Lunar Habitation Strategies

NASA/ JSC/ Kriss Kennedy, Space Architect
NASA/ JSC/ Larry Toups, Space Architect
NASA/ MSFC/ David Smitherman, Space Architect

Abstract

This paper will describe lunar habitation strategies necessary to support the Vision for Space Exploration. Space habitats are a re-creation of the earth environment for the purpose of sustaining human life beyond our home planet. Included are pressurized habitable volumes such as laboratories, living quarters, and repair and maintenance facilities. The space environment in which habitats must operate is characterized by vacuum, orbital debris, microgravity for orbital space stations and transfer missions, partial gravity for planetary exploration missions, radiation, and planetary dust. These characteristics are the major design challenges for space habitation systems. The objective is to achieve increasingly self-contained human habitats of various sizes and functionality for use in space and on planetary surfaces. As will be discussed in this paper, the space environment found on the moon is particularly inhospitable to human life and presents many challenges to designing lunar habitats such as mass constraints, volume requirements, efficient packaging, and managing risks to the crew.

Introduction

Habitation as defined in Webster's New World dictionary comes from the word Habitat. Habitat is defined as [1] the region where a plant or animal naturally grows or lives, and [2] the place where a person or thing is ordinarily found. Therefore Habitation is [1] the act of inhabiting; occupancy, [2] a place in which to live; dwelling; home, [3] a colony or settlement. Understanding the psychological and physiological needs of humans to create habitable spaces for the crew to live and work on the Moon is paramount. Many studies of historical space craft volumes per crew member per mission duration have been performed (fig 1). The mission durations for the purposes of gross volume estimates are defined as short duration [a few days to a week or so]; medium duration [a few weeks to a couple of months]; and long duration [six months or greater]. Numerous studies have been completed on the isolation and confinement of humans in hostile environments including jails, off shore oil platforms, submarines and Antarctic facilities (Connors, et al, 1985).

Social Environment of Space Habitats

Humans on long duration space missions are extracted from their normal social environment and placed into a micro society. This society becomes the human's entire world for the duration of the mission. Humans under normal circumstances on earth are embedded in a complex social matrix that links them with family, friends, large-scale organizations, and society (Connors et al., 1985). Humans on long-duration space missions are completely withdrawn from their normal social environment, which creates special privacy requirements for habitats. In recent years, the rigid autocratic, pyramidal command structure has become more relaxed in favor of "team" decisions with Team leadership. In the near future, "team" structures will probably continue with a clear, single leader in control.

For habitat design, the command structure will probably have little impact. Volume is at a premium and the crew commander may only have the additional equipment necessary for effective command, but not more volume. This is different than the military structure, and is indicative of the changing command environment as well as the economics of space habitation. For application to medium and long duration habitation design, consideration should be given to separating male and female quarters and personal hygiene facilities as is current practice in earth architecture.

Couples working and living together in space poses new challenges. Couples in small micro-societies may promote jealousy from other crew members who are separated from their partners and the potential for companionship. Couples on medium and long duration missions will want to live together thus requiring larger crew quarters. Longer stays will require larger quarters. Designs should include two sleeping quarters that can be merged into one space for couples. This requires specialized interior configurations which will likely limit the practice of couples on space exploration missions for the near term. Isolation experiments should be conducted to understand the aspect of couples vs. singles performance and well being for long term missions.

Psychological and Physiological Environment of Space Habitats

The psychological and physiological affects on the crew are in-part a correlation of the habitat design that is a result of the design environment, mission duration, and crew size. The longer the mission, the more crew privacy and recreation that has to be provided. Also, increasing crew size increases the need for human solitude as well as the added complexity of human interaction and the social structure. This section discusses effects of mission duration and crew size on habitability and privacy requirements.

De-conditioning - Human physiological de-conditioning 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 temporarily lost—which may not be applicable to long-duration exploration missions. Physiological de-conditioning of the human body in microgravity affects the cardiovascular system, musculoskeletal system, immune system, reproductive system and causes fluids in the body to shift. These effects are because the human body is designed to survive in a gravity environment. Without this gravity, the body changes in an effort to adapt to the new gravity environment. These effects are lessened and slowed in partial gravity environments like the Moon or Mars, but de-conditioning still occurs.

Mission Duration - For mission durations of a few days to a 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 near as much volume for recreation, exercise, dining, and private crew quarters due to the short mission duration and the fact that crews can rotate shifts, which reduces redundancy of volume requirements.

For mission durations of up to six months, crews require their own private personal quarters for sleeping as well as 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.

For mission durations of six months or more, crews require all the necessary "comforts of home." Each crewmember 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.

