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THE VERNACULAR OF SPACE ARCHITECTURE

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ABSTRACT

Space architecture is a unique, undeveloped field. There have been many glimpses into the future of space architecture via comic books, cartoons, and movies that conjure up fanciful massive stations and 100-kilometer Moon or Mars domes. However, realistic space architecture started when the space race put humans into orbit, then progressed with the Apollo moon missions and the initial space stations. Space Architecture has now evolved into the International Space Station that is 220 nautical miles in orbit above Earth. As NASA and the space community look beyond low Earth orbit to interplanetary spacecraft, space facilities at libration points, and Moon and Mars bases, the beginnings of a true and real space architecture vernacular of the early twenty-first century takes shape.

This paper describes the current vernacular of Space Architecture of the early twenty-first century. At this juncture of the century, Space Architecture is comprised of launch vehicles, pressure vessels (modules) and the systems to support human life. Of course many elements, systems, and hardware are involved within these broad categories. The launch vehicles are a part of this vernacular because they constrain the size and mass that will be transported to orbit. This paper focuses mainly on the habitable systems of space architecture—the pressure vessels or modules that provide the primary structures and contain the atmosphere to enable humans to live and work in space.

INTRODUCTION

Space structures—whether a space station, an interplanetary transfer spacecraft, a Moon or Mars base, or some futuristic space hotel—all share common architectural elements. These elements are pressure vessels (for living, working, and logistics), docking or berthing connections for spacecraft, transition spaces (airlocks and nodes), support structure, power collection and distribution, thermal control, communications, and propulsion with guidance and control. This paper focuses on the pressure vessels or habitats, but gives a brief overview of the other elements of space architecture.

The space environment heavily influences the design of the space architecture elements. Pressure vessels can consist of laboratories, habitats, interconnecting modules (nodes), airlocks, and areas for logistics, storage, and work. Currently all of these large and heavy preintegrated pressure vessels are brought from Earth on a launch vehicle. Eventually, as our space civilization evolves, we will be able to live off the "land," producing and manufacturing habitats on other planetary bodies.

SPACE ARCHITECTURE ELEMENTS

The basic vernacular of space architecture draws its vocabulary from a modular kit of space elements. An orbital station, an interplanetary spacecraft, and a planetary surface base have common elements. All architectural solutions require a transportation system to take these elements to space, an infrastructure to provide structural support, and utilities to provide functionality. The transportation system places constraints on the size and mass of the element being delivered to space—much as ground transportation does for terrestrial building components.

The infrastructure for an orbital facility or an interplanetary spacecraft includes structural arrays or a truss system to attach power systems, radiators, berthing ports, airlocks, and living modules. Utilities include power generation and distribution, removal of excess waste heat through radiators, communications, and propulsion with guidance and control (GN&C). The infrastructure for a planetary surface base includes living modules, airlocks, power generation and distribution, radiators, berthing/docking ports, communications, and surface transportation. There are many papers and books about the design of these space elements. The following are major elements in space architecture.

- Habitat
- Laboratory
- Node (transition element)
- Airlock
- Berthing/docking systems
- Logistic supply
- Structural system
- Power system
- Thermal system
- Communications system
- Propulsion with GN&C

Space Environmental Factors

Space habitats are designed to sustain human life in the inhospitable environment of space. These habitats are pressurized vessels which include laboratories, living facilities, support systems, and repair/maintenance facilities. The space environment is characterized by its vacuum, orbital debris, microgravity (on orbital space stations and transfer missions), partial gravity, radiation, and planetary dust. These characteristics are the major design challenges for space habitation.

Microgravity, with its absence of a strong gravitational force, presents challenges and opportunities for designers of orbital and transfer habitats. The microgravity environment eliminates the physical need for normal up and down orientation and the typical area method of space allocation. It provides an opportunity to use volume rather than area. The International Space Station (ISS) is a good example of the use of volume.

Induced artificial gravity on transportation systems incurs a mass penalty over microgravity systems, depending on configuration and propulsion system selection (Capps, 1991). It has not been conclusively proven that these systems are required for Mars transportation, but if they are, since mass translates to cost in space transportation, the added mass translates to at least 5-15% additional development cost.

Environments with less gravity than that on Earth pose interesting habitat design challenges. Human physical reactions and performance in a reduced gravity environment differ from those in Earth gravity. The main difference is that microgravity places less restriction on human locomotion than does the gravity of Earth, where the specific up and down orientation and reach envelopes increase volume requirements.

Planetary dust is a potential problem for any planetary surface element system or activity that is repetitive or has long-term exposure. A layer of fine dust-like particles (regolith) covers the Moon's surface. Lunar dust is very abrasive and can cause many problems if it gets into mechanical equipment or the human lungs. The Apollo missions experienced many problems associated with lunar dust contaminating the Lunar Module and surface equipment. Mars dust is much less understood than lunar dust. The Viking landers provided data that lead scientists to believe that Mars dust is much like dirt on Earth. This suggests that Mars dust will be less of a design issue than lunar dust, but certainly not something to ignore. Lunar and Mars dust can adhere to most objects and cause problems that will influence design of new exploration systems.

