innermost 10 percent of the Sun's mass where energy from nuclear fusion is generated:
  - The core temperature reaches 16 million K, and the density is 160 g/ cm<sup>3</sup>.
  - Energy is transported outward by radiation in the convective envelope zone.
- Rising and falling gas transfers energy to the photosphere (the Sun's visible surface):
  - Dark sunspots from which rope-like magnetic fields rise and descend are known as "coronal holes".
  - The chromosphere is a thin layer above the photosphere and is hotter than the photosphere (the temperature increases outward into the corona).
  - Fast-moving ions from the corona escape the sun to form solar winds.



**The Sun's Structure**

## Solar Processes

### SPACE RADIATION

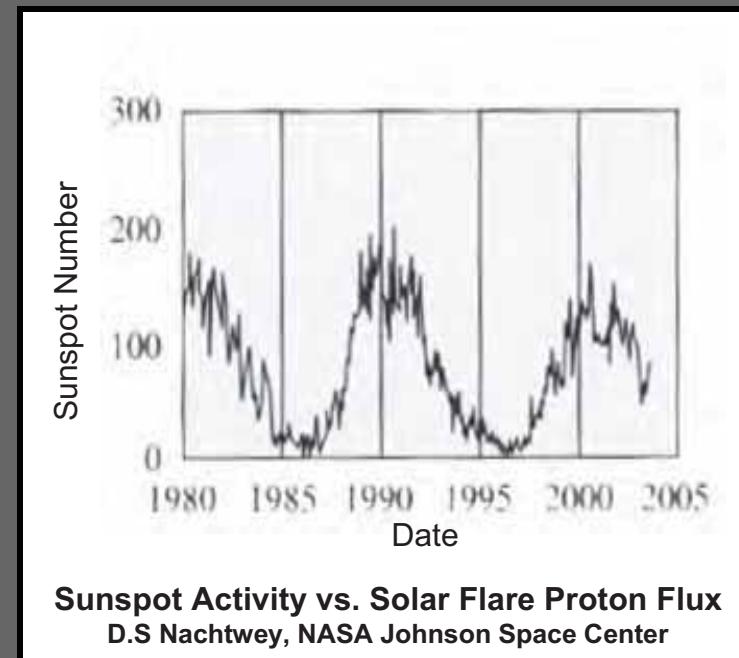
### BACKGROUND



Sunspots are “cool” regions which form in the photosphere (7,600°F) that accompany other surface events which fluctuate in frequency over 11 year cycles:

- At “solar maximum” more bright clouds of gas called “prominences” form above sunspots, as well as powerful solar flare eruptions:
  - Smaller “quiet prominences” form either in the corona about 40,000 km above the surface or in loops of hydrogen that follow magnetic field loops.
  - “Surge” prominences lasting up to a few hours shoot gas up to 300,000 km.
  - Solar flare electrons and protons move with enough energy to escape the Sun’s gravity and reach beyond Earth.
  - Solar flares can interfere with radio communications on Earth and in space, and present radiation hazards to expeditions beyond LEO.

## SPACECRAFT SYSTEMS DESIGN & OPERATIONS



## Solar Events

### SPACE RADIATION

### BACKGROUND

Solar energetic particles (including electrons and protons) comprise the “solar wind” that stream past Earth at speeds up to one million miles per hour:

- The particles are redistributed and accelerated by the Earth’s magnetic field in a region called the magnetosphere:
  - Redistribution of solar energy results in channeling large amounts of energy, equivalent up to 100 million kilowatts of energy each day to the Earths atmosphere in polar regions.
  - Energetic particles collide with elements of the upper atmosphere at altitudes between 90-150 kilometers, producing the emission of light (an aurora).



The Earth’s magnetosphere provides protection from energetic particles.

## Solar Wind

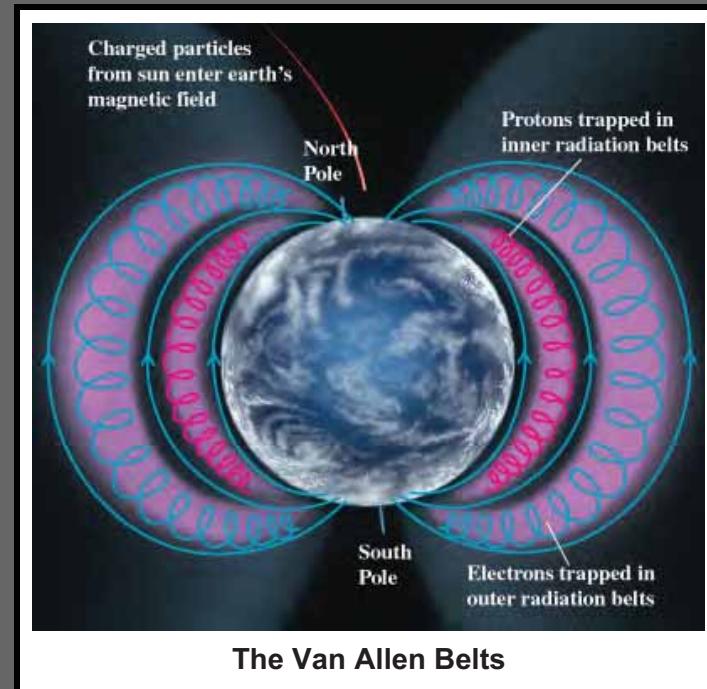
## SPACE RADIATION

## BACKGROUND



Solar radiation is a dominant source in the vicinity of Earth:

- Large solar flares can produce dangerous Solar Particle Events (SPEs):
  - SPEs can produce lethal radiation intensities for unprotected astronauts.
  - Polar orbits inside Earth's magnetosphere are exposed to elevated levels because the magnetic field dips down at the poles.
- Radiation trapped by Earth's geomagnetic field in Van Allen Belts is particularly hazardous:
  - Protons comprise the primary source within the inner zone.
  - The most intense inner zone is the "South Atlantic Anomaly", a region between Africa and South America where orbits of spiraling protons reach closest to Earth.
  - The outer belt, primarily comprised of electrons, has a total intensity about an order of magnitude higher than the inner zone.

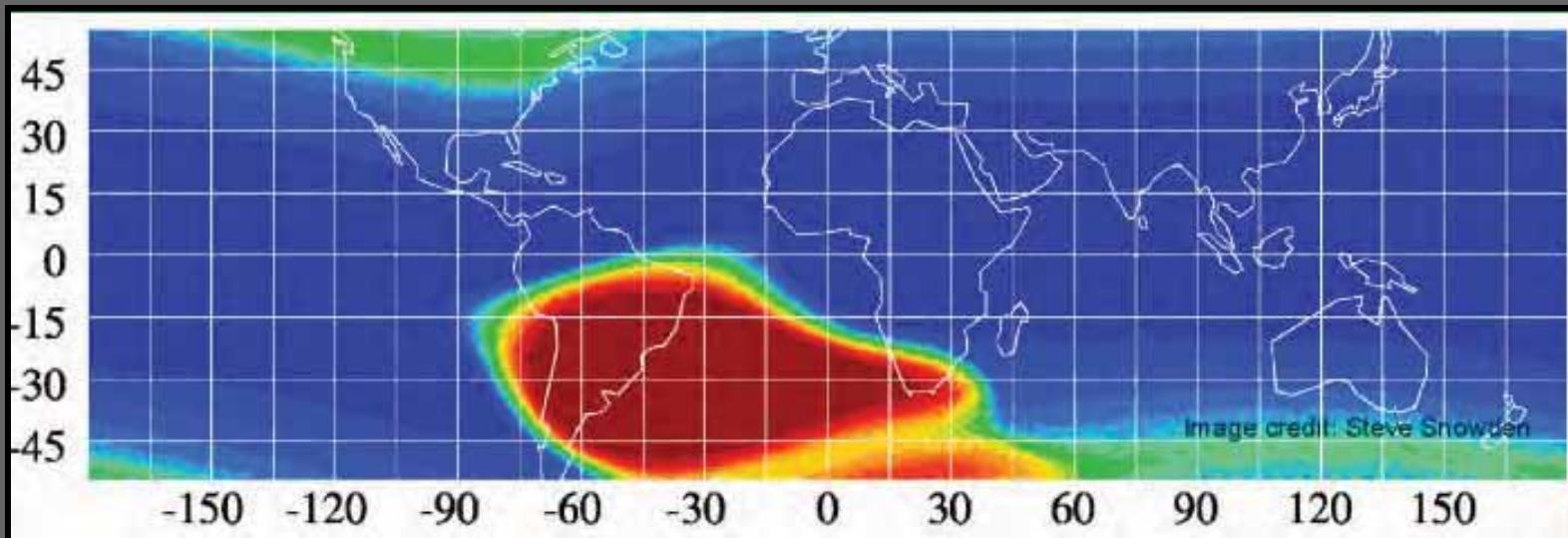


**The Van Allen Belts**

## Radiation Environments

### SPACE RADIATION

### BACKGROUND



**South Atlantic Anomaly**

**SPACE RADIATION**

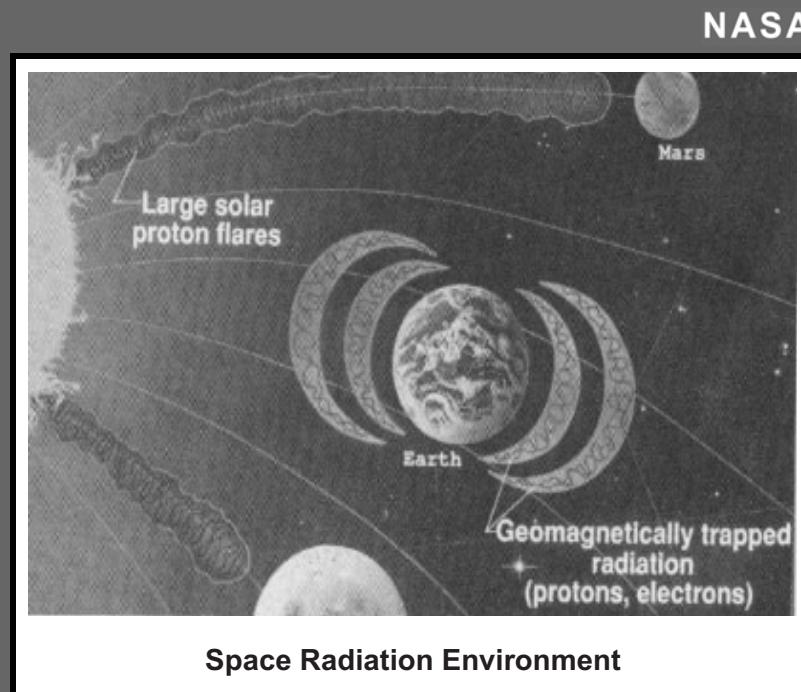
**BACKGROUND**



G-8

Space regions beyond the Van Allen Belts are dominated by Galactic Cosmic Radiation (GCR):

- These particles are created by cataclysmic events such as supernova explosions outside the Solar System:
  - Particle energies are typically very high, measured up to 10<sup>20</sup> electron volts (eV).
  - GCRs consist primarily of protons, with smaller contributions of helium and heavier ions such as iron.
  - Although GCRs have very low flux densities, their extremely high energy levels enable them to penetrate virtually any passive shield of reasonable mass.
  - In the unlikely event that shielding is capable of stopping primary radiation particles, secondary particles such as neutrons, pions and recoil nuclei would still be emitted, limiting health benefits to a crew.



## Galactic Cosmic Radiation

## SPACE RADIATION

## BACKGROUND



An atom is ionized when one or more electrons is stripped away, such as from a collision with a speeding proton:

- Injury to a living organism occurs when high energy protons, cosmic rays, x-rays or gamma rays penetrate and split apart cell molecules, damaging or killing them:
  - Particles passing through an obstruction such as spacecraft walls, create another hazard called secondary radiation.
  - Heavy cosmic ray particles such as nuclei of carbon, oxygen and iron atoms do the most damage because they carry greater positive electrical charges than protons, causing more ionization within the cells.
  - Protons, however, do the most overall damage because there are so many of them since they comprise the primary substance of most cosmic rays.

The degree of damage to organisms from various ionizing radiation types is estimated according to assigned value standards:

- **Particle Energy (MeV/ GeV):**
  - Cosmic rays have energy levels extending to 10<sup>20</sup> eV, but mainly between 100s MeV to 20 GeV.
  - Trapped electrons in the Van Allen Belts range in energy between several hundred MeV.
  - SPEs lasting from a few hours to several days can produce energies up to several GeV.
- **Charge (Z):**
  - High-Z and high energy particles associated with GCR are of particular concern in planning exploratory missions beyond the magnetosphere.
- **Quality (Q):**
  - This is a value set by the International Commission on Radiological Protection (ICRP) as a factor that, when multiplied by dose, projects biological cell damage.

## Biological Effects

### SPACE RADIATION

### IONIZING CHARACTERISTICS

Types	Chg. (Z)	Q	Locations	Neutrons		Produced by nuclear interaction; found near the planets, the Sun and other matter
X-Rays	0	1.0	Radiation belts, solar radiation and in the secondaries made by nuclear reactions	0.05 eV (thermal)	0	2.8
Gamma Rays	0	1.0		.0001 MeV	0	2.2
Electrons			Radiation belts	.005 MeV	0	2.4
1.0 MeV	1	1.0		.02 MeV	0	5.0
0.1 MeV	1	1.0		.5 MeV	0	10.2
Protons			Cosmic rays, inner radiation belts, solar cosmic rays	1.0 MeV	0	10.5
100 MeV	1	1-2.0		10.0 MeV	0	6.4
1.5 MeV	1	8.5				
Heavy Primaries	$\geq 3$	See Text	Cosmic rays	<b>Alpha Particles</b>		Cosmic rays
				5.0 MeV	2	15.0
				1.0 MeV	2	20.0

## Radiation Types & Locations

### SPACE RADIATION

### IONIZING CHARACTERISTICS



G-11

The extent to which ionizing radiation causes biological damage is influenced by the amount of energy absorbed (dose) and the radiation type:

- Dose is expressed in rad or Gray are determined by multiplying dose (expressed in rad or Gray).
  - Relative biological effectiveness of different radiations is determined by multiplying dose times quality factor Q to determine a dose-equivalent (expressed in terms of rem or sievert (Sv)).
  - One Sv equals 100 rem .  
(1mSv= .0001 Sv=1 rem).
- NASA limits the amount of radiation received deep in "Blood Forming Organs" (BFO's) to maximum levels:
  - Career limits depend upon an individual's gender and age at beginning of exposure.

## NASA

Depth	BFO (5 cm)	Eye (0.3 cm)	Skin (0.01 cm)
30 days	25 rem	100 rem	150 rem
Annual	50	200	300
Career	100-400*	400	600

*These limits are recommended to NASA by the National Council on Radiation Protection and Measurements (NCRP) subject to approval by the NASA Administrator, expected in 1989.*

*\*Career depth dose-equivalents are based upon a max. 3% lifetime excess risk of cancer mortality. Total dose-equivalent yielding this risk depends on sex and age at the start of exposure. The career dose-equivalent limit is nearly equal to:*

*200 + 7.5 (age-30) rem, males, up to 400 rem max.  
200 + 7.5 (age-38) rem, females, up to 400 rem max.*

## Ionizing Radiation Exposure Limits

## Evaluation Criteria

## SPACE RADIATION

## HEALTH RISK ASSESSMENTS

### 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

**SPACE RADIATION**

**HEALTH RISK ASSESSMENTS**



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.

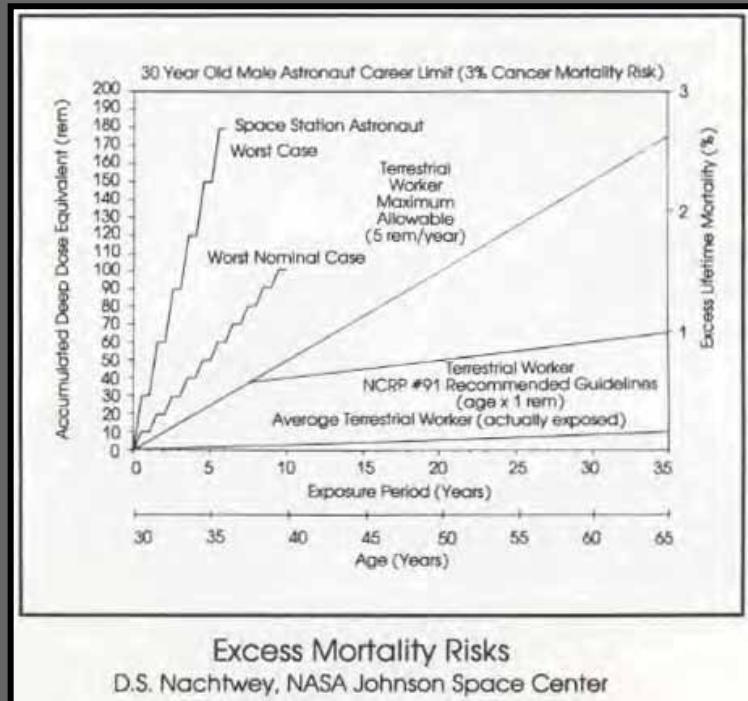
## NASA

<i>Effect in Healthy Adults</i>	<i>Acute Dose</i>
• Blood count changes common	50 rad
• Vomiting, "effective threshold"	100 rad
• Mortality, "effective threshold"	150 rad
• LD <sub>50</sub> minimal medical treatment	320-360 rad
• LD <sub>50</sub> supportive medical treatment	480-540 rad
• LD <sub>50</sub> bone marrow/blood stem cell transplant	1000 rad
<i>Effects on Reproductive Systems</i>	
• 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

## SPACE RADIATION

## HEALTH RISK ASSESSMENTS



**NASA**

<i>From Life on Earth</i>	<i>Exposure</i>
• Transcontinental round trip by jet	0.004 rem
• Chest x-ray (lung dose)	0.010 rem
• Living one year in Houston	0.100 rem
• Living one year in Denver	0.200 rem
• Xeromammography (breast dose)	0.383 rem
• Barium enema (intestine dose)	0.875 rem
• Living one year in Kerala India	1.300 rem
• Max. allowable radiation worker/yr	5.000 rem

<i>Manned Spaceflight</i>	
• Skylab 3, 84 days (blood forming organs)	7.94 rem
(eye lens)	12.83 rem
(skin)	17.85 rem
• Max. allowable space worker/yr	50.00 rem

**Radiation Dose Examples**  
D.S. Nachtwey, NASA Johnson Space Center

## Exposure Comparisons

### SPACE RADIATION

### HEALTH RISK ASSESSMENTS



GCRs which present consistent low level background radiation on Earth are highly problematic in deeper space:

- Levels are inversely proportional to the Sun's storm actively due to the changing magnetic field on the Sun:  
 -GCR is made up of atomic nuclei of densities ranging from helium (low) to iron (high) with extremely high energy levels.  
 -As GCRs pass through tissue, they scatter atomic particles (electrons, protons, gamma rays, etc.) with each collision and produce very harmful secondaries.
- While the rem and rad have often been used to signify radiation effects, more recently standard international units are often used; the Gray (Gy) and the Sievert:  
 -Radiation Dose:  
 $1 \text{ Gy} = 100 \text{ rad} = 1000 \text{ mGy} = 1 \text{ J/kg}$   
 -Biological Equivalent Dose:  
 $1 \text{ Sv} = 100 \text{ rem} = 1000 \text{ mSv} = \text{Gy} \times Q$

<b>Natural Sources:</b>	
Cosmic	0.29mSv
Terrestrial	0.29mSv
Radon (varies by location)	2.00mSv
Internal (K-40, C-14, etc.)	0.40mSv
<b>Man-made:</b>	
Diagnostic X-ray	0.39mSv
Nuclear Medicine	0.14mSv
Consumer Products	0.11mSv
All others (fallout, air travel)	0.02mSv
<b>Average annual total</b>	<b>3.6mSv</b>
For smokers, add 2.8 mSv/year (Zeitlin et al.,2003)	
<b>Dose</b>	<b>Probable Effects</b>
0- 500mSv	= No obvious effects; possible minor blood changes
500-1000mSv	= Radiation sickness in 5-10%; no serious disability
1000-1500mSv	= Radiation sickness in 25% of exposed personnel
1500-2000mSv	= Radiation sickness in 50%;some deaths anticipated
2000-3500mSv	= Radiation sickness in most personnel; 20% deaths
3500-5000mSv	= Radiation sickness; about 50% deaths
10000mSv	= Probably no survivors
An astronauts chance of fatal cancer is increased by 2 to 5 percent for each 500-mSv dose of exposure.	