Gross Pressurized Volume - The gross pressurized volume required for space habitats can be estimated based on historical data about human space exploration and remote environments on earth (fig. 1). 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 show the habitation volumes divided into three categories; minimum tolerable limits, minimum performance limits, and preferred limits (fig. 2). These rules-of-thumb are applicable for medium duration missions. Short duration missions will be roughly analogous to the Shuttle, and for long duration missions there is little data available to make a determination. When determining the initial volume required, one should consider a parametric range of volumes based on the mission objectives and requirements.

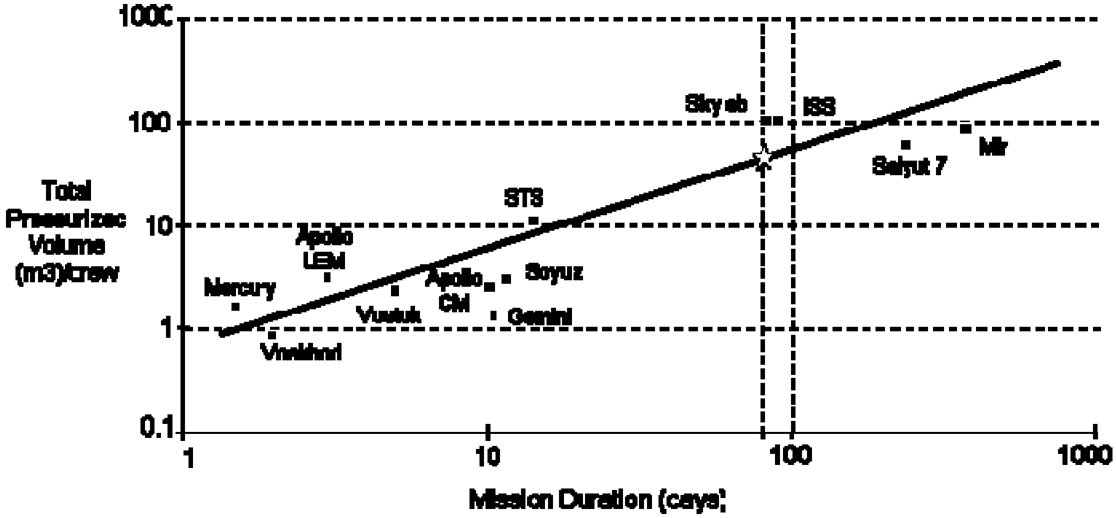

Figure 1: Habitation Historical Zero Gravity Volumes

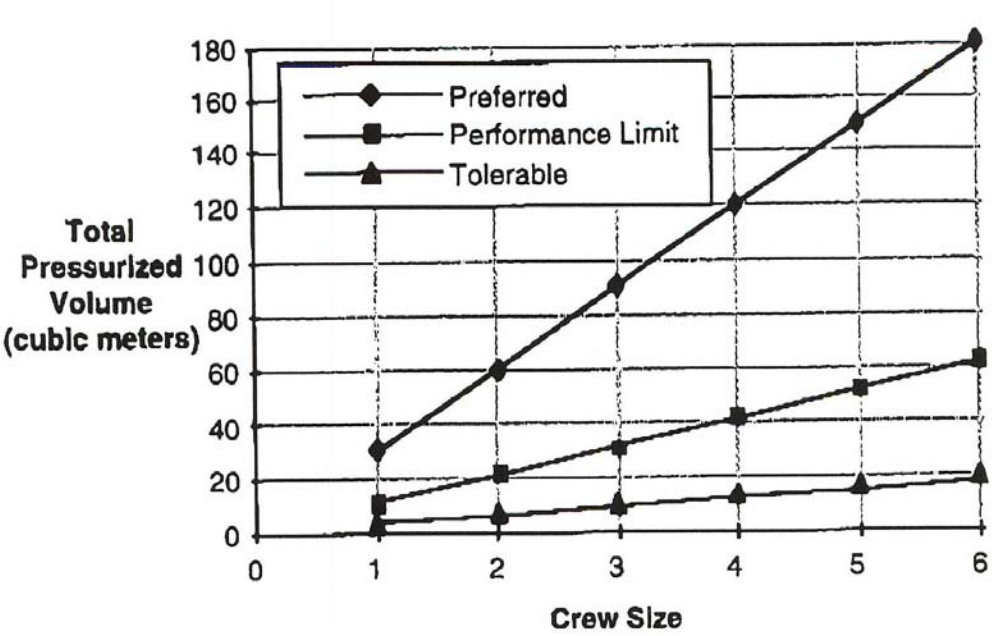

Figure 2: Habitable Volume for Increasing Crew Size

From these and other research studies habitation volumes have been classified in the Human Systems Standards (Human-Systems Integration Standards, CxP 70024) as tolerable, performance, and optimal. Habitation volumes are grossly estimated at the total pressurized volume and then the habitable volume is determined. Table 1 shows the rules-of-thumb for first order habitation volume sizing.