The goal of dust control is to limit dust penetration into a mechanism or environment. If an effective dust control program is not implemented, the results will be a higher number of mechanism failures, and increases in risks, maintenance, repairs, resupply, and contamination of the living environment. The latter is of particular concern because of its effect on the crew's health and the crew accommodation systems. Dust characteristics and design solutions are discussed in many articles, reports, and papers.

Space Habitats

Space habitats are categorized into three classes. Class I is preintegrated—entirely manufactured, integrated, and ready to operate when delivered to space. Class II is prefabricated and is space- or surface-deployed with some assembly or setup required. Class III is in-situ derived, with its structure manufactured using local resources available on the Moon or Mars. Figure 1 shows the relationship of habitat technology, habitat classes, and time. The next few sections present a top-level discussion of space habitat design considerations for the various elements that make up space architecture.

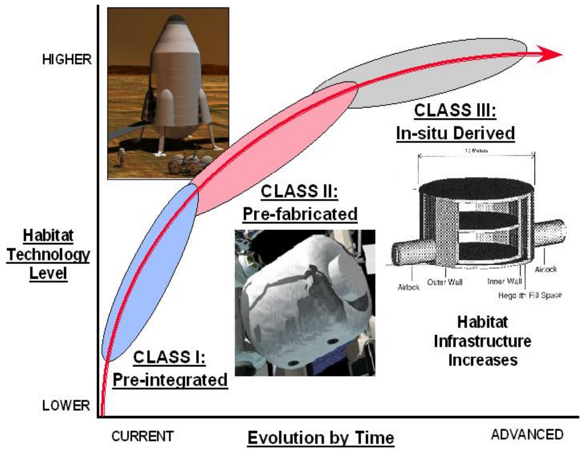


Figure 1. Habitat Classifications

CLASS I: Preintegrated Characteristics

- Earth-manufactured
- Earth-constructed
- Fully outfitted and tested prior to launch
- Space-delivered with immediate capability
- Volume and mass limited to launch payload size capability and mass capability

CLASS II: Prefabricated – Space/Surface-Assembled Characteristics

- Earth-manufactured
- Requires space assembly or deployment
- Requires robotic and human time during assembly
- Partial integration capability for subsystems
- Requires some or all internal outfitting emplacement
- Critical subsystems are Earth-based and tested prior to launch
- Requires assembly prior to operability
- Allows for larger volumes
- Less restricted to launch vehicle size or mass capability

CLASS III: In-Situ Derived and Constructed Characteristics

- Manufactured in-situ with space resources
- Space-constructed
- Requires manufacturing capability and infrastructure
- Requires robotic and human time during construction
- Requires integration of subsystems
- Requires all internal outfitting emplacement
- Critical subsystems are Earth-based and tested prior to launch
- Requires assembly to become operable
- Allows for larger volumes
- Not restricted to launch vehicle size or mass capability

Space habitats naturally attract great interest for a human-exploration program because they are sophisticated pressurized structures that contain and protect the ultimate payload—humans. They are the beginnings of a new architecture for space civilization. Habitats are complex, heavy, expensive elements around which support systems are functionally arrayed, both in transportation systems and permanent facilities like space stations and future planetary bases. Their concept development and selection requires careful consideration. Space habitats can be divided into three categories based on duration: short (days to weeks), medium (weeks to months), and long (months to years). Volume requirements for space habitats vary based on crew size and mission duration. Historical habitat gross volumes are illustrated in figure 2.

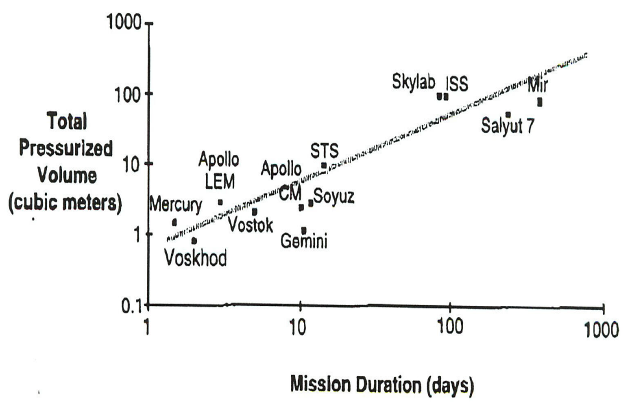


Fig. 2. Historical Space Habitat Pressurized Volume.

Long-duration space habitats impose especially stringent requirements on space stations, transfer vehicle systems, and planetary surface systems. Multi-year stay times represent an order of magnitude increase in mission duration over the ISS and the Russia's Mir space station. For transfer and surface systems, direct escape is impractical, and given the current high cost of space transportation, resupply and crew rotation schedules will be sparse. The duration and distance from Earth compounds the problem of crew isolation and confinement—exacerbating the concerns for human psychological needs. Also, commonality, defined as the usability of an element in multiple settings throughout a program architecture, can become a key consideration. The extremely high cost of developing space hardware is a strong influence in favor of multi-use elements.