## SPACE RADIATION

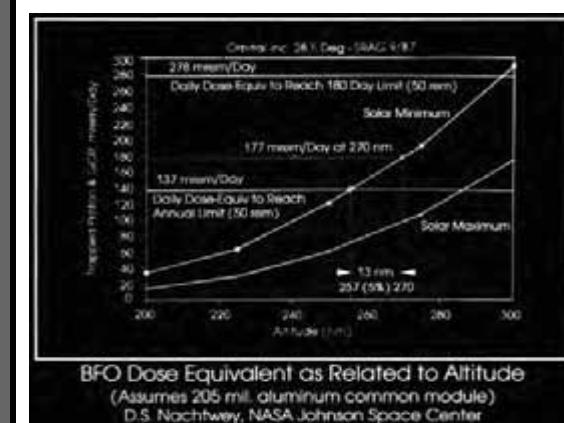
## HEALTH RISK ASSESSMENTS



For Earth-orbiting spacecraft, the altitude of the vehicle and inclination of the orbit are important dose rate determinants:

- Spacecraft Altitude:
  - LEO spacecraft receive substantial shielding from the Earth's magnetic field.
  - Geomagnetic shielding benefits decrease with higher altitude, disappearing at about 6 Earth radii (geosynchronous orbit).
- Orbit Inclination:
  - A 28.5 degree inclination orbit will carry the spacecraft through the South Atlantic Anomaly, adding about 0.1 rem/ day over Earth levels (equivalent to about 10 chest x-rays/ day).
  - The Russian Mir space stations 52 degree orbit passed through the South Atlantic Anomaly more rapidly, producing lower radiation dose exposures.

NASA



Mission Orbit	Radiation Source	Days	Dose Equiv. (mSv)	
			Bone Marrow	Skin
28.5° inclination	South Atlantic Anomaly and GCRs for all missions	90	98	200
57° inclination		90	82	203
90° inclination		90	73	163

LEO Space Station Dose Estimates  
(Assumes 1.0 g/cm<sup>2</sup> aluminum shielding and 450 km altitude)  
W. Atwell, Rockwell International, and A. Hardy, NASA JSC

## Attitude & Inclination Influences

### SPACE RADIATION

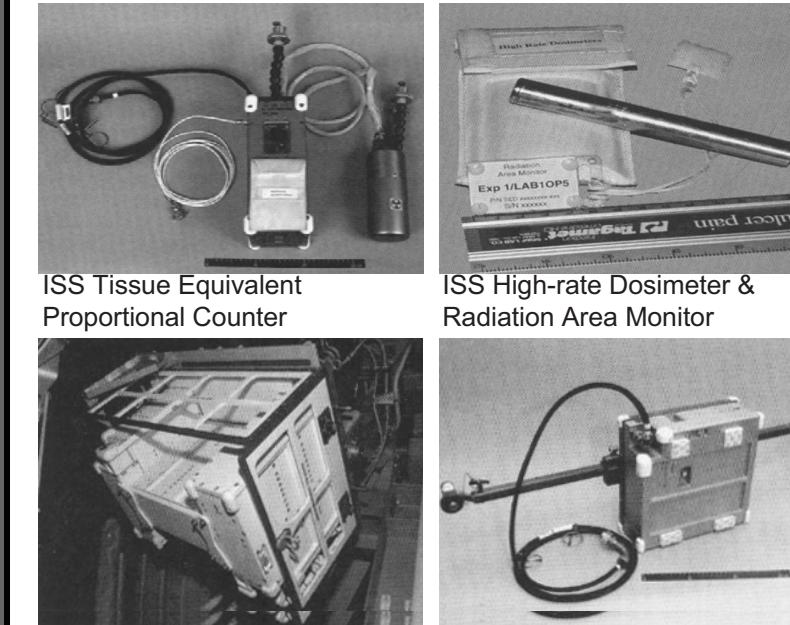
### MISSION CONSIDERATIONS



Alpha particles do more damage in humans than x-rays because they have a higher Q factor. For low-inclination orbits (35 degrees or lower) the Q factor is approximately 1, so that a rem is about equal to a rad.

- Doses on Shuttle flights have ranged from 0.05-0.65 rem (well below flight crew exposure limits of 75 rads/ year-whole body, and 400 rad career limit).
- Skylab's longest 85 day mission resulted in less than 8 rems (whole body) and 17.85 rems (skin).
- The highest radiation exposure in space was 160 rems received during cosmonaut Sergi Avdeyev's 784 day stay on the Mir space station.

## SPACECRAFT SYSTEMS DESIGN & OPERATIONS



## Recorded Crew Exposures

## SPACE RADIATION

## MISSION CONSIDERATIONS

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

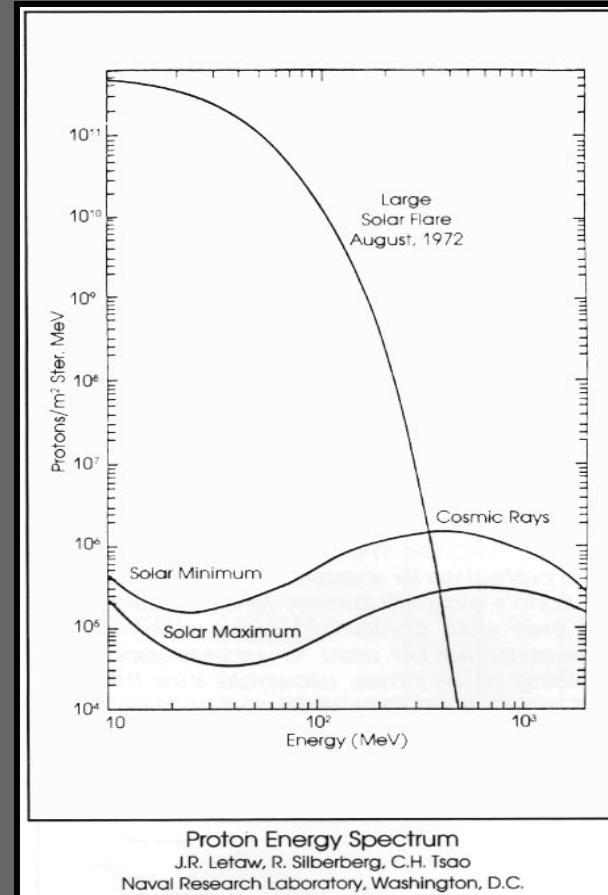
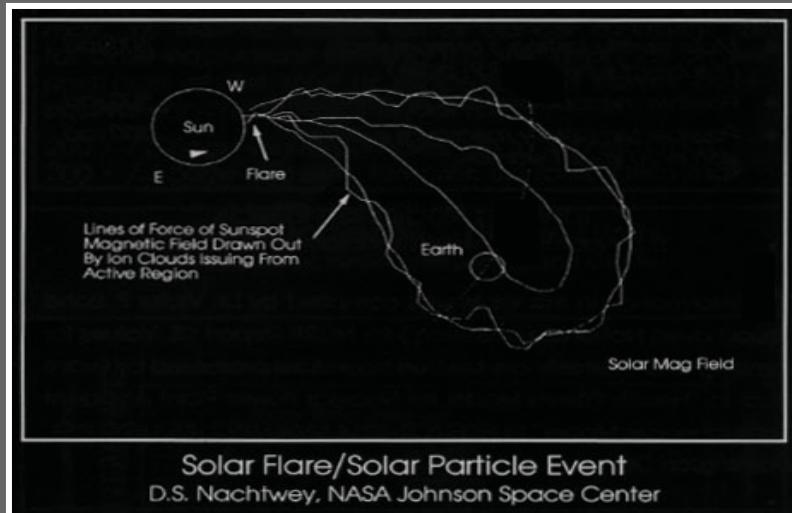
- There may never be “career” astronauts in the context of long-term, continuous professional livelihoods.
  - A 30 year-old male on his first 180 day LEO mission could look forward to a maximum of 5 more similar duty tours before exceeding the 200 rem career limit set for his age group and gender.
  - 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/ cm<sup>2</sup> (0.75 cm Al) shielding, potentially creating serious but non-lethal illnesses. (Acceptable 14 rem levels would require 20 g/ cm<sup>2</sup>/ 7.5 cm Al shielding.)

**Flight Frequency & Length****SPACE RADIATION****MISSION CONSIDERATIONS**



SPE occurrences correlate with sunspot activity:

- Extremely large flares are relatively rare, occurring only a few days per decade.
- Accurate predictions of occurrences or intensities are currently impossible.
- Although SPE particles are less penetrating than GCRs due to lower energies, their high flux density can make them very dangerous.



## Solar Energetic Particle Events

### SPACE RADIATION

### MISSION CONSIDERATIONS



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 <sup>a</sup> Long. 160° W, 2 g/cm <sup>2</sup> Al	Van Allen Belts GCRs	15	56
Lunar Mission 4 g/cm <sup>2</sup> Al	Van Allen Belts GCRs	90	74 1000
Mars Mission	Van Allen Belts GCRs, SPE <sup>b</sup> and Power Sources	1095	1800

<sup>a</sup> Geosynchronous  
<sup>b</sup> 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

## Voyages Beyond LEO

### SPACE RADIATION

### MISSION CONSIDERATIONS



**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 Earth's 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.

## Risk Mitigation Approaches

### SPACE RADIATION

### POSSIBLE COUNTERMEASURES



G-22

Spacecraft cabin walls provide some shielding in LEO, but will not offer much protection in higher orbits:

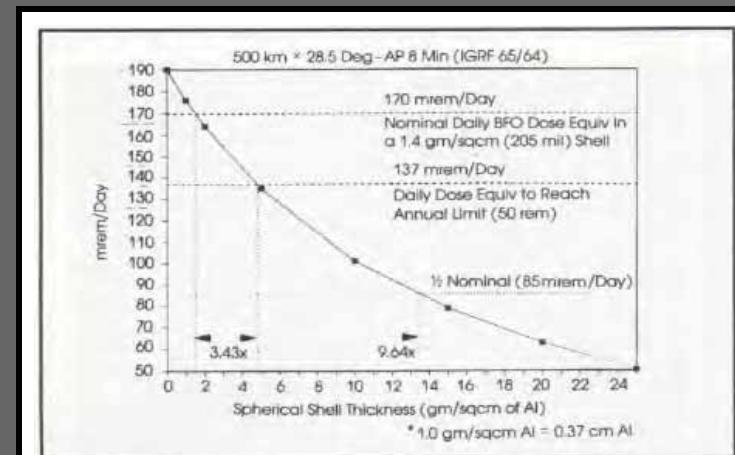
- Secondary Radiation:

- Radiation produced when a primary cosmic ray strikes and ionizes a metal spacecraft material (typically aluminum) will readily penetrate the cabin and scatter numerous times, multiplying the destructive potential.
- Ionizing effects of electrons that populate the outer radiation belt and beyond are of great concern, contributing to radiation levels in geosynchronous orbit (GEO) which are about 3 orders of magnitude worse than LEO.

- Aluminum Shielding:

- Aluminum is commonly used for spacecraft construction due to light weight and moderate cost.
- Capabilities of the material to provide GCR and SPE protection outside the Earth's magnetosphere will be severely limited by shell thickness vs. launch mass constraints.

NASA



Modeled Depth Doses vs. Shell Thickness  
D.S. Nachtwey, NASA Johnson Space Center

Reducing the nominal daily BFO dose equivalent from 170 mrem by approximately half in a 500 km x 28.5° orbit will increase an aluminum shell thickness about 9 times.

## Aluminum Shielding Limitations

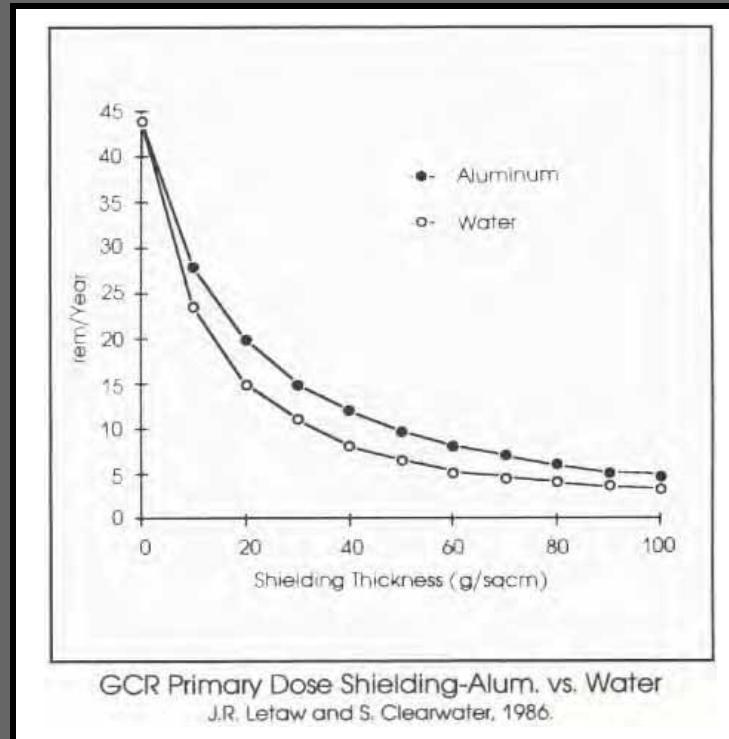
## SPACE RADIATION

## POSSIBLE COUNTERMEASURES



Protection from large SPEs might be accomplished by adding mass ( $\geq 20\text{g/cm}^2$ ) to or within the walls of a habitat or special storm shelter refuge area :

- Using additional thickness or layers of aluminum, plastics or other solid materials will present launch mass problems (a half-sphere aluminum shelter of 2 meter diameter will exceed 1.3 metric tons).
- Bladders of stored water used for logistics may offer a reasonable alternative, since a substantial amount will be required to support mission operations and would impose little or no extra launch mass.
- Ionized water has a short radiation half-life and could be safely consumed for drinking within hours or days following a SPE.



## SPACE RADIATION

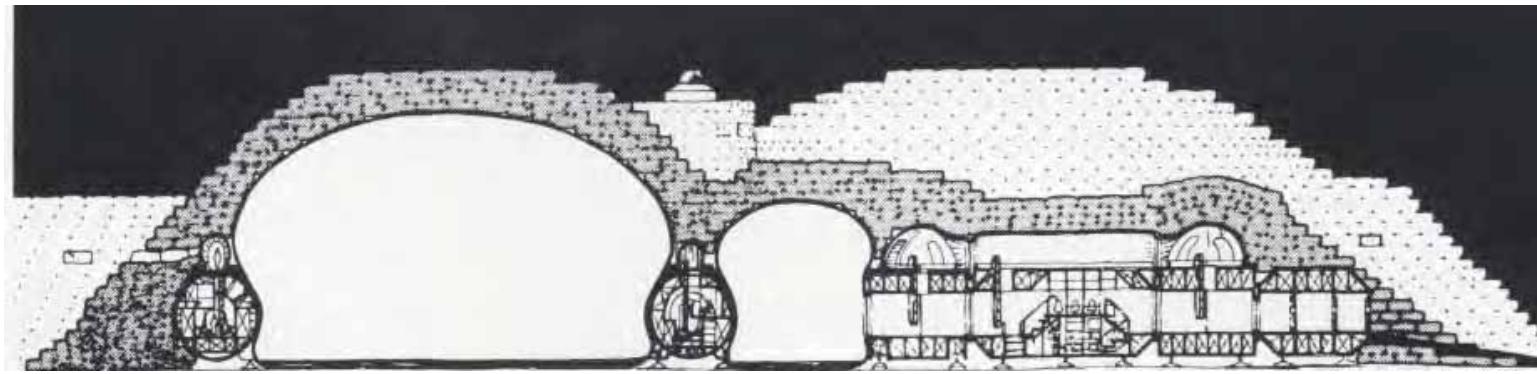
## POSSIBLE COUNTERMEASURES

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.