Table 1: Space Habitation Recommended Volumes.

Mission Duration	Total Pressurized Volume	Standard	Recommended total vol, 4 crew, 180d stay
Short [3 – 14 days]	5 – 15 m3 / crew	Tolerable	20 – 60 m3
Medium [2 wks - ~4 months]	30 – 50 m3 / crew	Performance	120 – 150 m3
Long [> 6 months]	60 – 80 m3 / crew	Optimal	240 – 320 m3

Induced Artificial Gravity

Human Mars exploration mission transfers range between six (6) and 12 months each way depending on propulsion system, trajectory, and planetary alignment. The microgravity transfer environment has deteriorating effects on the human body, which suggests the potential need for countermeasures to counteract bone and muscular deterioration. Induced gravity, or artificial gravity produced by spinning, has been proffered as necessary or highly desirable from a human-factors standpoint by leading space physiologists for long-duration human exploration missions of greater than 6 months. Other countermeasures include rigid exercise regimes, rotating beds inducing gravity for sleep periods, pharmaceuticals, and tension devices to reduce bone and muscle deterioration.

The environment created by a spinning vehicle is very different than earth gravity, which suggests design limitations based on human tolerance and adaptation. From these design limitations, a basic set of human factors design requirements can be derived that will drive vehicle configuration. The gravity level, gravity gradient, and the Coriolis force characterize the induced gravity environment. Table 2 summarizes this environment.

Table 2: Induced Gravity Environment Characteristics.

Characteristic	**Equation**	**Comments**
Gravity level	w^2r	• Centripetal acceleration produced by rotation • Increase in either radius or angular velocity increases gravity level - Increased radius increases cost and complexity of system - Increased angular velocity increases physiological/psychological acceptance • Divide equation by 9.8 m/s^2 or 32.2 feet/s^2 to convert to equivalent Earth g's
Gravity gradient	$\frac{\Delta r}{r}$	• Change in gravity level between human head and feet
Coriolis force	$-2wr$	• An apparent force applied to humans moving linearly within a rotating system • Directions of force varies depending on geometric relationship between spin axis and velocity vector

Where:
w = Angular velocity in radians / second
r = Radius
v = Velocity of human movement

There has been substantial research and studies on the effects of induced gravity. Design limitations for induced gravity transfer systems are based on experimental data from early Mars mission planning experiments in the late 1960's (Loret, 1963; Reason & Graybiel, 1970; Graybiel & Knepton, 1972; Clark & Graybiel, 1961; O'Laughlin, Brady, & Newsom, 1968). Figure 3 summarizes these data and provides a design envelope based on the results of these experiments.

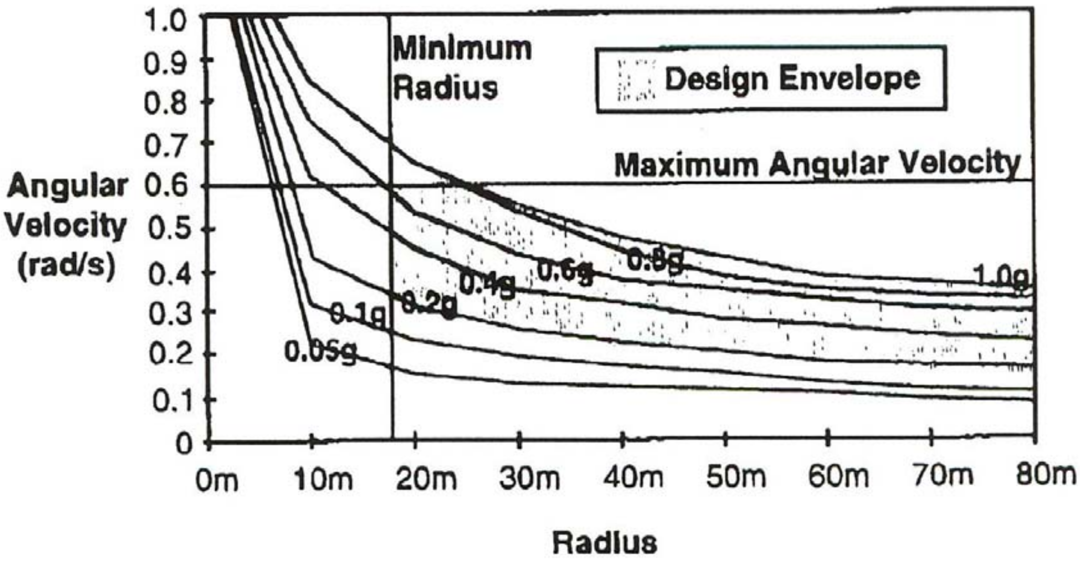

Figure 3: Induced Gravity Human Factors Design Envelope (Loret, 1963).

In summary, induced gravity physics and experimental data suggest the following human factors design requirements (table 3).