Each habitat type requires a different design approach, but all have to meet the requirements of providing a pressurized environment for the humans to live and work within. Common requirements, regardless of destination, include the following:

- Crew safety
- Acceptable physiological and psychological support for humans
- Successful accommodation of mission objectives
- Reliable structural integrity with adequate safety margins
- Forgiving failure modes (e.g., leak before rupture)
- Ability to be tested to a high level of confidence before being put into service
- Ability to be integrated with available launch systems
- Straightforward outfitting and servicing
- Easily maintained
- Long design life
- Commonality at the system or subsystem level

Space habitation configurations vary according to user requirements, destination, and mission. However, a core group of human needs must be provided for: food, water, oxygen, personal hygiene, and waste management. Factors in the space environment not inherently conducive to human habitation must be addressed to create as "Earth-like" an environment for humans as possible. Table 1 shows the five main environment considerations and the different requirements based on destination. Each environmental consideration is briefly described herein so that designers and architects understand the environment for which they are designing.

A typical ISS module demonstrates the emphasis on modularity and the absence of the normal up and down relationship (fig. 3). However, it is highly recommended that a local vertical be established within the module to aid the crew. Equipment configuration, lighting, airflow, and interior colors are used to provide a common orientation for the crew. This is a very efficient equipment configuration because it maximizes the use of module volume and provides the largest single open space.

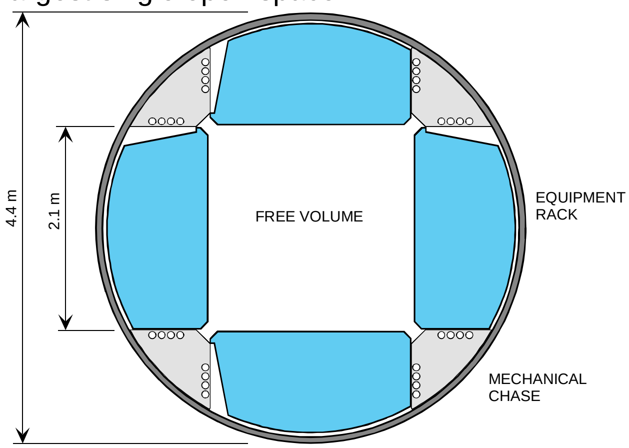


Figure 3. ISS Four-Standoff Rack Configuration

The module diameter was designed to take full advantage of the Space Shuttle Orbiter payload bay diameter (4.5 m), and the length was determined by the largest single integrated mass that could be launched to the ISS with the Shuttle (15851 kg).

The equivalent area of an ISS module is approximately 16 m^2, or the size of an average bedroom on Earth. On the ISS, six humans will be living for at least 90 days at a time in five modules—four laboratories and one habitation module. This demonstrates the efficient volume usage of microgravity designs as well as the volume premium based on cost.

Psychological and Physiological Considerations

The psychological aspects of habitat design are affected by mission duration and crew size. The longer the mission, the greater the need for crew privacy and recreation. Increasing crew size increases the need for human solitude and adds to the complexity of human interactions and social structure. This section discusses effects of mission duration and crew size on habitability and privacy requirements.

Short-Duration Missions - For mission that last a few days to couple of weeks, crews can share personal quarters by rotating shifts, as is done when the Space Shuttle carries Spacelab. Crew members also do not need nearly as much volume for recreation, exercise, dining, etc. due to the time factor and the fact that crews can rotate shifts, reducing the need for redundant spaces.

Medium-Duration Missions - For missions of up to 6 months, crews will require their own private personal quarters for sleeping and for private recreation (reading and communication with relatives), and will require more volume for grooming and personal hygiene. Crews will also begin to work standard shifts, which will result in more volume needed for dining, recreation, exercise, and meeting areas.

TABLE 1. Space Habitat Design Environment Considerations

Consideration	**Earth Orbital**	**Lunar/Mars Transfer**	**Lunar/Mars Surface**
1. Vacuum	Pressurized enclosure	Pressurized enclosure	Pressurized enclosure
2. Debris	Growing problem requiring heavy shielding	None	None
3. Gravity	Microgravity	Microgravity Induced gravity	Partial (less that 1 Earth g); changes interior architecture
4. Radiation	Protected by Van Allen Belts South Atlantic Anomaly potential problem	Lunar transfer protection probably not required Mars transfer protection required	Lunar protection required Mars partially protected by atmosphere; possible protection required
5. Dust	None	None	Lunar dust is a design challenge Mars dust a potential issue, but not really known

TABLE 2. Subsystem Descriptions

Subsystem	**Description**
Structure/Enclosure	Basic structure and enclosure to contain pressure
Environment Control & Life Support System (ECLSS)	Life support system that provides oxygen and water (degrees of system closure, or recycle, depends on mission length); includes waste management storage or recycling equipment in a closed system
Thermal Control System (TCS)	Heat collection and dissipation system
Power	External power source (typically solar arrays and batteries) and internal power distribution
Data Management System (DMS) / Communications	Equipment for management of mission data and communications with Earth
Internal Audio/Video	Internal communications system
Crew Accommodations	Crew quarters, galley, dining areas, and recreation facilities
Experimentation Equipment	Mission-specific science and experimentation equipment
Stowage	Storage volume for personal and mission related equipment
Radiation Shelter	“Storm shelter” for solar proton events

Long-Duration Missions - For missions of 6 months or more, crews will require all the necessary "comforts of home." Each crew member will need a private sleeping area with personal storage, a dressing area, and a sitting area. More generous recreational and exercise facilities will be required as well as a complete health maintenance facility.