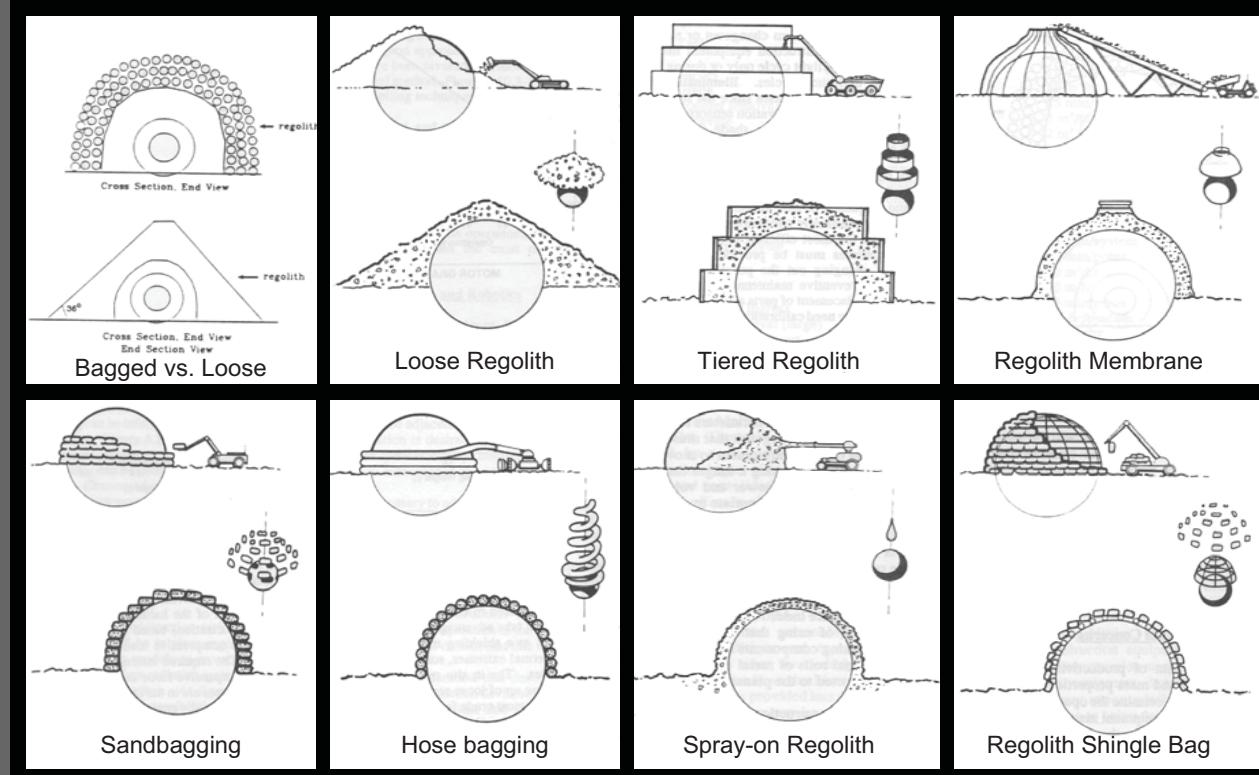
### Use of In-situ Shielding Materials

## SPACE RADIATION

## POSSIBLE COUNTERMEASURES



NASA



## Lunar Regolith for Shielding

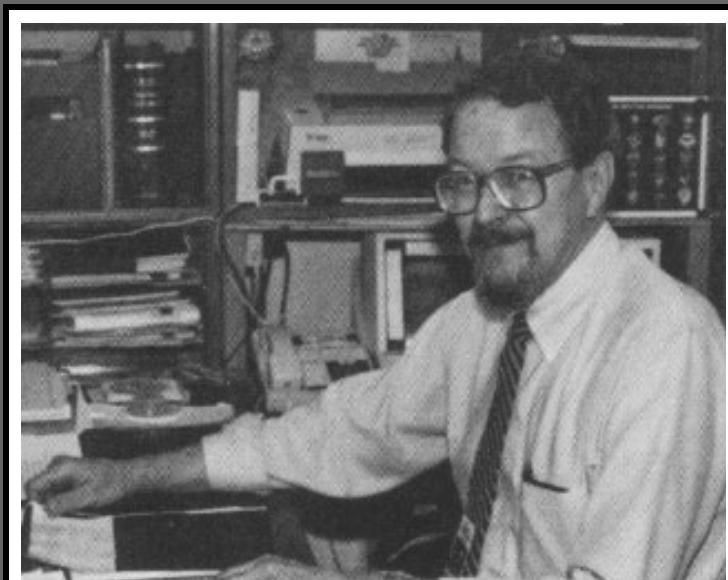
SPACE RADIATION

POSSIBLE COUNTERMEASURES



G-26

We are grateful to our friend, the late Stuart Nachtwey, who has contributed valuable information and advice to SICSA on the subject of space radiation, some of which is cited in this section. Dr. Nachtwey managed the Space Radiological Health Program at the NASA Johnson Space Center for many years.



Dr. Stuart Nachtwey, Radiological Health Officer,  
NASA Johnson Space Center

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## SPACE RADIATION

## REFERENCES



Additional information relevant to this section can be found in Part I, Section A (space structures) and B (habitat support systems) of this SICSA Space Architecture Seminar Lecture Series, along with other publications listed below:

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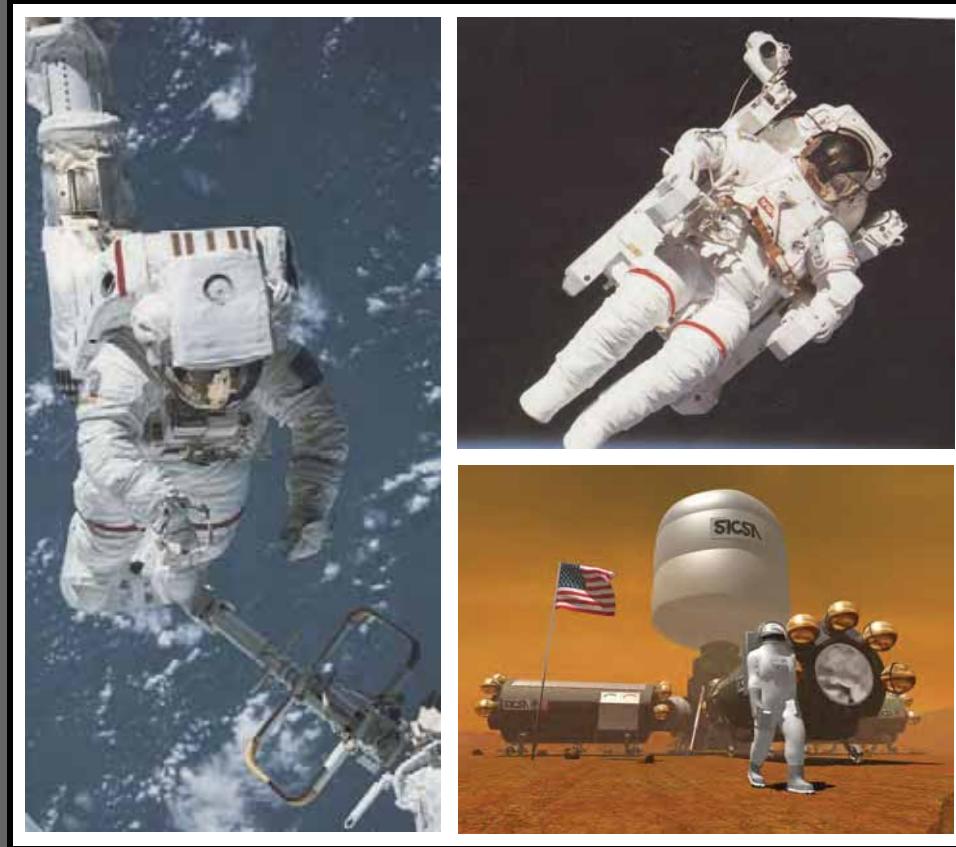
## SPACE RADIATION

## REFERENCES



## SECTION H: EVA EQUIPMENT & OPERATIONS

H-1





EVA space suits designed for LEO and lunar/ Mars conditions must respond to special environmental operating influences:

- Gravity levels determine carry weight, body posture, translation movements and work leverage:
  - Carry weight includes the suit, backpack, tools, and objects being manipulated.
  - Body posture in weightlessness is neutral  $-g$ , becoming more normalized with partial-gravity.
  - Translation movement in weightlessness is primarily hand-over-hand using hands and firearms, vs. "bounding" on the Moon/ Mars using legs.
- Radiation levels are most severe beyond LEO:
  - Except for passes through the South Atlantic Anomaly, greatest LEO risks are from SPEs.
  - The Moon is protected only by hemispheric mass of the planet during night, while the thin Mars atmosphere affords some additional protection.
- Micrometeoroids represent a special hazard for LEO EVA crews:
  - Space suits with an outer protective layer can afford some protection.
- Dust presents particular problems on the Moon and Mars:
  - It can abrade suit coverings, scratch helmet visors, cover external displays, degrade outer garment absorptivity and emissivity, and contaminate seals and bearings.
  - On Apollo 17, dust made it difficult for astronaut Jack Schmitt to secure his suit gloves, and wore through the outer layer after only 3 EVAs.
  - Electrostatic and mechanical dust properties cause it to cling to suits.

## Operating Environments

### EVA EQUIPMENT/OPERATIONS

### SUIT DESIGN CRITERIA



- Sharp and jagged edges that penetrate EVA suits can be fatal:
  - Boots and gloves must be designed to handle rough/ sharp objects, and the entire outer garment must resist damage from inadvertent falls/ scrapes.
  - Sharp edges on hardware (spacecraft, experiments, equipment and rovers) should be avoided.
- EVA suits can be exposed to chemical hazards:
  - Spacecraft propellants and cooling systems use chemicals that can damage suit materials and present hazards when brought back into airlocks.
  - Dangerous chemicals may also be encountered as part of planetary base construction, scientific tests and processing of in-situ surface resources.
- Thermal control is one of the space suit's most critical functions:
  - A typical 90 minute orbit in LEO results in about 55 minutes in hot sun and 35 minutes in cold shadow.
  - The US Shuttle's space suit has a white outer garment with 5 layers of aluminized mylar, liquid-cooled inner garments and resistance heaters in gloves for on-demand heating.
  - The thermal environment on the Moon changes gradually, with temperatures ranging from 114°C at lunar noon, to -183°C during lunar night.
  - Thermal extremes on Mars are significant and radiator devices may be required since heat rejection through multi-layer insulation will be degraded by gravity compression of the layers .

## Operating Environments

### EVA EQUIPMENT/OPERATIONS

### SUIT DESIGN CRITERIA



H-4

## HUMAN SPACEFLIGHT

- Lighting control is essential during EVAs:
  - In LEO, suits have protective visors and lights to enable crews to work in alternating sunlight/shadow.
  - The lack of an atmosphere in LEO and on the Moon, and the thin atmosphere on Mars, prevent/minimize filtering of light that occurs on Earth, causing very high illumination levels and harsh shadows.
  - Sun angles on the Moon can cause “whiteout” conditions, so that EVA operations are best scheduled when shadows add visual dimensions.
  - Since the Earth’s brightness is 60 times that of the Moon, reflected Earth light enables near-side EVAs during lunar night.
  - The diurnal cycle on Mars is similar to Earth’s, presenting similar lighting conditions.

Environmental Factors	LEO/Weightless Conditions	Moon/Mars Conditions
Gravity-related differences	Crew restraints Neutral body posture Translation by hand	Possible restraints Weight carrying Bounding gait
Radiation (ionizing and non-ionizing)	Greatest in South Atlantic Anomaly	Homospheric protection (night conditions) UV and IR protection
Micrometeoroids/penetrations	Layered materials Spacecraft hardware	Layered materials Construction/rocks
Natural/Spacecraft Contaminants	Propellant contamination	Dust & propellant contamination
Atmosphere influences on suit design	Vacuum conditions	Vacuum conditions Low pressure CO <sub>2</sub> (Mars)
Thermal extremes	Alternating direct sun-shadow	Fixed sun position (hot and cold)
Natural lighting	Alternating sun shadow each 90 m.n.	15 day cycle (Moon) Earth-like (Mars)

### Environmental Influences on EVA Suit Design

## Operating Environments

## EVA EQUIPMENT/OPERATIONS

## SUIT DESIGN CRITERIA



H-5

## SPACECRAFT SYSTEMS DESIGN & OPERATIONS

Space suits have systems ranging from minimum physiological limits at 25.9 kPa, to the limits of glove performance at 57.2 kPa:

- For pure oxygen, the maximum pressure to avoid toxicity is 41.3 kPa for continuous exposure, and 68.9 kPa for up to 18 hours of exposure every 120 hours.
- Transitioning from a higher pressure habitat with mixed gases to lower pressure suits using pure oxygen requires a period of prebreathe to purge nitrogen from the blood.
- Prebreathe time ensures safety, but adds significantly to EVA schedules.
- Going from a 2-gas atmosphere to a single gas atmosphere requires purge time, also adding to schedules.
- Current planning requires about 4 hours to go from the ISS at 101.3 kPa to the US's EVA Mobility Unit (EMU) at 29.6 kPa. (This eliminates rapid EVAs or using a suit for emergency backup if pressure fails.)

Making pressures more similar for habitats and suits reduces prebreathe time:

- If 24 hours before an EVA, the Shuttle's cabin pressure is lowered from 101.3 kPa to 70.3 kPa, prebreathe time is reduced to 1 hour during cabin pressure reduction, followed by 40 minutes of additional prebreathing prior to the EVA.
- The Russian protocol requires 30 minutes to transition from 101.3 kPa to 40 kPa.

Protocol	In-Suit	10.2 (12 hr)	10.2 (24 hr)	Exercise
<b>Mask prebreathe time</b>	None	1 hour	1 hour	80 minutes
<b>In-suit prebreathe time</b>	4 hours	75 minutes	40 minutes	1 hour
<b>Operations overview</b>	Breathe O <sub>2</sub> in-suit for 4 hours while cabin is at 14.7, go out the door	Breathe O <sub>2</sub> in mask while depressing cabin to 10.2, wait 12 hours before in-suit prebreathe, go out the door	Breathe O <sub>2</sub> in mask while depressing cabin to 10.2, wait 24 hours before in-suit prebreathe, go out the door	Exercise on bike for 10 min. at beginning of mask prebreathe, depress airlock to 10.2, breathe in-suit for 1 hour, go out the door.

### Preparations for EVA operations

## Spacecraft Atmospheres

## EVA EQUIPMENT/OPERATIONS

## SUIT DESIGN CRITERIA

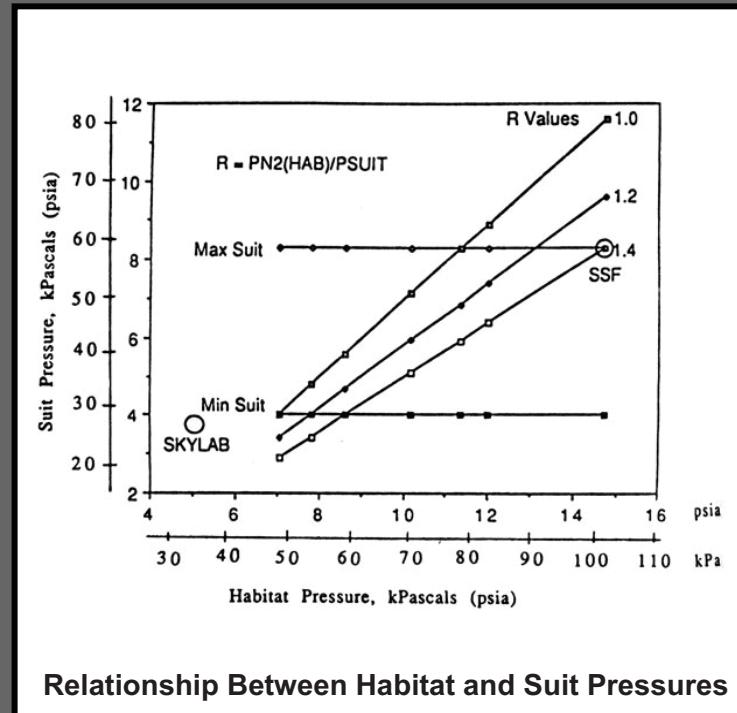
Selecting space suit pressure involves a trade off between reduced risk of bends and greater glove mobility:

- Relationships between habitat and suit pressures:
  - Bends (decompression sickness) occurs when nitrogen in the blood stream passes into surrounding tissue and expands as atmospheric pressure decreases.
  - This is significant for EVAs because space suits typically operate at lower pressures than the spacecraft.

#### HUMAN SPACEFLIGHT

	Apollo	Skylab	Shuttle	Mir	ISS
Vehicle pressure, kPa	34.5	34.5	101.3	101.3	101.3
Vehicle atm., %O <sub>2</sub> /N <sub>2</sub>	100% O <sub>2</sub>	72/28	21/79	21/79	21/79
Suit pressure, kPa @ 100% O <sub>2</sub>	26.9	26.9	29.6	39.2	29.6 EMU 39.2 Orlan

Comparison of Spacecraft and Suit Atmospheres



#### Spacecraft Atmospheres

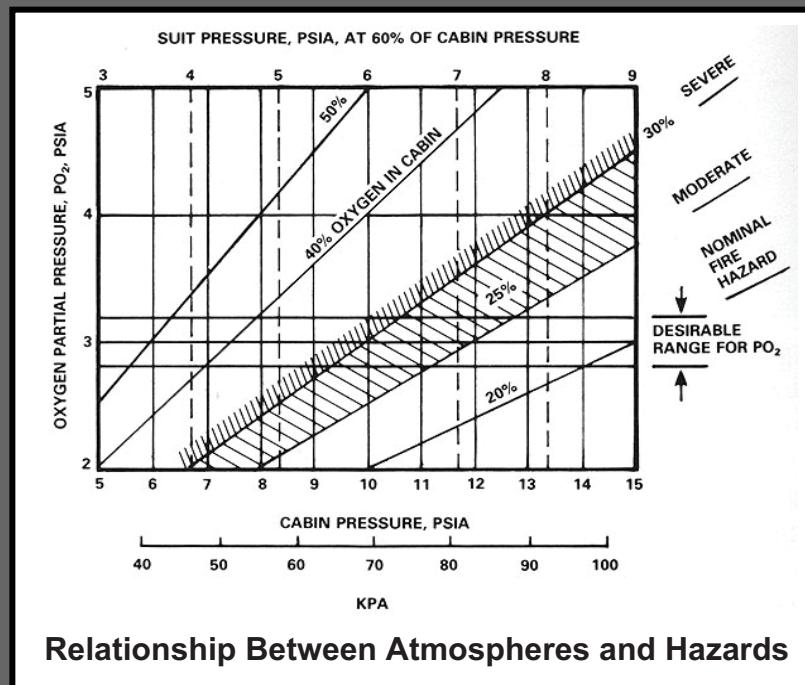
## EVA EQUIPMENT/OPERATIONS

## SUIT DESIGN CRITERIA



- The effort required to close one's hand in a glove under pressure is fatiguing during long EVA sessions involving a great deal of hand work:
  - Final pressure suit selection must consider adequate glove mobility as well as cabin pressure and minimum suit pressure to eliminate bends risk.
  - Suit pressures equal to about 60 percent of cabin pressure is usually considered safe from aeroembolism (bends).
- Atmosphere selection must also consider other hazards:
  - Oxygen enrichment in cabin air increases fire hazards.
  - Above 30 percent oxygen, flammability risks severely limit materials that can be used in a habitat.