The gross volume required for space habitats can be estimated based on historical data about human space exploration and remote environments on Earth. A first-order parametric volume estimation based on crew size and mission duration gives the designer a starting point for the space habitation system. Historical data combined with ISS data indicate that habitation volumes are divided into three categories; minimum tolerable limits, minimum performance limits, and preferred limits. Short-duration missions will be roughly analogous to those on the Shuttle, but little data is available to make a determination for long-duration missions. More research is required on long-term isolation.

Human physiological deconditioning occurs in microgravity. The heart and other muscles weaken, bones lose density, the sense of balance is upset, lung and kidney functions change, and the appetite is lost. Physiological deconditioning of the human body in microgravity affects the cardiovascular system, musculoskeletal system, immune system, and reproductive system; it also causes fluids in the body to shift. These effects occur because the human body is designed to survive in a gravity environment and must change in an effort to adapt to the new environment. The effects are lessened and slowed in partial-gravity environments like the Moon or Mars, but de-conditioning still occurs. Complete effects and whether or not the deconditioning stabilizes in partial gravity are unknown at this time. Countermeasures such as exercise and possibly pharmaceuticals are planned at this time. The application of drugs as a countermeasure is primarily to prevent bone mass loss and motion sickness. Drug use for bone mass loss has been tried only in bed rest studies; however, drugs for mitigation of motion sickness in space have been very effective. Implementing exercise countermeasures will necessitate more exercise equipment, facilities, and volume.

Systems of a Space Habitat

This section discusses the habitation elements as a system and addresses overall design considerations. Table 2 defines the typical habitat subsystems. Detailed discussions of each of these subsystems are not included in this paper, but there are many references about these subject areas.

The systems that support human life within habitable modules include environmental control and life support, active thermal control, command and data handling, power, communications, habitability (human accommodations), and crew health care.

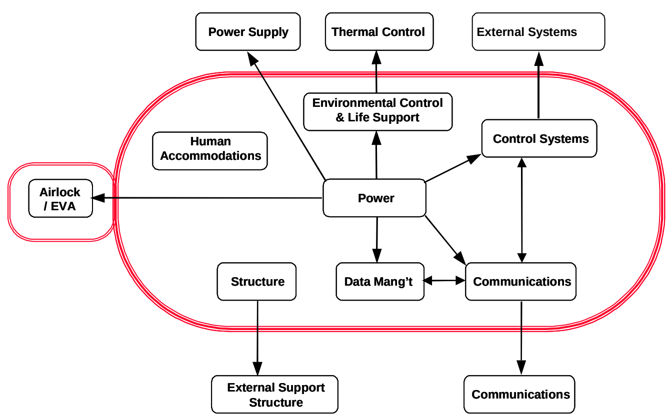


Figure 4. Habitat Elements and Interfaces

Figure 4 shows the relationship of these systems within a habitat and how they relate to the external interfaces. The habitation system interfaces with external systems in all architectures. The overall space system—whether orbital, transfer, or surface–provides critical infrastructure support, much like structures on Earth provide utility interfaces. The external systems must provide a source of power, thermal control in the form of radiators, support structure, and communications. Other external systems can include experiments, sensors for monitoring the system infrastructure, and extravehicular activity (EVA) systems that support the crew outside the pressurized shirt-sleeve environment. EVA systems include transition spaces such as airlocks, as well as the EVA suits the crew wear while working and exploring outside of the modules. All of these system designs are based on reuqirements by safety of the crew, mass, power, volume, and reliability or robustness.

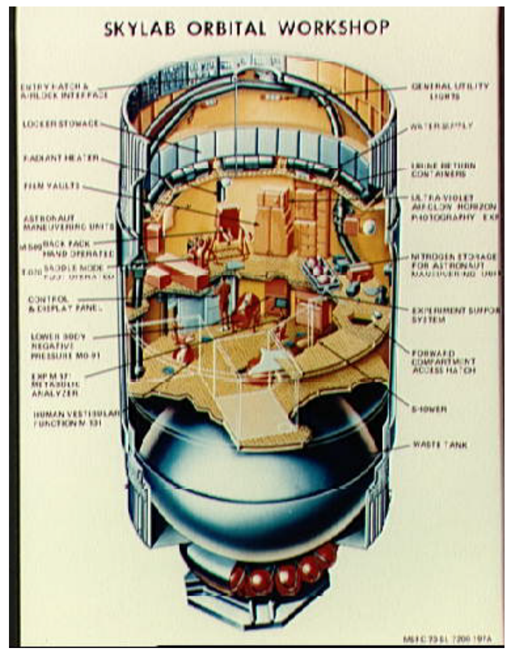
Habitat Design Applications

Space habitat configurations vary according to the design program. Habitats in general are designed to be used as orbital facilities, interplanetary transfer vehicles, or facilities on the surface of another planet. Overall, a space habitat configuration combines all the subsystems required to provide and maintain a living and working environment in space. The habitat configuration can vary from the single open-volume space of a short-duration spacecraft, to a single volume with separated spaces in a medium-duration facility, to the complex and sometimes multiple volumes of a long-duration habitat. Table 3 gives a quick overview of habitat design trades and considerations.

Orbital Habitats

Since the early 1970s, humans have been living and working in space. The Russians have the most experience with and knowledge of long-duration space facilities. Historical and current habitation facilities include Skylab (fig. 5), Spacelab, Salyut 7, Mir, and the ISS. These space habitats demonstrate an evolution in habitation design and technology. Except for Skylab, early space habitats provided only the necessities to survive in low Earth orbit. Little was understood about the effects of space on humans or how to accommodate them.

The ISS habitation facilities (fig. 6) have culminated all the previous experiences in and research on isolation and space effects. These facilities now accommodate humans by providing increased free volume per crew member, private spaces such as crew quarters, separate laboratory facilities, areas for group functions, recreation capabilities, exercise areas, and quality hygiene facilities. Previous habitats did have some form of these, but such accommodations have been given more emphasis on ISS to address human physiological and psychological well-being. The TransHab concept (fig. 7) culminated with the optimum orbital habitat design solution for living in space.



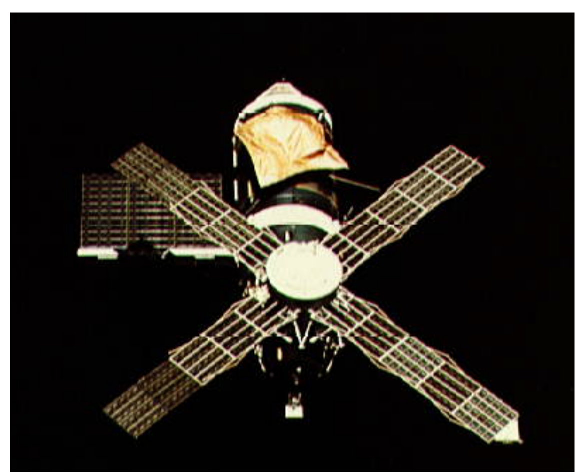


Figure 5: **Skylab**

TABLE 3. Space habitation design trades and rules of thumb.

Configuration Driver	**Trade**	**Rule of Thumb**
Habitat function	Habitat layout, hab/lab	Separate hab and lab functions and activities for long duration missions.
Number of crew	Volume required	Vol/crew member: larger no. of crew require much more volume.
Mission duration	Habitat size	Short duration requires less volume; long duration requires much more volume.
Structure	Aluminum, composites, inflatables	Aluminum for preintegrated short duration habs; inflatables for prefab long-duration habs.
Life support	Percentage open, partial, closed	Open for short missions. Try for 100% closure for long-duration habs.
Data handling and management	Computers, automation	Open architecture with fault-tolerant parallel processing. Automated integrated habitat health monitoring for long-duration habs.
Communications	Direct, Relay	Utilize Deep Space Network. Emplace array network satellites for planetary colony.
Thermal control	Body mount, deployable radiators, thermal sink	Body mount on transfer vehicle when possible. Deployable for large heat rejection. Utilize heat sink underground if on another planet.
Power	Generation source: battery, fuel cell, solar, nuclear	Look at nuclear for long-duration mission that requires a lot of power deep in space.
Crew accommodations	Social interaction, privacy, exercise, recreation	Space condition for short transfers. Privacy and social interaction required for long duration.
Environment protection	Radiation, dust, orbital debris, micrometeoroids	Orbital hab requires protection from radiation, orbital debris, and micrometeoroids. Transfer hab requires protection from radiation and some micrometeoroids. Lunar/Mars requires some protection from radiation, dust and micrometeoroids.
Risk	Level of redundancy	Fail op-fail safe on critical hardware

Figure 6. U.S. Hab Module

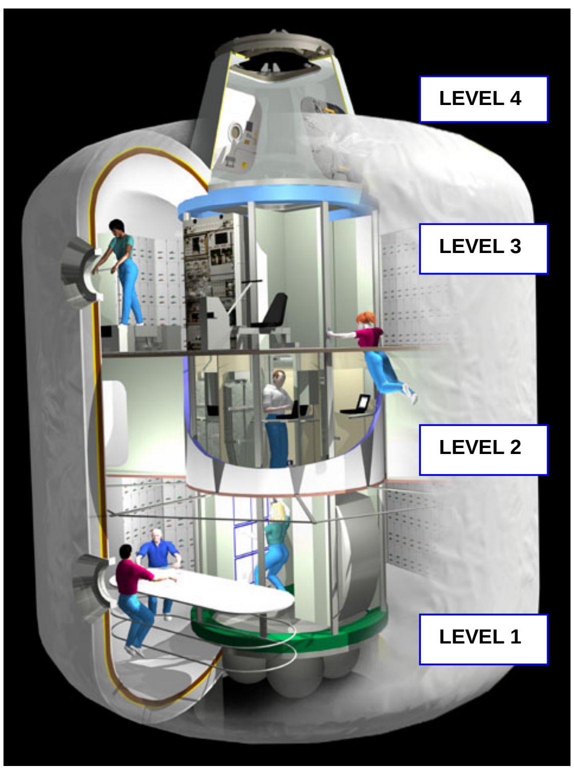


Figure 7. TransHab Module

Transfer Habitats

There are also numerous examples of space habitat, both historical and conceptual, designed for transfer of humans from one place to another—interplanetary or near-Earth objects. Space habitats used during transfer or spaceflight could be as small as the Apollo Service/Command Module (fig. 8) or the Space Shuttle Orbiter (fig. 9). However, interplanetary transfer habitats used to go to Mars or to an asteroid would require more volume (fig. 10). Current space habitat concepts represent an evolution in habitation design and technology.