## SPACE STATIONS AND PLATFORMS



## Spacecraft Atmospheres

### EVA EQUIPMENT/OPERATIONS

### SUIT DESIGN CRITERIA



Space suit selection and design is influenced by operational conditions in different environments and the nature of workload activities to be performed:

- Operating in a pressure suit requires a great deal of effort:
  - The suit's mass and torque required to move joints impose high workloads.
  - Maintaining stability and responding to transverse forces on the Moon/ Mars requires special concentration due to suit mass influences that change the center of gravity.
  - Visibility is constrained by the helmet and visor, presenting special mobility and operational challenges (such as falling or bumping into obstacles).
- High workloads can produce rapid body fluid losses:
  - As much as 3 kg of body weight can be perspired away during a few hours of EVA.
  - Liquid-cooled garments can control body temperature to decrease perspiration, and drink bag dispensers in helmets can replenish lost fluids.
  - Metabolic rates determine temperature control requirements.
- Under high workloads, astronauts use more oxygen and produce more CO<sub>2</sub>:
  - Due to the small atmospheric volume, high percentages of CO<sub>2</sub> can rapidly build up in suits.
  - Even relatively low percentages of CO<sub>2</sub> can cause physiological reactions such as increased heart and perspiration rates, mental depression, headaches, and dizziness/ nausea.
  - High CO<sub>2</sub> concentrations produce mental stupor, unconsciousness and death.
  - Life support systems remove CO<sub>2</sub>, and ventilation systems prevent buildup.
  - Production of CO<sub>2</sub> depends upon metabolic rate and perspiration quotient (the ratio of O<sub>2</sub> intake and CO<sub>2</sub> production).
  - High-carbohydrate diets yield higher CO<sub>2</sub> production than high-fat diets.

## Suit Life Support Requirements

### EVA EQUIPMENT/OPERATIONS

### SUIT DESIGN CRITERIA



Space suits present special limitations, constraints and requirements associated with radiation safety, orientation adaptation and visibility:

- EVA suits offer little protection against space radiation:
  - SPEs pose the biggest and potentially a lethal threat, and can happen at any time.
  - Outside the protection of LEO, the only effective response is a retreat to a sheltered enclosure.
  - EVA crews on the Moon will have only about a 30 minute warning. (Assuming an average walk-back rate of 2 km/hour, or a rover ride at 8 km/hour, they should only explore 1-4 km from a storm shelter.)
- EVA presents a special case for space orientation:
  - To help Shuttle crews adapt to weightlessness, no EVAs are scheduled for the first 72 hours following launch. (This is partly to prevent possibilities of vomiting in the suit.)
  - EVA in orbit lacks visual up/ down orientation references except for foot restraints (while orientation on the Moon/ Mars is aligned with the gravity vector and horizon reference).
- Since EVA crews must be able to see to work and survive, good suit visibility is essential:
  - Hand-over-hand translation used in weightlessness requires overhead visibility (similar to climbing a ladder).
  - The Russians have incorporated overhead viewing features into their Orlan M space suit for ISS.
  - Planetary EVA suits should provide downward visibility for walking and locating/ reaching surface objects.
  - Helmet visors are necessary to reduce glare and avoid direct sunlight.
  - Ventilation and low humidity is essential to prevent helmet fogging.
  - Replaceable visors are important to eliminate scratches and dust buildups that interfere with viewing.
  - Displays should be designed or covered to avoid dust films and reflections that obscure effective use.

## Suit Limitations & Priorities

### EVA EQUIPMENT/OPERATIONS

### SUIT DESIGN CRITERIA



H-10

Suit hygiene is important to protect users from illness and discomfort:

- Perspiration during EVAs can be a source of microbial contamination:
  - US crews must dry and wipe suits with a biocide material following use, requiring good access for inspecting and cleaning interior parts.
  - Russian suits are an expendable space-based system along with consumables supplied from Earth.
  - The Shuttle's EVA Mobility Unit (EMU) is a reusable ground-based system that draws upon consumables supplied by the Shuttle/ ISS.
- Since total pressurized suit time can be up to 8 hours, mitigating techniques and special garments are necessary for handling urine and feces:
  - A low residual diet is applied to reduce waste products.
  - Crew members wear a urine collection device (male) or disposable trunk to absorb and contain waste as an extra precaution.

Human factors for EVA must consider ways to size suits for different individuals and conditions:

- EVA effectiveness and comfort is directly influenced by suit fit:
  - Russians use one size to fit cosmonauts of a particular size range.
  - The Shuttle suit is modular and reusable, intended to adapt from 95<sup>th</sup> percentile US males, to 5<sup>th</sup> percentile US females.
  - Future ISS or lunar/ Mars suits must be designed to consider means to adjust sizes for changeouts among crews using modular or adaptable elements.
- Proper fit must match changes in physical measurements that occur in space:
  - In weightlessness, the spinal column extends about 3 percent, requiring that suits sized for Earth training must be changed.
  - Similar changes may also occur on the Moon due to reduced gravity conditions.

## Hygiene and Human Factors

EVA EQUIPMENT/OPERATIONS

SUIT DESIGN CRITERIA



Space suits adapt to biomechanical requirements imposed by different EVA environments and tasks:

- Mobility and flexibility:
  - Different gravity levels influence locomotion methods (hand-over-hand in weightlessness and bounding gaits on the Moon).
  - Fixed foot restraints used in weightlessness require that suits incorporate a rotational waist bearing to provide maximum reach flexibility.
  - Astronauts on the Moon and Mars may sometimes need to right themselves back on their feet if they happen to fall, requiring flexibility in knees and elbows to accomplish this.
  - Lunar/ Mars astronauts will need to be able to pick up and carry massive objects, requiring bending of legs, arms and shoulders.
- Dexterity and tactility requirements:
  - Glove dexterity must allow free wrist movement and grasping, and tactility requires the ability to feel shapes through the glove material.
  - Layers of material that provide pressure restraint and thermal insulation work against these capabilities.
  - The most desirable features of gloves are snug fit without pressure points or discomfort, and low torque finger, thumb and wrist joints to minimize hand fatigue.
  - Enhanced glove performance is the greatest benefit of lower pressure suits.

### Biomechanical Features

## EVA EQUIPMENT/OPERATIONS

## SUIT DESIGN CRITERIA



Space suit design can mitigate fatigue and enhance EVA length and productivity:

- For EVA, fatigue critically affects comfort and safety:
  - On the Moon and Mars, crewmembers will use legs and arms to carry the weight of the portable life support system, part of their suit and other items.
  - In weightlessness, they will depend upon their hands to control movements of mass.
  - Under all conditions, joint torque contributes greatly to fatigue, and the common and limiting source of fatigue is glove pressure.
  - Repeatedly grasping a gloved hand is very tiring and painful, so it is desirable to design tasks around other suit joints such as the shoulders
- During typical 6 hour EVAs, suit comfort is an enabling requirement rather than a luxury:
  - Suits must not only fit well, but must be comfortable in terms of temperature, humidity, air flow rate and noise control.
  - Ease of donning and doffing suits is also important, since it can be an exhausting procedure. (Shuttle suits can go on and off in less than 10 minutes, and rear-entry Russian Orlan DMA or NASA's MKIII take even less time.)
  - Soft suits allow for some give without producing irritation or bruises at contact points, and also avoid limits to joint flexure associated with many hard suit designs.

### Fatigue & Comfort Factors

## EVA EQUIPMENT/OPERATIONS

## SUIT DESIGN CRITERIA



H-13

EVA planning must optimize information management and display:

- Exploration missions will present new requirements:
  - While Shuttle EVAs are usually well defined and rehearsed many times before a mission, operations on the Moon and Mars will require a more open plan that supports quick decisions.
  - Communication delays from Earth to Mars will make real-time ground instructions and responses impossible, requiring that suits be equipped with on-board navigation, lookup references, procedures and systems status monitors.
  - Helmet noise must be controlled to reserve sound for voice communications and acoustic alarms.
  - To support informed decisions, the crew must be able to access reference material immediately, often using internal visual displays.

#### Application Environment

Influences of gravity level upon body posture, translation and restraints.  
Biomechanical implications of tasks and gravity level.  
Post conditions influencing seals, contamination and helmet/display viewing, temperature ranges influencing suit ventilation and thermal/humidity control.

#### Habitat Design

Atmosphere/pressure differential between habitat and suit influencing prebreathe.  
Accommodations for suit storage, cleaning following use and repair/replacement.  
Emergency access to a habitat safe haven during SPBs.

#### Suit Features

Ease of donning, doffing, cleaning and repair.  
Biomechanical flexibility and glove dexterity for task performance.  
Adaptability for individuals of different size and gender.  
Information management, communications and display systems.

### Summary Suit Selection Considerations

## Information Management & Display

## EVA EQUIPMENT/OPERATIONS

## SUIT DESIGN CRITERIA



Careful planning and preparations are essential to ensure that EVA procedures respond effectively to routine and anomalous requirements:

EVA operations are classified as scheduled, unscheduled or contingency:

- Scheduled operations are carefully planned and trained for in advance, including special mission tasks and routine spacecraft inspections and maintenance activities.
- Unscheduled events requiring EVAs can include verifying satisfactory functioning of an external mechanism and repairing or replacing a failed part.
- Contingency operations involve responses to emergency events which may be time, mission and life safety-critical.

EVAs generally consist of phased activities:

- Procedures are reviewed and systems are checked out.
- Prebreathe is accomplished for transitioning to the EVA environment.
- Tools and work aids are gathered for designed tasks.
- Readaptation to the spacecraft atmosphere occurs at the EVA conclusion.
- Suits are then be inspected for damage, wiped to remove perspiration and dust contamination, and replenished with consumables.

## EVA Types & Phases

### EVA EQUIPMENT/OPERATIONS

### PLANNING CONSIDERATIONS



Mission requirements dictate EVA frequency, number of suits required, and support items that must be inventoried and stowed:

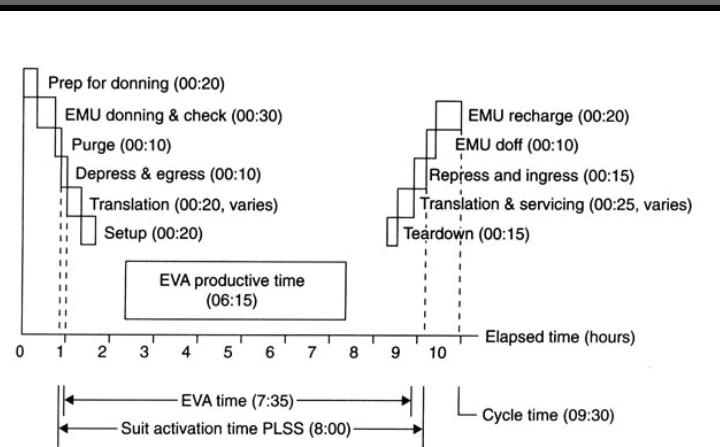
- EVA accommodations:
  - Each Shuttle mission supports up to 8 scheduled and contingency EVAs, and pressure suits are worn during ascent reentry.
  - ISS operations call for up to 25 EVAs per EMU (before returning the EMU to Earth for ground maintenance).
  - Russian suits don't return to Earth, and can support 10 EVAs (or up to 20 EVAs with on-orbit replacement of suit soft goods).
  - EVAs use a buddy system (2 or more crew members) which affects the size of airlocks and amounts of consumables (water, oxygen and CO<sub>2</sub> scrubbers), and surface rover accommodations.
- Tools and work aids:
  - For Apollo missions, tools to support lunar sample return included geologist's hammers, rakes, scoops and core drills.
  - Shuttle EVA tools include special items for contingency closing of payload bay doors, and modified commercial hand tools for payload assembly.
  - Shuttle and ISS work aids include safety tethers, portable foot restraints, helmet-mounted lights, and a "mini work station" on the front of the EMU.
  - ISS EVAs are also supported by various US and International partner-supplied remote manipulator systems.

### Accommodations, Tools & Work Aids

## EVA EQUIPMENT/OPERATIONS

## PLANNING CONSIDERATIONS

## HUMAN SPACEFLIGHT



EVA planning must compare productive time with overall elapsed time requirements from preparation for suit donning to EMU doffing. Due to overhead functions for EVA, only about 6 hours of productive work will be accomplished during 8 hours of activation time.

Item (US EMU)	Rate (Per EVA)
LIOH (per crewmember)	2.9 kg (includes the canister)
Oxygen (per crewmember)	0.63 kg
Water (per crewmember)	3.5 kg minimum 5.4 kg maximum
Air loss (cycling airlock per EVA)	10% per airlock cycle
Electrical power (per EMU)	26 A·h at 16.8 V dc (3.5 A·h during prebreathe)
Electrical power (pump 90% airlock)	0.133 kWh (4.5 kW for 8 minutes)

EVA consumable can have significant impacts upon spacecraft mission masses and volumes that must be dedicated for replenishment of space suit life support and thermal control systems. Some systems share consumables and technologies with their host vehicle.

## Mission Timelines & Consumables

### EVA EQUIPMENT/OPERATIONS

### PLANNING CONSIDERATIONS



H-17

## HUMAN SPACEFLIGHT

Program	Host Vehicle EVA System	Overall Concept	Shared Technology
Apollo	Lunar Module Apollo EMU	Expendable, 1-mission vehicle Expendable, 1-3 EVAs, Suits tailored to individuals	Revitalizing the atmosphere: closed loop CO <sub>2</sub> removal: expendable LiOH Power: AgZn batteries Heat rejection: Water sublimator
Shuttle	Orbiter Shuttle EMU	Reusable, 100 flights, ground service between flights Up to 8 EVAs per mission, ground serviced and resized, 15 year life	Revitalizing the atmosphere: closed loop CO <sub>2</sub> removal: expendable LiOH
International Space Station	US On-Orbit Segment ISS EMU	10-year life with on-orbit maintenance Upgrade the Shuttle's EMU for up to 25 EVAs in 270 days on-orbit, including resizing and maintenance. Up to 20 missions in 10-year period	Atm. Revitalization: closed loop CO <sub>2</sub> removal: regenerable MOL sieve Maintenance concept: orbit-replaceable units

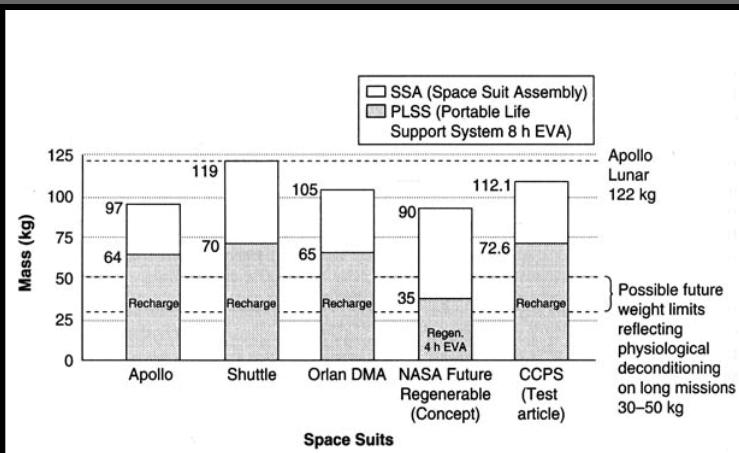
## Shared Technologies & Consumables

### EVA EQUIPMENT/OPERATIONS

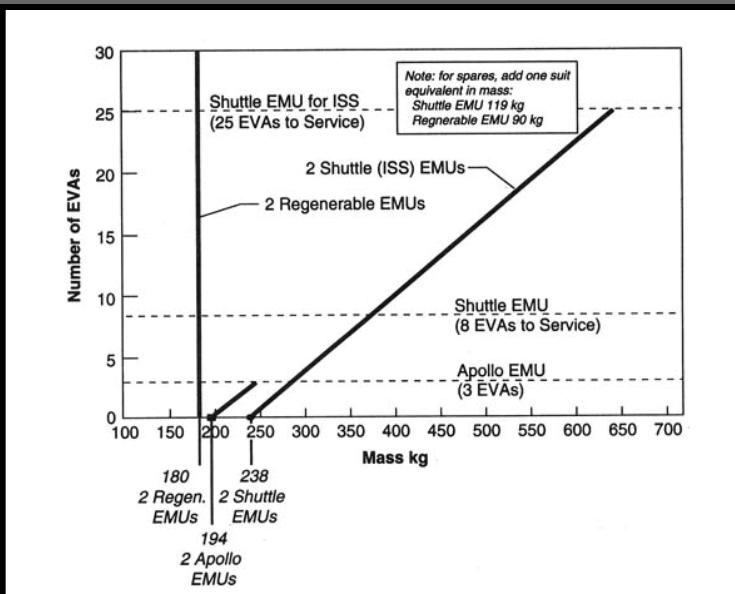
### PLANNING CONSIDERATIONS



## HUMAN SPACEFLIGHT



Overall mass determinations for EVA systems must include the space suits, EVA Maneuvering Units and consumables. Current regenerable and rechargeable space suit concepts may be too heavy for long-duration lunar/ Mars applications due to astronaut deconditioning and fatigue limitations.



The combined mass of suits, consumables and spares must be accounted for in mission planning.