Much like the early orbital habitats, transfer habitats started by providing only the necessities to survive in low Earth orbit or the transfer to the Moon because designers did not understand much about the effects of space on humans or how to accommodate them. Transfer habitats now provide much more free volume per crew member, private space such as crew quarters, separate laboratory facilities, group function areas, recreation capabilities, and exercise and quality hygiene facilities. Although previous habitats had some form of these accommodations, their importance has increased for the sake of human physiological and psychological well-being.

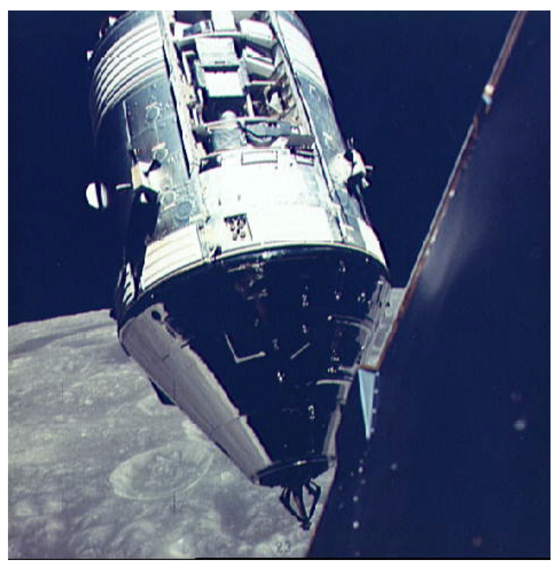


Figure 8. Apollo Command Module

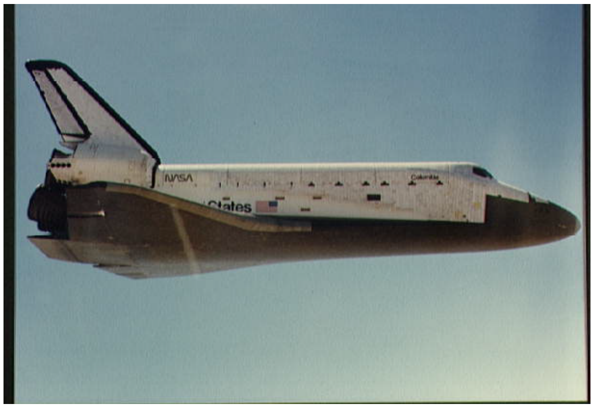


Figure 9. Space Shuttle Orbiter—STS 1

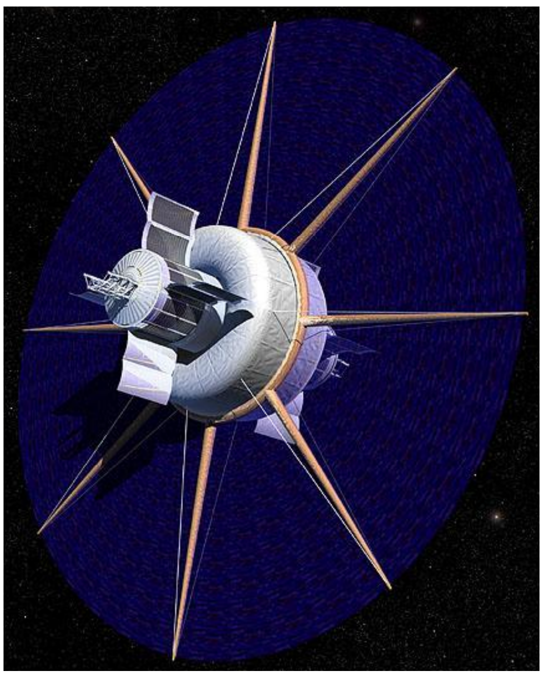


Figure 10. Asteroid Mission Module

Planetary Habitats

Only one space habitat has actually been used on another planetary body—the Apollo Lunar Module (fig. 11). It represented what would be required, as a minimum, to survive on another planet. However, it was very small and cramped, not human-accommodation sensitive. Based on lessons learned from Apollo, designers have been proposing many ideas for future space habitats for the Moon and Mars. These range from preintegrated space-station-derived modules (fig. 12), to prefabricated inflatable structures (fig. 13), to in-situ derived and constructed units (fig. 14). Figures 15 through 19 show other design concept examples—an ISS airlock, a planetary airlock, a planetary node, a planetary communication system, and a pressurized surface rover. These habitat concepts are shown for discussion purposes only and do not reflect a preferred choice.