## Overall Mass Contributions

### EVA EQUIPMENT/OPERATIONS

### PLANNING CONSIDERATIONS

The beginnings of space suit technology began in the 1930s with Wiley Post's high altitude suit for aircraft:

- Humans need artificial pressurization above about 12 km (40,000 feet).
- Emergency high-altitude suits were developed in response to post-World War II military interests.
- By the mid-1950s, the US Air Force had developed a partial-pressure suit adequate to keep an airman alive in a high-altitude emergency until the aircraft could be brought to a lower altitude.
- By 1959, the Navy had developed a full pressure suit that was the technical precursor to the space suit used on Mercury flights.



### Early Developments

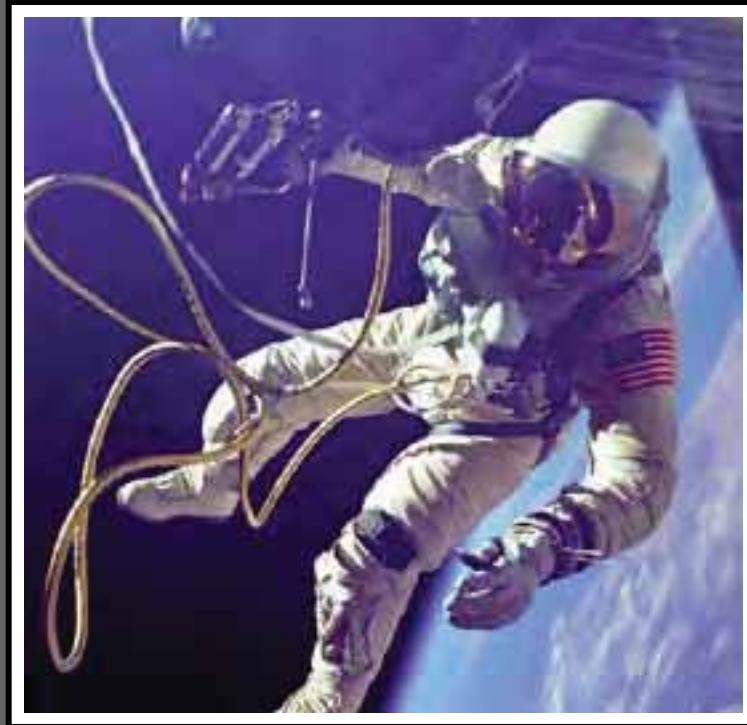
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## EVA EQUIPMENT/OPERATIONS

## SUIT HISTORY AND STATUS

The Gemini suit offered improved arm and leg mobility and was the first American suit actually used for EVA:

- Astronaut Ed White wore the suit for a 20-minute “spacewalk” on Gemini 4:
  - It did not have a portable life support system, and was connected to the spacecraft by an umbilical that provided oxygen.
  - The suit operated at about 24 kPa (3.5 psi), and heat was removed by sweat evaporation from the skin.
  - Sweat evaporation did not work well because the oxygen purge was uneven and the visor fogged up during hard work.



Gemini Space Suit

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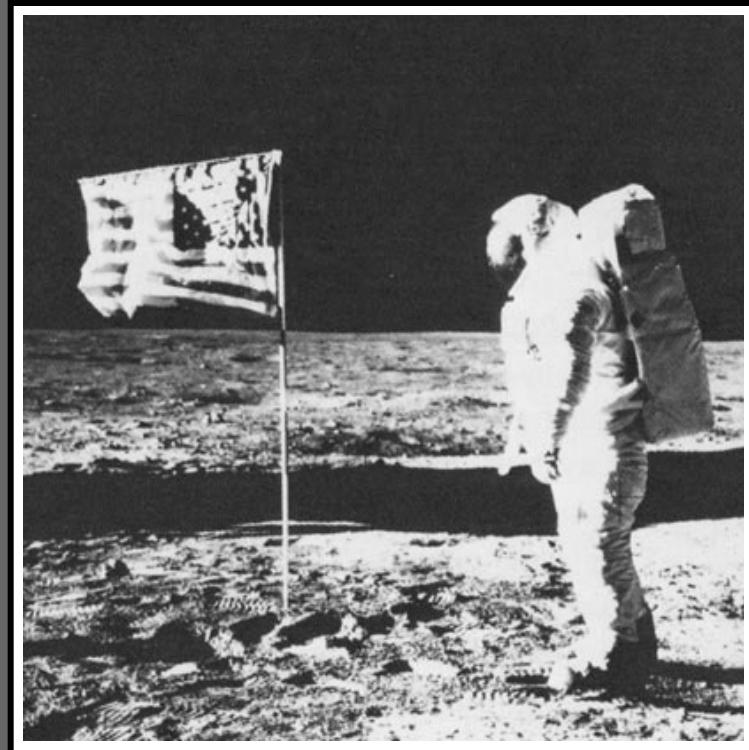
## EVA EQUIPMENT/OPERATIONS

## SUIT HISTORY AND STATUS

**SPACE STATIONS  
AND PLATFORMS**

The Apollo suit had to be fully functional to permit locomotion by walking on the lunar surface:

- The suit had a portable life support system capable of supporting EVA for about 8 hours with some margin:
  - A liquid-cooled inner garment covering the entire body except for head and extremities was in contact with the skin for heat removal.
  - The garment was comprised of a nearly contiguous network of small tubing through which the liquid flowed, and provided adjustable temperature control.
  - The suit operated at 24 kPa of pure oxygen, and CO<sub>2</sub> was removed by lithium hydroxide (LiOH) canisters.
  - Heat was rejected by water evaporation at about 0.5 kg/ hour at typical EVA metabolic rates.



**Apollo Space Suit**

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**EVA EQUIPMENT/OPERATIONS**

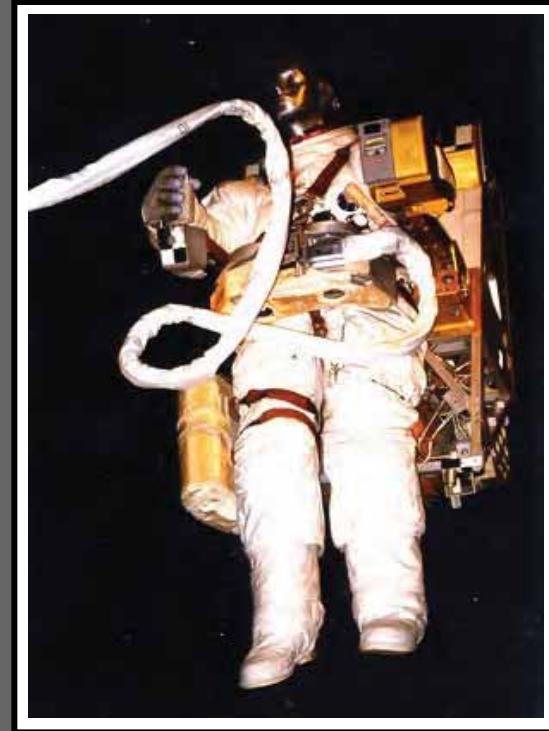
**SUIT HISTORY AND STATUS**



H-22

The Skylab suit was derived from the Apollo suit, but did not include a portable life support system:

- All EVAs were planned and conducted adjacent to the vehicle, enabling practical use of umbilicals.
- EVA was used extensively for planned mission activities as well as unscheduled ones:
  - The EVA capability saved the Skylab Program, beginning with a critical solar wing repair and sunshade installation conducted during the first crew visit.
  - Skylab missions had more unplanned than planned EVA hours.



Skylab Space Suit

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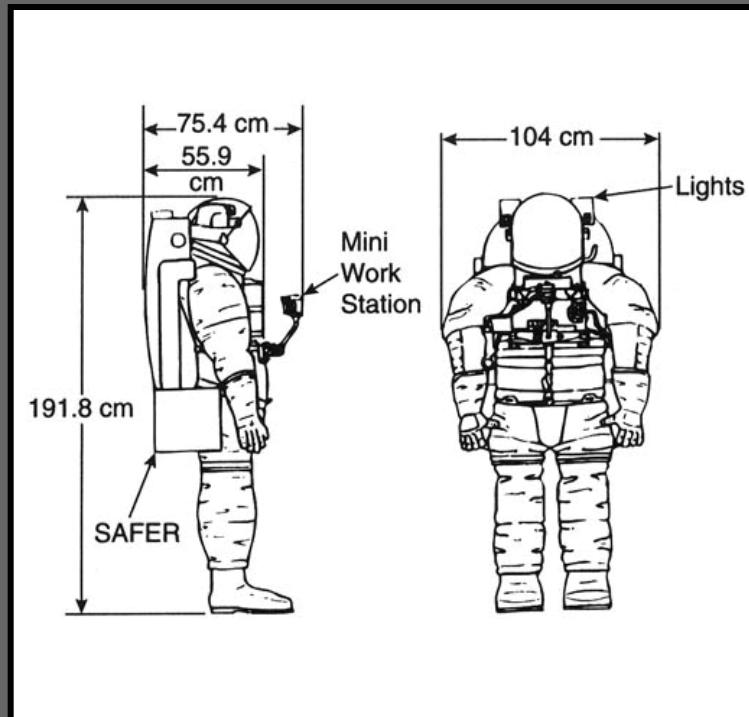
EVA EQUIPMENT/OPERATIONS

SUIT HISTORY AND STATUS

## HUMAN SPACEFLIGHT

The Shuttle Extravehicular Mobility Unit (EMU) is similar to the space suit used for Apollo, but provides improved mobility and a new portable life support system:

- Unlike earlier suits which were individually tailored to each astronaut, the Shuttle suit is modular:
  - Various parts such as arm and leg sections come in different sizes that can be selected to fit specific users.
  - The EMU has a hard upper torso that is elliptic rather than cylindrical in cross section to provide a more useful work area for the crewperson's hands in front of the chest.
  - The Shuttle EMU operates at a slightly higher pressure than its predecessors, 28 kPa (4.1 psi) because the Shuttle cabin operates at a much higher pressure, 100 kPa (14.7 psi).



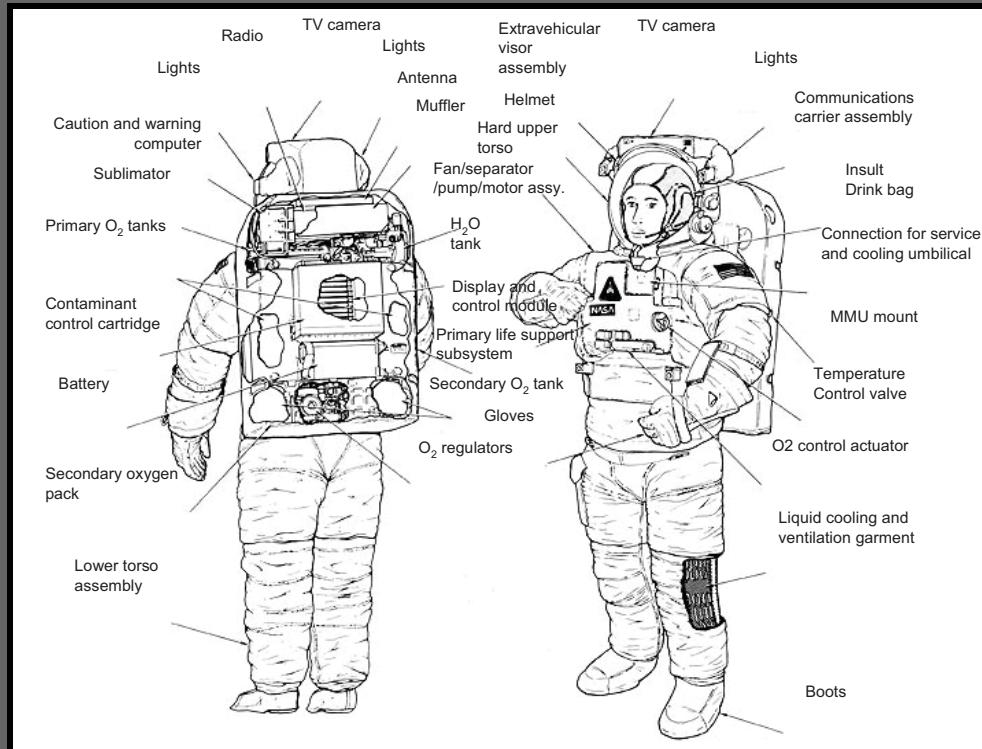
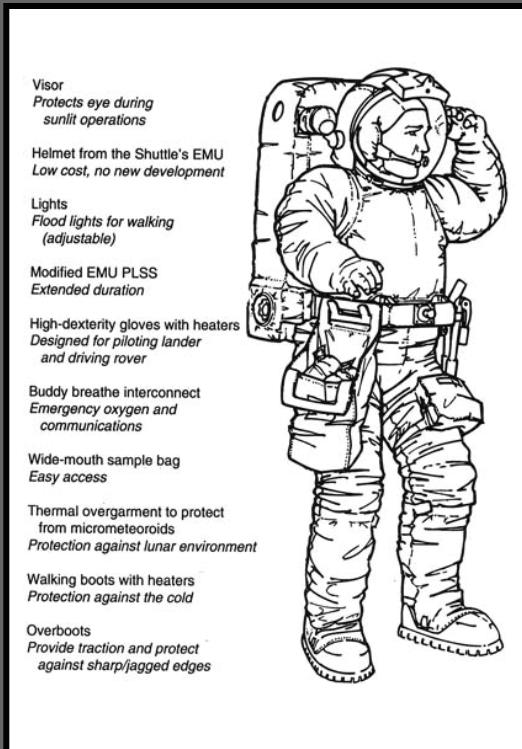
Shuttle EMU System

## EVA EQUIPMENT/OPERATIONS

## SUIT HISTORY AND STATUS

## HUMAN SPACEFLIGHT

### SPACECRAFT SYSTEMS DESIGN & OPERATIONS

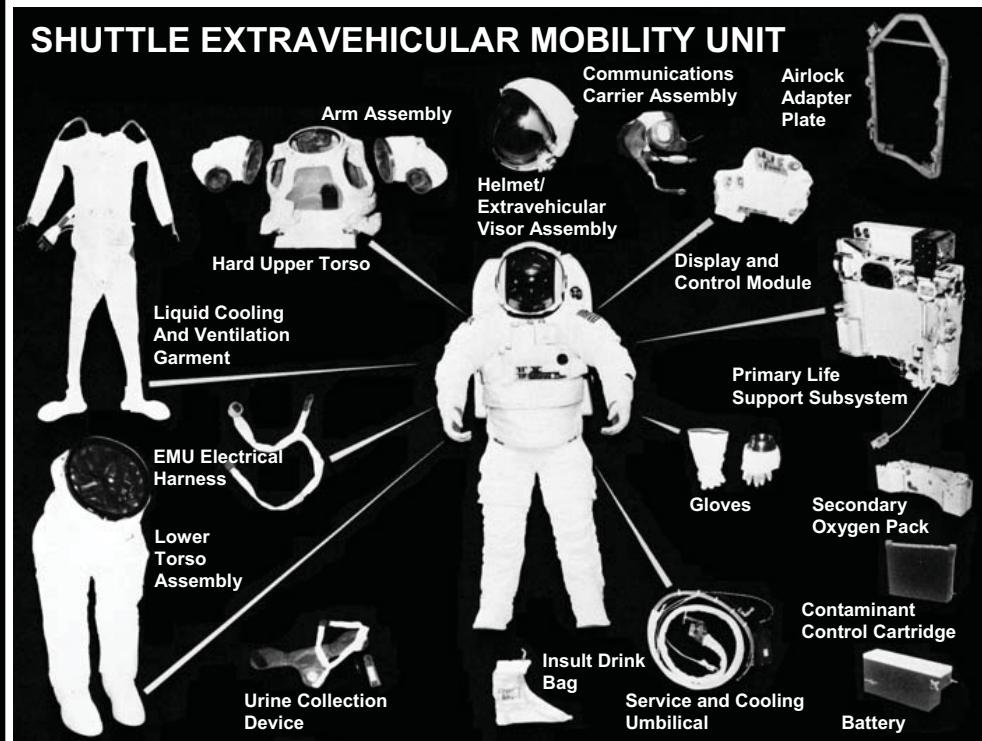


Shuttle EMU System

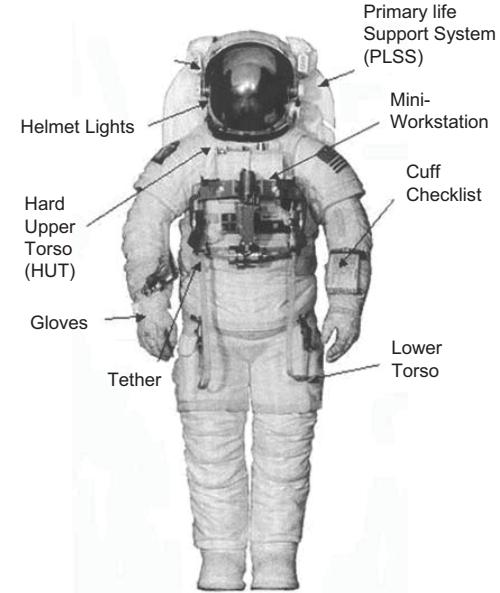
## EVA EQUIPMENT/OPERATIONS

## SUIT HISTORY AND STATUS

**SPACE STATIONS  
AND PLATFORMS**



**SPACECRAFT SYSTEMS  
DESIGN & OPERATIONS**



**Shuttle EMU System**

**EVA EQUIPMENT/OPERATIONS**

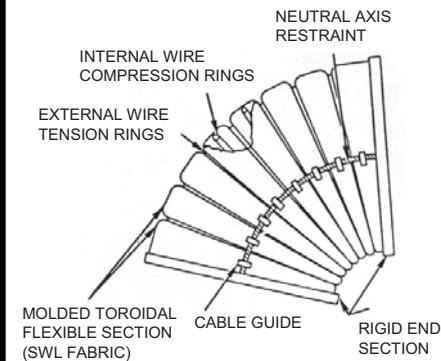
**SUIT HISTORY AND STATUS**

## SPACE STATIONS AND PLATFORMS

Large differences between cabin and suit pressures present serious operational problems including long prebreathe times, causing Orbiter pressures to gradually be reduced to about 65 kPa (8 psi) prior to EVAs. Experimental hard suits have been developed to operate at this pressure for possible future applications:

- Joint design principles for hard suits have not been applied to gloves:
  - The small parts size presents design and use difficulties, and volume compensation has proven problematic.
  - Final selection of a higher new suit pressure will require glove design improvements to prevent hand fatigue during extended periods of use.

Suit pressures significantly above 25 kPa permit 2-gas atmospheres. Hard suit leakage is expected to be low enough that only oxygen will need to be replenished since the initial nitrogen charge will be adequate. Hard suit technology may also increase suit life to dozens or possibly hundreds of users.



**Hard Space Suits**

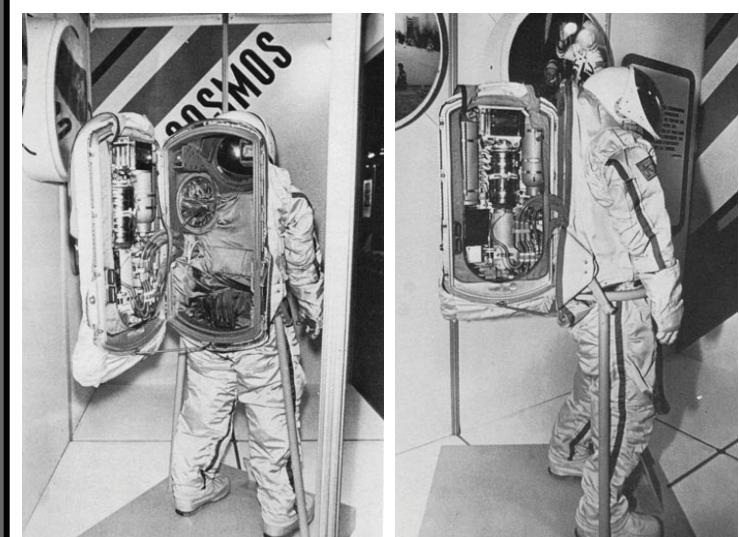
## EVA EQUIPMENT/OPERATIONS

## SUIT HISTORY AND STATUS

The Russians were the first to accomplish an EVA.

- From the beginning, their suits have featured portable life support systems:
  - The Soviet suit used on the Salyut is a derivative of earlier designs.
  - The entire life support unit hinges open, providing a large and convenient space for cosmonauts to enter the suit which is easier to don and doff than the Shuttle suit.
  - The US and Russians have both used liquid cooling garments to control body temperatures.

#### SPACE STATIONS AND PLATFORMS



A hinged, swing-open life support backpack aids donning/ doffing and equipment servicing.

**The Orlan DMA**

#### Russian Space Suits

#### EVA EQUIPMENT/OPERATIONS

#### SUIT HISTORY AND STATUS



H-28

Spacesuits must be constructed to contain pressure, resist penetrations, operate in a pure oxygen atmosphere, optimize mobility, minimize weight, provide desirable thermal properties, extend design life, afford inspectability and repair, and be comfortable:

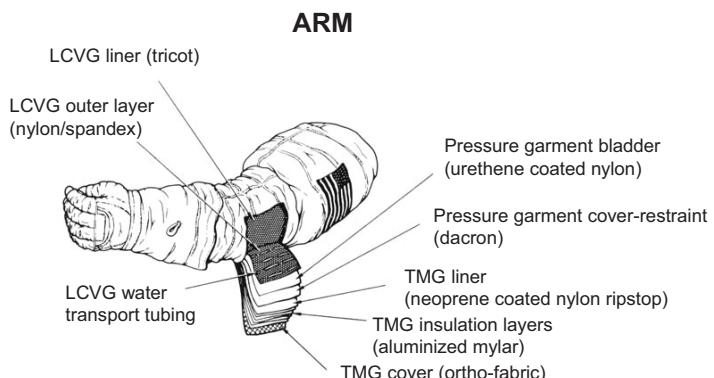
- Soft suits use layered fabric materials that are selected to meet a variety of requirements:
  - A urethane-coated nylon bladder inner layer contains pressure, and a woven Dacron fabric restrains it against ballooning and provides shape control at joints for mobility.
  - Middle layers of insulation protect against radiant heat transfer.
  - An outer layer "orthofabric" is made of a blend of Teflon, Kevlar and Nomex fabrics that resist puncture, abrasion and tearing, and is white to reflect sunlight.
  - EVA suits for the Moon and Mars must control dust and maintain necessary thermal properties using tightly woven materials with a smooth finish, or a separate disposable outer garment cover.
- Hard suits and parts of soft suits combine different materials and elements:
  - Upper torso sections can be formed from cast aluminum and fiberglass.
  - Bearings and connectors are typically made from machined stainless steel or aluminum. (These components must resist damage from abrasion, particularly in a dusty environment such as on the Moon or Mars.)
  - A key motivation in creating an all-aluminum AX-5 suit developed by NASA's Ames Research Center is to achieve precision and repeatability using machine production rather than hard tailoring.
  - Transparent bubble helmets are made from an impact and pressure resistant polycarbonate.

### Type & Construction

EVA EQUIPMENT/OPERATIONS

SUIT HISTORY AND STATUS

## SPACE STATIONS AND PLATFORMS



**Shuttle EMU Arm Construction to Provide Flexibility and Temperature Control**

## HUMAN SPACEFLIGHT

### Liquid Cooling Ventilation Garment

- Designed to control body temperature and minimize perspiration
- Tubes woven through the garment circulate cool water to conduct heat away from the skin
- Flexible ducts attached to the arms and legs reduce perspiration by concentrating airflow at the hands and feet
- For repeated use, mission planners should consider how to clean the garment

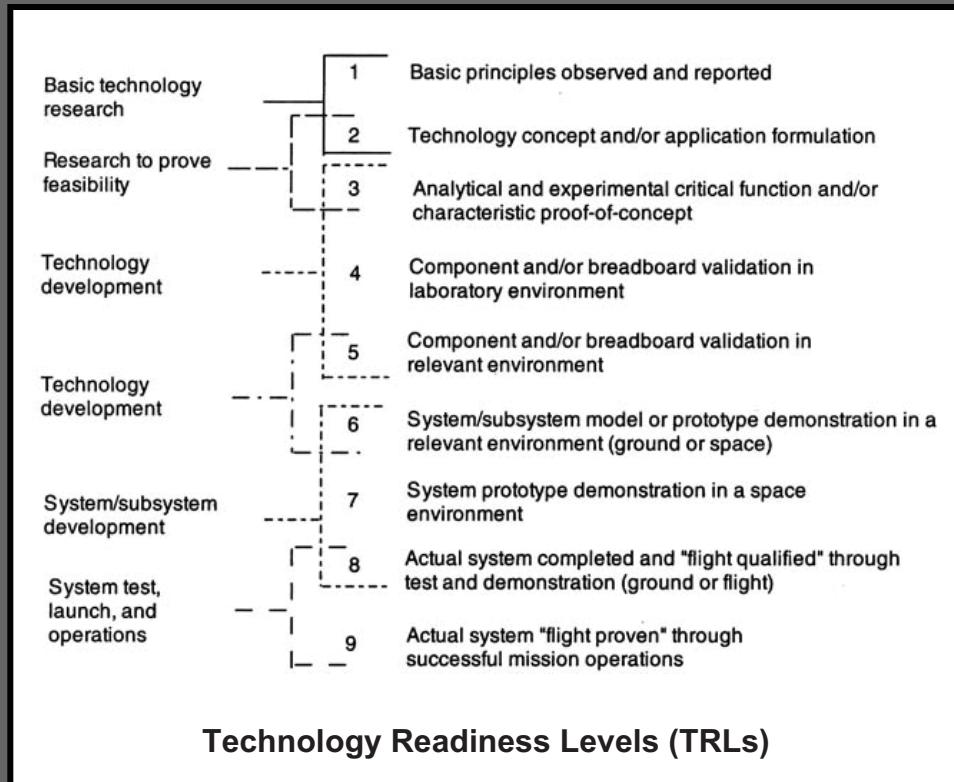


**Liquid Cooling Ventilation Garment Concept Used By The US and Russia**

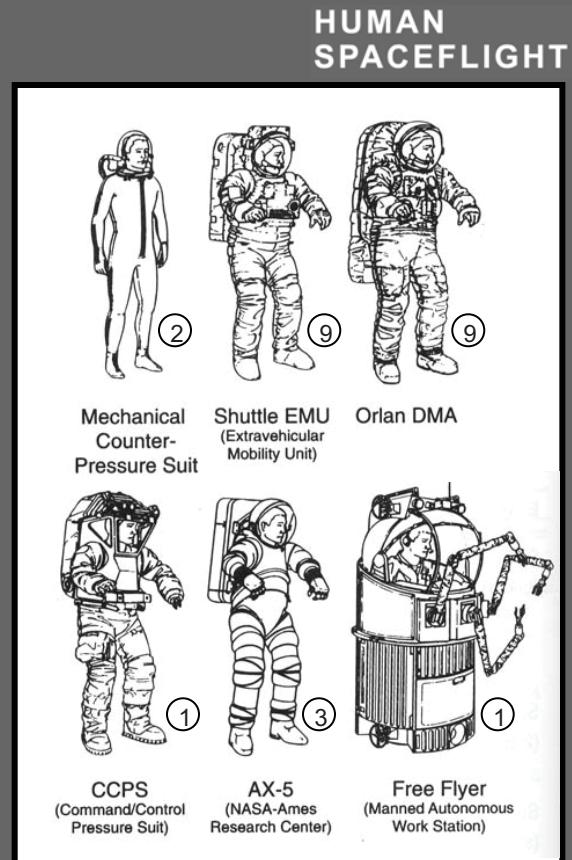
### Type & Construction

## EVA EQUIPMENT/OPERATIONS

## SUIT HISTORY AND STATUS



### Suit Development Status Categories



### Type & Development Status

## EVA EQUIPMENT/OPERATIONS

## SUIT HISTORY AND STATUS



Life support for a space suit is packaged with atmosphere control, electrical power, communications and thermal control. These capabilities can be provided using umbilicals or Portable (sometimes called “primary”) Life Support Systems (PLSSs).

- Umbilicals such as those used in the Gemini and Skylab can offer certain application advantages:
  - The systems are simpler and cheaper because they utilize services and gases from the host facility.
  - They reduce carry weight for the astronauts because they use no backpacks.
  - They can be used to augment or substitute for a PLSS on part of the mission or for emergency operations.
  - Umbilicals connected to landers or rovers minimize use of backpack consumables during transit.
  - Umbilicals can offer “buddy breathing” capabilities during emergencies.
- The PLSS offers much greater range and mobility than is afforded by umbilicals:
  - It is often referred to as a “backpack” and provides EVA crew members with oxygen for breathing, pressurization, ventilation, and water for cooling.
  - The PLSS is made of fiberglass, and provides mountings for other EMU components, including a secondary Suit Oxygen Package (SOP).
  - The primary oxygen system and water bladders can support 7 hours inside the EMU, and the SOP can extend suit pressure for 30 minutes if needed.

## Umbilical & Portable Systems

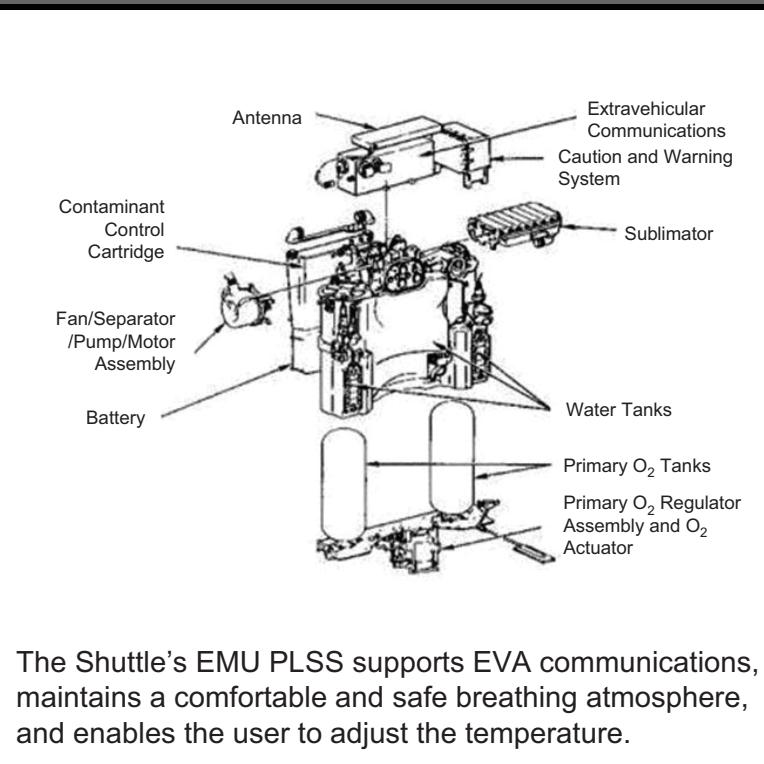
### EVA EQUIPMENT/OPERATIONS

### SUIT LIFE SUPPORT

## SPACECRAFT SYSTEMS DESIGN & OPERATIONS

### Atmosphere Control:

- The Shuttle's EMU uses bottles of compressed O<sub>2</sub> to provide breathing through a dual-mode, single-stage regulator that reduces pressure to 29.6 kPa:
  - Emergency O<sub>2</sub> systems protect users from critical failures (loss of primary O<sub>2</sub>, suit leakage or an inoperable ventilation fan motor.)
  - Operation is automatic, beginning when pressure falls below 27 kPa for leakage rates up to 2.36 kg/hour (enough margin to avoid the bends).
- A fan directs the air supply over the user's face to carry off expired CO<sub>2</sub>:
  - CO<sub>2</sub> is removed from the ventilation flow stream by lithium hydroxide (LiOH) for the Shuttle, and by a reusable metal oxide canister for ISS.
  - Activated charcoal absorbs contaminants in replaceable canisters.



The Shuttle's EMU PLSS supports EVA communications, maintains a comfortable and safe breathing atmosphere, and enables the user to adjust the temperature.

### Portable Life Support System (PLSS)

## EVA EQUIPMENT/OPERATIONS

## SUIT LIFE SUPPORT



#### Cooling:

- Air flow keeps the dew point of exhaled breathing gas in the helmet below the helmet's wall temperature to avoid fogging:
- A sublimator dehumidifies the ventilation flow stream and cools both the ventilation gas and the liquid flowing in the cooling ventilation garment.
- The sublimator is a 3-fluid heat exchanger that rejects heat to space by sublimating ice to vacuum.
- Feedwater to replenish ice is stored as a consumable in the PLSS's water tanks. (Condensate makes up about 0.9 kg. or 18% of the feedwater supply.)
- Water cooling at 18% suppresses most perspiration to prevent dehydration.
- Crews can select cooling between 16°C-33°C. (The Shuttles EMU provides 2.05 kWh cooling with an average rate of 293 W, and a 15 minute peak rate of 586 W.)

#### Electrical Systems and Equipment:

- Electrical and electronic systems include electrical power, data management and communications (audio and visual):
  - The Shuttles EMU and Russia's Orlan DMA suit both use silver-zinc batteries.
  - The Russian system uses replaceable batteries with 19 A·H at 27 Vdc.
  - The US EMU uses rechargeable batteries that provide a 26.6 A·H at 16.8 Vdc power system.
  - Since a fire in a suit's pure oxygen environment would be catastrophic, the US EMU has separate PLSS and suit enclosures.
- Displays and controls provide information needed for mission tasks and suit health assessments:
  - The EMU has a single-line, 20-character LCD mounted on the chest to report status.
  - Additional capabilities proposed for lunar / Mars missions include an electronic cuff checklist, an external helmet-mounted display, and an integrated pair of voice-activated LCD monitors.

## Cooling & Electrical Systems

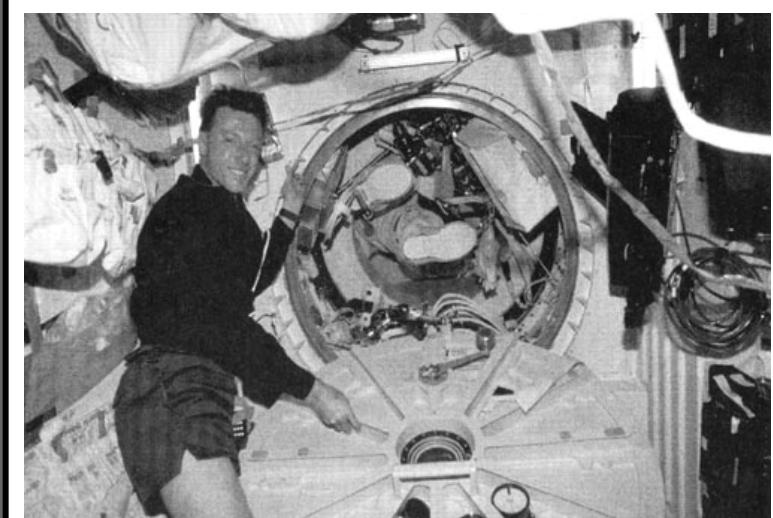
EVA EQUIPMENT/OPERATIONS

SUIT LIFE SUPPORT

## SPACECRAFT SYSTEMS DESIGN & OPERATIONS

Airlocks serve as the gateways between space vehicles and the external environments:

- Designs must be correlated with environmental and operational circumstances:
  - For the Shuttle, Mir and ISS, airlocks are places where suits are stowed, donned / doffed and serviced.
  - In weightlessness, crews can float through a 1 meter diameter opening, while in partial-gravity where the crew walks vertically, hatches should be dimensioned taller for vertical ingress and egress.
  - For lunar / planetary operations, airlocks should provide means for dust removal.



The Shuttle airlock is located in the crew cabin mid-deck enabling transfers into the payload bay. It is a 150 cubic ft. volume (63 inch diameter x 83 inches long) and can accommodate two fully-suited astronauts.