Figure 11. Apollo Lunar Module

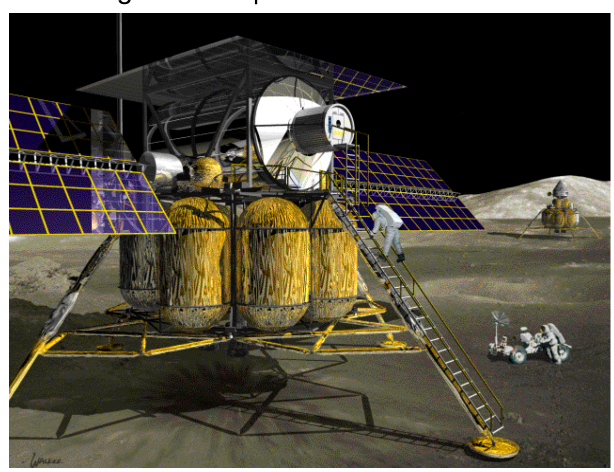


Figure 12. First Lunar Outpost

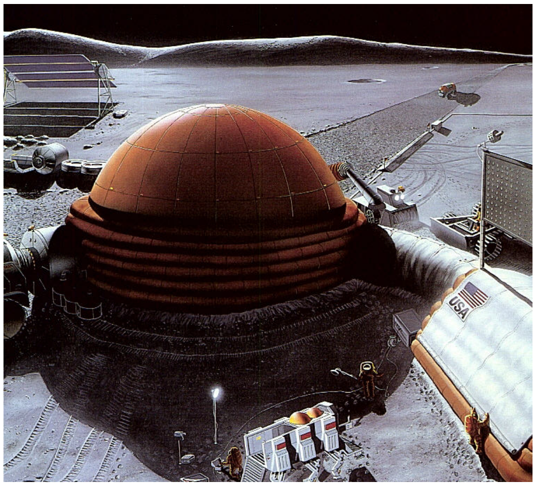


Figure 13. Inflatable Habitat Module

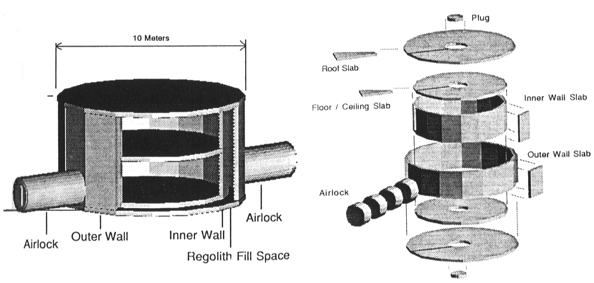


Figure 14. ISRU Derived Lunar Concrete Hab

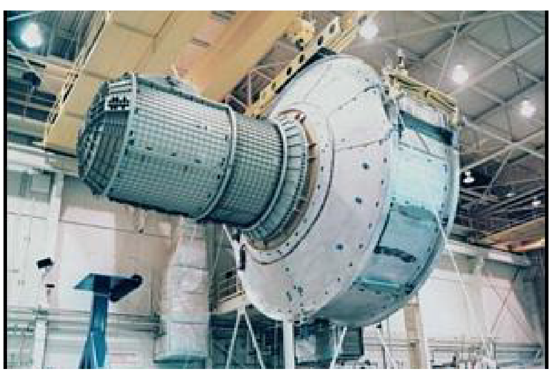


Figure 15. ISS Airlock

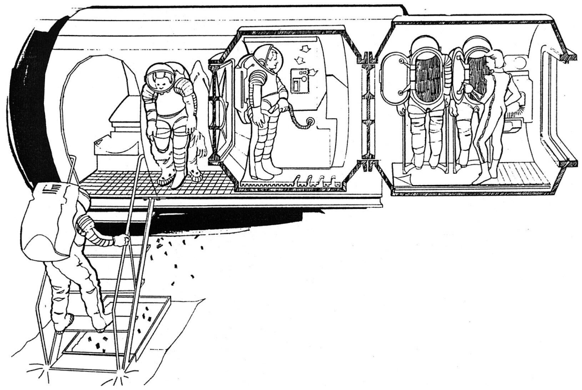


Figure 16. Planetary Airlock Concept

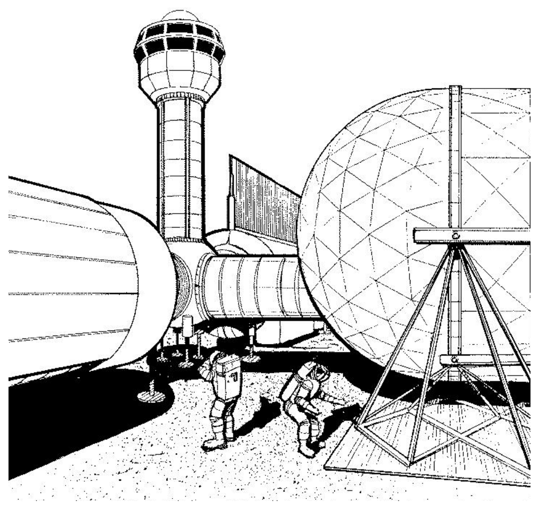


Figure 17. Planetary Node

Figure 18. Communication System

Figure 19. Pressurized Rover

Space Architecture at a Crossroads

With the emergence of space architects and TransHab in the space industry, NASA is at a crossroads, with its engineering disciplines no longer limited to cylindrical hard modules. Many wonderful and architecturally pleasing shapes will emerge, bringing in a new space era with the new century. NASA space architects like the author are ensuring that architectural design principles and practices are being used in the development of habitats, space vehicles, and planetary bases.