**Space Shuttle Airlock**

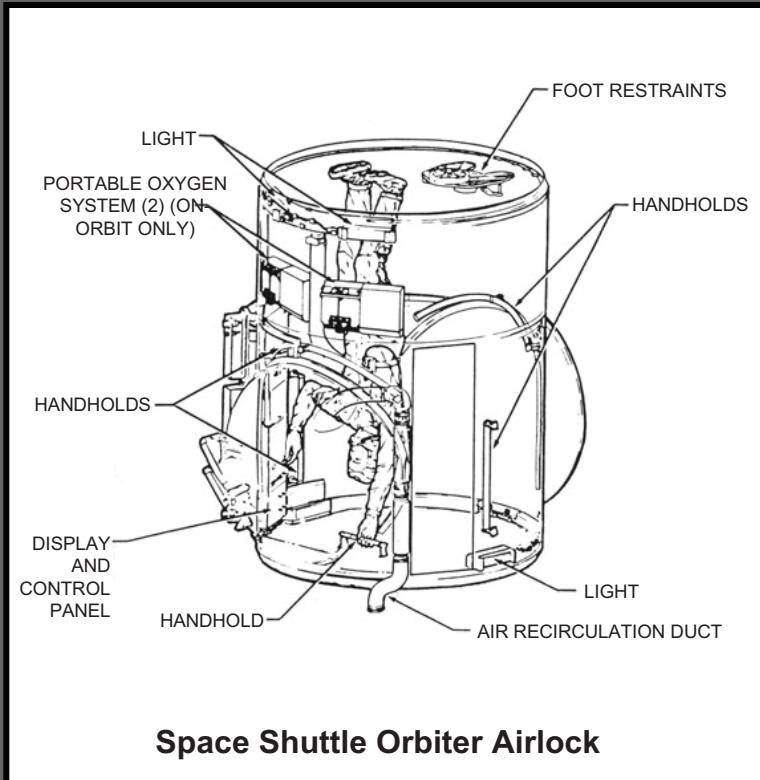
## Airlocks

## EVA EQUIPMENT/OPERATIONS

## SUIT INTERFACES

NASA

**SPACECRAFT SYSTEMS  
DESIGN & OPERATIONS**



The ISS Joint Airlock is comprised of two elements. An equipment lock is used for stowage, battery recharge / servicing and as a place to don / doff EMU and Russian Orlan suits. A crewlock section is the part that is depressurized to vacuum for crew egress / ingress.

**ISS Airlock (inside and exterior)**

**Shuttle & ISS Airlocks**

**EVA EQUIPMENT/OPERATIONS**

**SUIT INTERFACES**

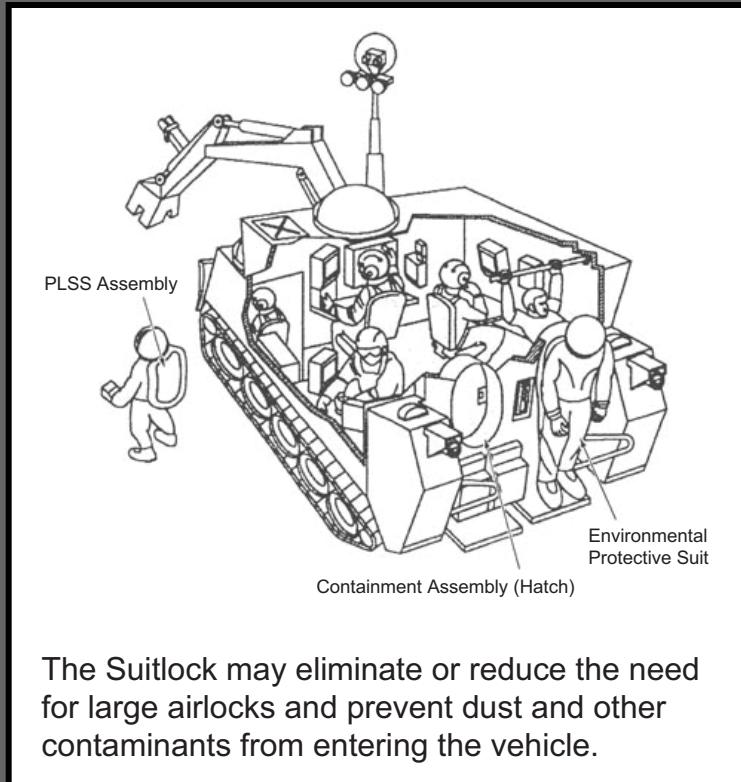


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NASA

The NASA Ames Research Center has proposed a Suitlock assembly concept that would enable EVA astronauts to transfer between the interior of a pressurized vehicle and outside environment without using a special airlock:

- The Suitlock assembly surrounds a large opening in the back of the suit that mates with a hatch on the vehicle:
  - The user enters and exits the special suit through the suit assembly which is “docked” with the vehicle’s assembly hatch ring.
  - Once a person is inside the suit, the suit assembly serves as a means for attaching / detaching a PLSS.
  - An inner pressure hatch cover is attached (before the EVA begins) or detached (before ingress) to retain the atmosphere inside the vehicle.



The Suitlock may eliminate or reduce the need for large airlocks and prevent dust and other contaminants from entering the vehicle.

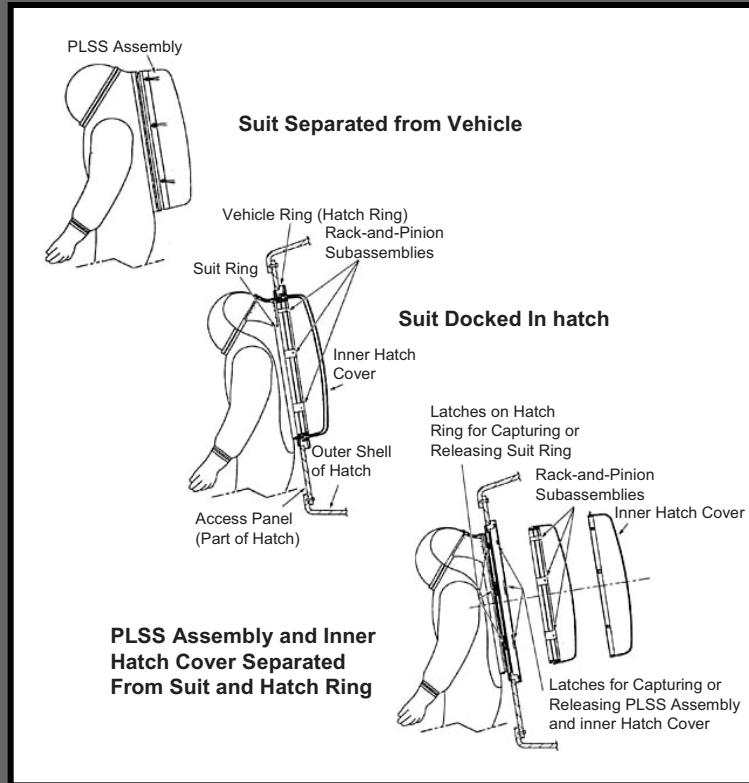
NASA Ames Suitlock Concept

EVA EQUIPMENT/OPERATIONS

SUIT INTERFACES

1. In preparation for entering the pressurized vehicle, the wearer maneuvers backward, inserting the PLSS into the vehicle hatch assembly and inner pressure seal recess.
2. Suit ring and elastomeric seals on the Suitlock assembly mate with sealing surfaces on the vehicle's hatch ring, enabling spring-loaded latches to capture the Suitlock assembly.
3. After a seal is accomplished, the interior of the hatch is purged to remove any dust or other contamination.
4. When the purge is complete, it is safe to open the hatch to the vehicle interior.
5. The wearer then actuates a cable linkage that activates rack-and-pinion subassemblies that detach the PLSS assembly from the suit, and the inner cover is removed.

NASA



**Suitlock Operation Stages**

## EVA EQUIPMENT/OPERATIONS

## SUIT INTERFACES



H-38

SICSA has applied the NASA Ames Suitlock concept to Lunar / Mars surface architecture module proposals for two important reasons:

- Volume and mass minimization:
  - Suitlocks offer a potential means to eliminate or reduce the need for large and heavy airlock elements that will substantially contribute to Earth launch, orbit transfer volume and mass requirements.
- Dust contamination control:
  - Since Suitlocks attach to the outside of the habitats, dust which collects on suits during EVAs will not be brought into crew compartments upon return.



Conventional type habitat modules with Suitlocks are shown attached to an inflatable module to optimize useable interior volumes for living and work.

### SICSA Suitlock Application Concept

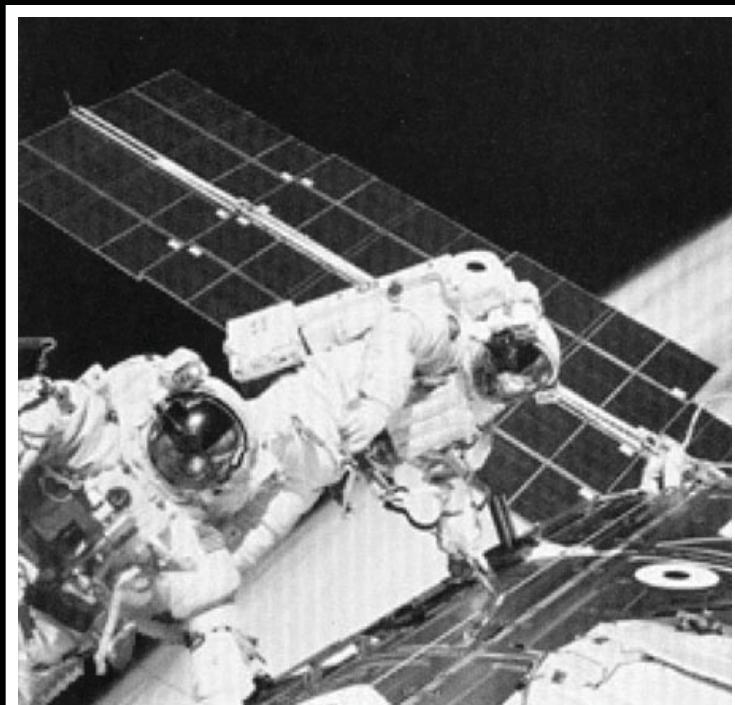
EVA EQUIPMENT/OPERATIONS

SUIT INTERFACES

**SPACECRAFT SYSTEMS  
DESIGN & OPERATIONS**

Safe and effective EVA operations under weightless conditions depend upon appropriately planned restraint systems:

- Tethers:
  - ISS EVA astronauts are attached to the station by two 55 ft. long waist tethers and a wrist tether at all times for safety purposes.
  - The standard protocol is to always make a new connection before any connection is broken.
  - A tether connected to the mini workstation (MWS) attached to the front of the EMU is used to connect an EVA crew member to a worksite, and can be used for translation of tools and small parts required for mission tasks.



**Tethers & ISS Assembly Operations**

**Tether Devices**

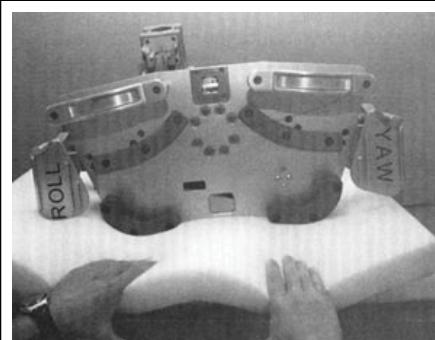
**EVA EQUIPMENT/OPERATIONS**

**RESTRAINT AND MOBILITY SYSTEMS**

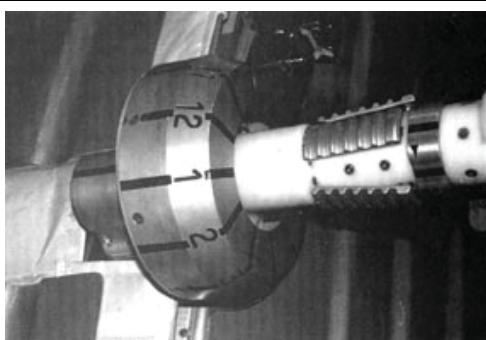
## SPACECRAFT SYSTEMS DESIGN & OPERATIONS

Foot restraints enable EVA astronauts to solidly secure themselves in place with arms and hands free to perform tasks :

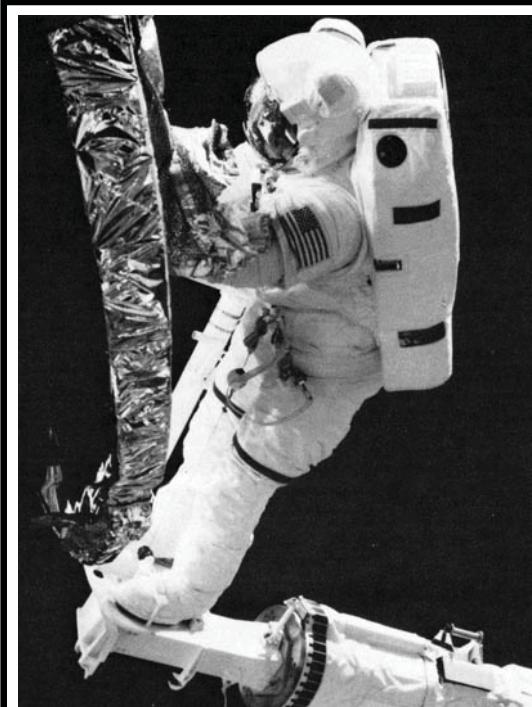
- A Portable Foot Restraint (PFR) is used on the Shuttles and ISS.
  - Crew members attach themselves to a platform by placing boots in foot pads.
  - Different types of devices are available, including universal, articulating and fixed types.



Portable Foot Restraint



Articulating Mechanism



Portable Foot Restraint (PFR)

Foot Restraints

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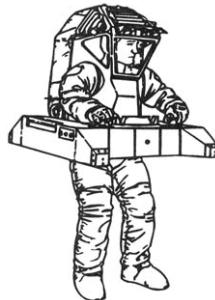
## EVA EQUIPMENT/OPERATIONS      RESTRAINT AND MOBILITY SYSTEMS

The Man Maneuvering Unit (MMU) was developed as an alternative to slow, cumbersome hand-over-hand translation and tether distance limitations under weightless conditions :

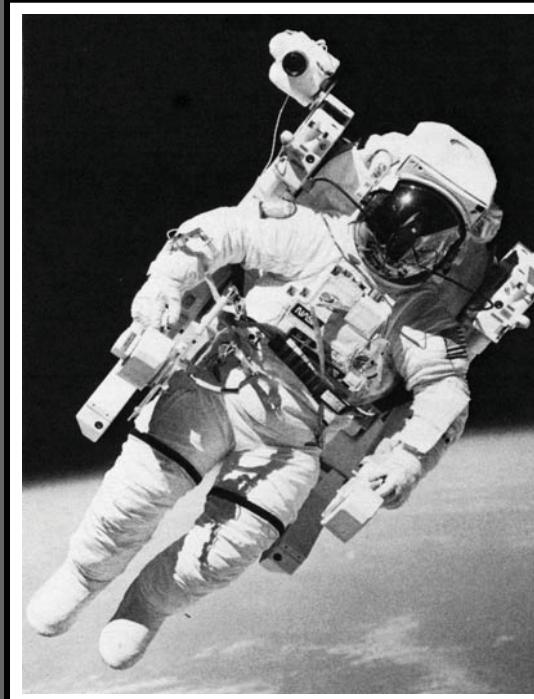
- The device is a piloted personal spacecraft with full attitude control capability including an inertial gyro:
  - It is propelled by cold nitrogen gas stored in pressure tanks.
  - EVA operations can extend to about 1km from the Shuttle or ISS.
  - A very similar Russian device has demonstrated successful use.



Russian  
MMU



US Command  
Control Pressure  
Suit (Under  
Development)



Astronaut Mc Candless on 1<sup>st</sup> MMU Test Flight

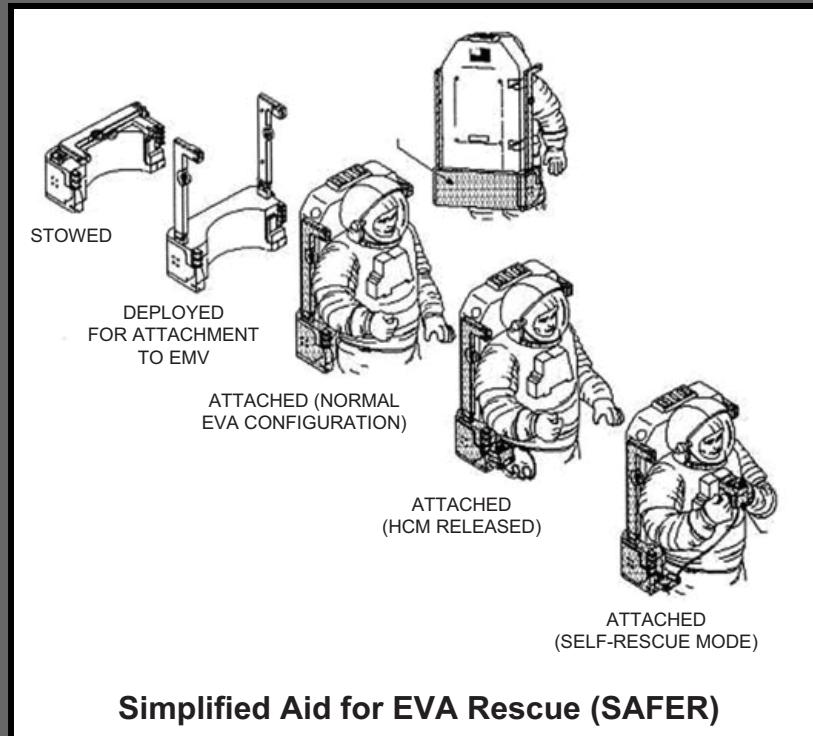
### Man Maneuvering Unit (MMU)

## EVA EQUIPMENT/OPERATIONS      RESTRAINT AND MOBILITY SYSTEMS

NASA is currently using a small 36 kg maneuvering device called the Simplified Aid for EVA Rescue (SAFER) that allows a crew member to return safely under emergency conditions:

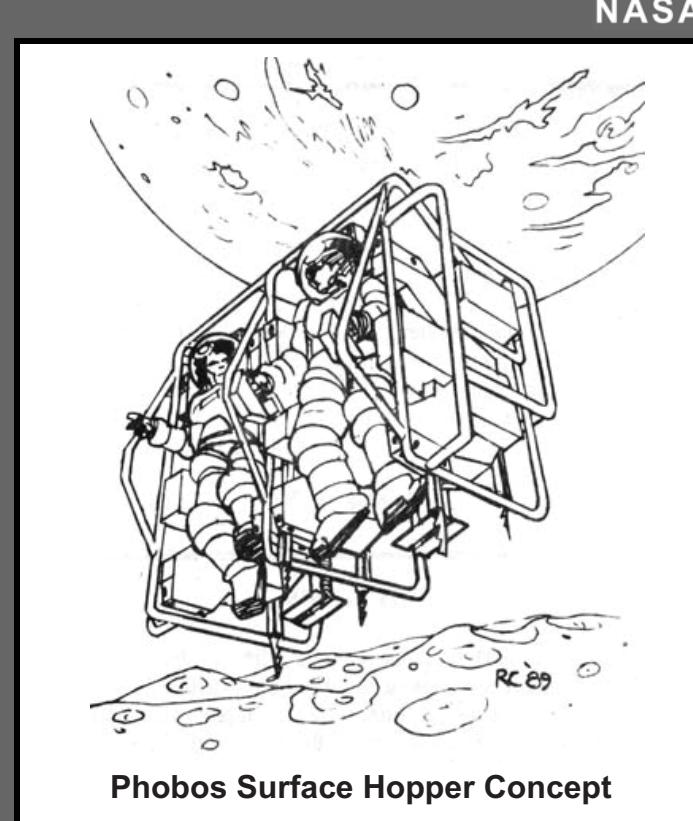
- SAFER is a self-contained propulsive backpack which is primarily intended for use if an astronaut becomes untethered.
- It offers about 13 minutes of propellant and power for one self-rescue.
- The unit is operated by a single hand controller, and uses pressurized nitrogen as the propellant.