No longer is the normal hard aluminum module accepted. Inflatable structures are leading the way among the promising new technologies for NASA. They will change how we think about designing habitats, laboratories, hotels, and resorts for space. They will also revolutionize the space architecture world by opening up the possibilities of shapes and sizes to create human settlement of the solar system. NASA has long been a leader in research and development of new technologies for space activities, many of which have spun off to benefit humankind and Earth. Prime examples are the fields of computers, medicine, and recycling, and there are many others. Numerous technology thrusts originated as NASA technology development needs. Although inflatable structures are in the forefront of the technology roadmap, there are other important areas such as robotic construction, self deploying structures, smart structures, and self-healing structures, to mention a few.

The author's advanced habitation vision is to continue working on innovative technologies required to enable NASA's Human Exploration and Development of Space Enterprise to meet the demands of the harsh space environment. Space and planetary habitation, pressure structures, and unpressurized shelters are being sought out for innovative structural solutions that combine high strength and light-weight materials to achieve reliability, durability, repairability, radiation protection, packaging efficiency, and life-cycle cost effectiveness. Advances in materials development and manufacturing techniques are considered enabling technologies for the migration of humans into space and their eventual settlement on Mars. These include materials that enable the structure to "self-heal;" and techniques to emplace, erect, deploy, or manufacture habitats in space or on the Moon and Mars. Integration of sensors, circuitry, and automated components to enable self-deployment and "smart" structures are considered necessary to allow a habitat system to operate autonomously.

The objective is to create an advanced habitat that becomes a "living" structure that not only runs autonomously, but also has self-healing capability. A number of technologies and techniques have been proposed that allow the delivery of deployable habitats to space and planet surfaces, or the manufacturing and construction of habitats on planet surfaces. Breakthroughs in biotechnology have opened up many exciting possibilities. The use of biotechnology combined with a fabric or matrix structure could someday produce a self-healing material analogous to our human skin.

Research is needed on methods and techniques for fully integrated inflatable "skin" and sensors/circuitry that enable "smart" structures to autonomously detect, analyze, and correct (repair) structural failure. Manufacturing methods should be considered for integrating miniaturization technology into the habitat skins, thus reducing weight and increasing self-autonomy. Methods for designing, manufacturing, and testing inflatable structures that meet human requirements should be developed for future habitats in space. Technologies of this nature will be required to develop large planetary bases as shown in figure 20.

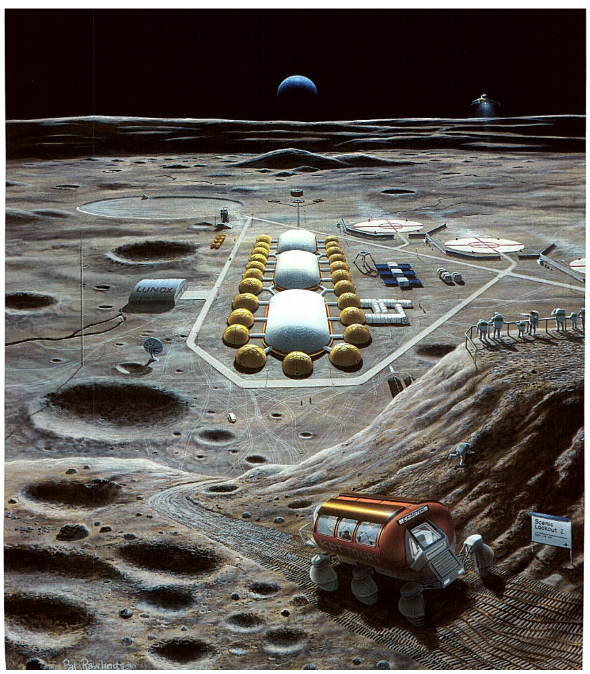


Figure 20. Lunar Base Concept

The Future of Advanced Habitats and Space Architecture

History has taught us that architects and engineers have shaped our built environment; and so will they our future—on Earth and in space. Groundbreaking work by architects and engineers at NASA is laying the technological foundation on which many will build for years to come. Although the TransHab team made incredible strides, there still remains a great deal of work on the ground and in space to get humans ready to live and work in space, on the Moon, and on Mars.

Space architecture is a fascinating field, with its high tech possibilities and limitless boundaries. As described in this paper, its vernacular will remain constant with the use of pressure vessels (habitats) and the infrastructure to support them. Space architects are at the forefront of a twenty-first-century architectural evolution from terrestrial architecture to the space architecture that will enable humans to settle on other planets. Indeed, these are exciting times.

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