### SPACECRAFT SYSTEMS DESIGN & OPERATIONS



Transporting EVA crew groups over longer distances in low-gravity environments (such as on Mars' moons Phobos and Deimos) may apply maneuvering unit principles.

- A Phobos Maneuvering Unit (PMU) might transport EVA crews of 2-4 several kilometers from the spacecraft landing location:
  - The gravity of Phobos (about 0.001 Earth gravity) would be too low to walk on, and an extremely small amount of thrust would be required for a "hopper" to be used.
  - The moon's small diameter (maximum 28 km) will limit travel distances, but will also present radio communication challenges. (The horizon will be only 270 meters away for a tall man standing.)



Possible Future Maneuvering Vehicles

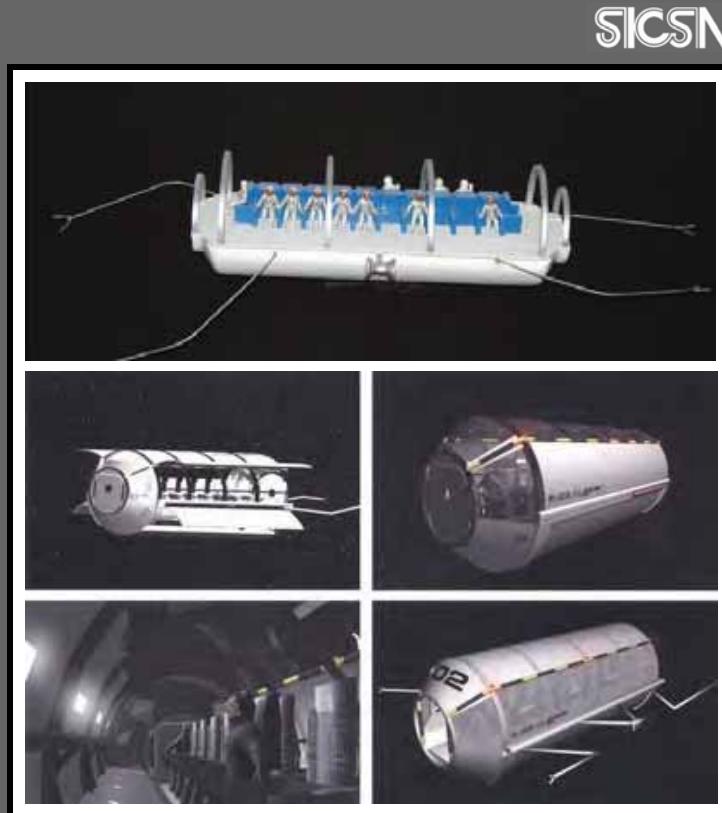
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## EVA EQUIPMENT/OPERATIONS      RESTRAINT AND MOBILITY SYSTEMS



H-44

- A proposed unpressurized multipurpose vehicle to transport people and cargo between LEO facilities:
  - Can be delivered in a dedicated Space Shuttle Orbiter or Russian Proton launch.
  - Maneuverable under automated, teleoperated or manual control.
  - Serves as an open “pickup truck” to transport space-suited crews, manipulate space station module-sized elements and support construction/assembly processes.
- Special design features include:
  - A Remote Manipulator System (RMS) for teleoperated or manual control.
  - Air supply to supplement EVA life support capacities.



SICSA Orbital Transfer Vehicle Concept

EVA EQUIPMENT/OPERATIONS

RESTRAINT AND MOBILITY SYSTEMS

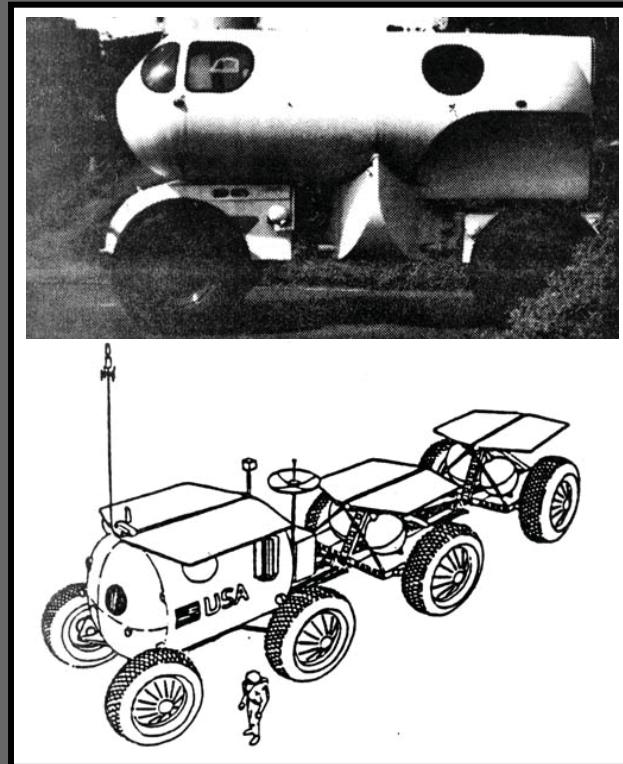


H-45

Numerous concept studies in connection with the Apollo Program propose pressurized lunar vehicles capable of supporting small crews over EVAs lasting a few weeks:

- The Grumman Mobile Lunar Laboratory (MOLAB) vehicle was created as a mockup on a full-size working chassis:
  - The vehicle was designed to support a crew of 2 for periods up to 6 weeks.
  - It would be capable of operating as an excursion habitat, and also as a prime mover to tow unpressurized trailers.
  - A variation of the design was an unpressurized rover option.

PLANETARY SURFACE SYSTEMS



Grumman MOLAB Vehicle

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EVA EQUIPMENT/OPERATIONS

LUNAR / MARS ROVERS

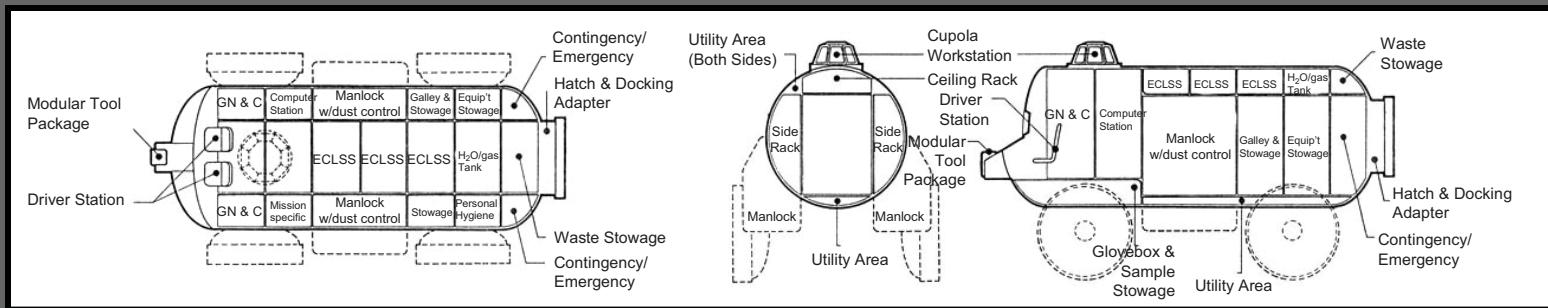
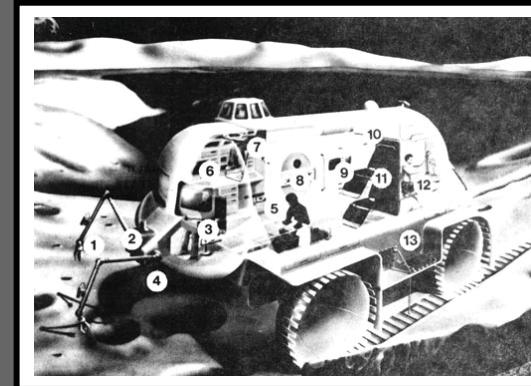


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## PLANETARY SURFACE SYSTEMS

### Rover Elements/Areas

- 1. 2 remote manipulators for sample collection.
- 2. Modular tool / instrument package
- 3. Driver's station & RMS controls
- 4. Scientific airlock for sample containment
- 5. Manually – operated conveyor belt.
- 6. Modular rack – mounted workstations
- 7. Cupola navigation & workstation
- 8. EVA manlocks (small volume airlock)
- 9. Galley & food supply for long excursions
- 10. Overhead space for equipment / supplies
- 11. Sitting & sleeping area
- 12. Compact personal hygiene facility
- 13. EVA "jump seats" for outside travel



NASA Johnson Space Center  
Pressurized Lunar Rover Concept

**EVA EQUIPMENT/OPERATIONS**

**LUNAR / MARS ROVERS**

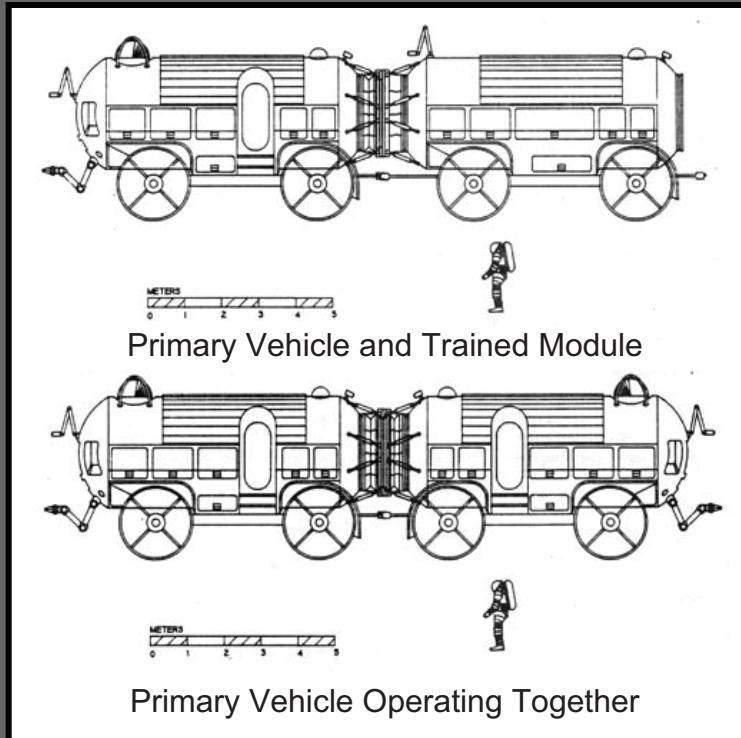


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## PLANETARY SURFACE SYSTEMS

Options include primary vehicles that pull trains of auxiliary units vs. primary vehicles traveling together.

- Short-range lunar vehicles were estimated to require 5-10 kW average power, possibly using batteries.
- A Dynamic Isotope Power Supply (DIPS) was considered as an alternative power source to reduce weight. (The nuclear device would use a plutonium isotope heat source with a small heat source power converter.)
- The favored power option was to use Shuttle-type liquid oxygen – hydrogen fuel cells. Current cell life, however, is only about 2,000 hours.



NASA Pressurized Surface Rover Concept

EVA EQUIPMENT/OPERATIONS

LUNAR / MARS ROVERS



H-48

SICSA has developed a multipurpose unpressurized rover concept for lunar and Mars applications.

- A universal chassis platform can be adapted to support a variety of EVA and/or teleoperated functions:
  - Transport of 4 or more EVA-suited astronauts with supplementary consumables.
  - A mobile drilling rig for obtaining and remotely investigating surface samples.
  - A mobile crane to place/remove large items on carriers and to support construction.
  - A mobile power plant containing batteries and other power or equipment systems.
  - A mobile winch/transporter to deploy electrical power cables and tow modules.



SICSA Surface Rover Concept

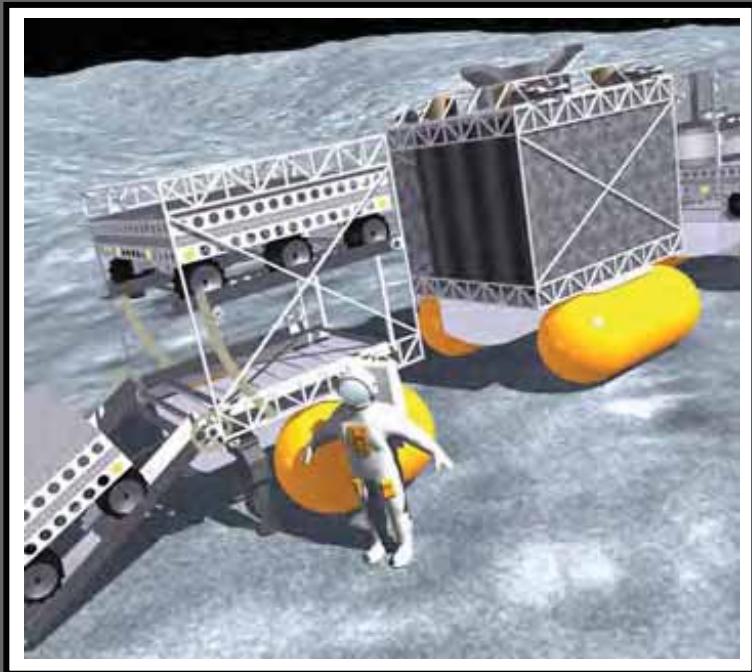
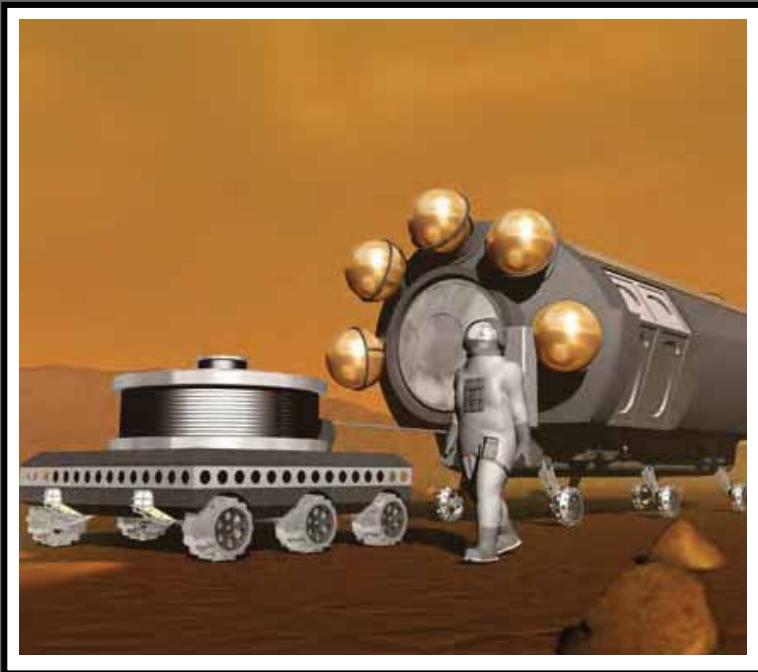
EVA EQUIPMENT/OPERATIONS

LUNAR / MARS ROVERS



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SICSA



SICSA Surface Rover Concept

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EVA EQUIPMENT/OPERATIONS

LUNAR / MARS ROVERS



H-50

Short Apollo and Shuttle missions have enabled crews to be trained on Earth for all scheduled EVA procedures and anticipated contingencies. This will be more difficult to accomplish for much longer ISS and lunar/ planetary missions.

- Shuttle training consists of classroom work, suited water tank weightless simulation, parabolic flights that induce short periods of weightlessness or reduced-gravity, and training exercises using various simulators and mockups:
  - Training requires about 1 year, with hardware available about 9 months before flight.
  - Crews can refer to pre-prepared paper checklists worn on suit forearm cuffs.
- Some ISS and lunar/Mars expedition training may have to be conducted during the missions:
  - NASA is developing a Virtual Reality (VR) training capability that can be applied on Earth and in space.
  - An electronic cuff checklist is also being developed for real-time EVA support, which will be updatable from Earth during a mission.

## Mission Influences

EVA EQUIPMENT/OPERATIONS

CREW TRAINING

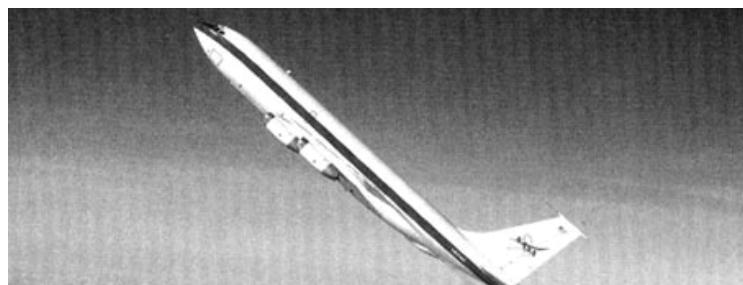


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## SPACECRAFT SYSTEMS DESIGN & OPERATIONS



Neutral Buoyancy Lab



Parabolic Flight Trainer



Environmental Test Article Chamber



Virtual Reality Lab

## Types of Facilities

EVA EQUIPMENT/OPERATIONS

CREW TRAINING



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Additional information relevant to this section can be found in Part I, Section E (robotic and mobility systems) of this SICSA SPACE Architecture Seminar Lecture Series, along with other publications listed below:

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**EVA EQUIPMENT/OPERATIONS      REFERENCES AND OTHER SOURCES**