Table 3: Human Factors Design Requirements.

Factor	Requirement
Gravity level range	0.2 - 1.0g
Gravity gradient maximum between head & feet	15 – 20 %
Angular velocity upper limit	0.67 rad/sec (6 rpm)
Change In gravity level due to tangential walking	20%
Crew compartment and sleep bunk orientation	Parallel to Spin Axis
Transport across spin axis	Avoid or minimize
Radial traffic flow	Minimize
Crew duty station orientation for head movement out of spin axis	Minimize

Induced gravity transportation systems incur 5-15% mass penalties 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.

Partial Gravity – Whereas the Moon or Mars gravity environment is more akin to Earth's gravity than the zero gravity of space, it still poses design challenges for habitats. Human physical reactions and performance in a reduced gravity environment are different than earth gravity. The main difference from earth gravity is human locomotion; while the main difference from microgravity is the specific up and down orientation and reach envelopes which increase volume requirements. Table 4 outlines the basic differences between earth gravity and partial gravity and the potential effects on design.

Table 4: Human Factors Effects on Partial Gravity Design.

Consideration	Differences from Earth Gravity	Habitat Design Impacts
Walking and Running	• Reduced gravity changes the gait because of a change in force (Margaria & Cavagna, 1964) • Reduction in force reduces the traction and increases starting and stopping distances • Bouncing occurs because humans expend earth gravity forces	• Traction surfaces are required in major circulation paths • Corridors should be clear of obstructions and mobility aids should be provided • Low ceiling heights in personal spaces and higher ceiling heights in circulation paths and public spaces (2.1 - 3.0 meters)
Posture	• In reduced gravity, as locomotion speed increases, body inclination increases dramatically as compared to Earth conditions (Figure 5) which decreases traction	• Traction surfaces in major circulation paths
Jumping	• Humans can jump about seven times as high in lunar gravity (Hewes & Spady, 1964 and Spady & Krasnow, 1966) • Extrapolation suggests humans can jump three to four times as high in Mars gravity	• Allowing for partial adaptation over time, stair risers should be about 0.5 meters on the Moon and 0.4 meters on Mars • High ceilings should be provided in recreation areas (<6.1 meters on the Moon & 4 meters on Mars)
Equipment Handling	• Reduced gravity reduces equipment weight and allows humans to move mass	• Allows the potential for more equipment movement without handling aids

Space Habitats

Space habitats are systems designed to maintain a productive environment for humans living and working in space. Space habitats naturally attract great interest for a human exploration program because they are sophisticated pressurized vessels, which contain and protect the ultimate payload -- people. 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. The following discusses space environment design considerations and their impact on humans, elements of habitation systems and their interfaces, the design analysis process for evaluating and selecting appropriate habitation systems, and application of these to various environments (table 5).

Table 5: Space Habitation Design Steps

Step	Considerations
1. Assess environmental constraints	• Vacuum • Debris • Gravity • Radiation • Dust
2. Assess human considerations	• Psychological • Physiological
3. Define habitation system elements	• Internal subsystems • External systems and Interfaces
4. Determine key design decisions and trades	• Environmental • Human • Subsystem
5. Assess design application	• Orbital • Transfer • Planetary surface

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 International Space Station (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, re-supply and crew rotation schedules will be sparse. The duration and distance away from earth compounds the problem of crew isolation and confinement, exacerbating the concerns for human psychological needs, which must be addressed effectively. Also, "commonality," defined as the ability to use 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:

1) Acceptable physiological & psychological support for humans.
2) Successful accommodation of mission objectives.
3) Reliable structural integrity with adequate safety margins.
4) Forgiving failure modes (leak before rupture).
5) Ability to be tested to a high level of confidence before being put into service.
6) Ability to be integrated with available launch systems.
7) Straightforward outfitting and servicing.
8) Easily maintained.
9) Long design life.
10) Commonality at the system or subsystem level.

Space habitation configurations vary according to user requirements, destination and mission. However, a core group of functions is required in order-to sustain basic physiological human needs in the space environment: food, water, oxygen, personal hygiene, waste management.

Table 6: Surface habitation functional requirements

- Sleeping: Private Crew Quarters
- Food Preparation: Galley
- Eating/Dining: Wardroom
- Recreation & Relaxation
- Hygiene
- Personal: Full Body & Hand wash
- Waste Management (Toilet)
- Mission / Station Operations
- Workstation(s)
- Telerobotic Workstation?
- EVA Operations
- Airlock & Ops
- Dust Control
- Suit Storage & Maintenance
- Crew Accommodations
- Crew Health Care (CHeCS) / Medical
- Logistics Supply / Stowage
- Food / Water
- Spares
- Circulation: Vertical & Horizontal
- Mechanical Systems
- Structure
- Pressure Shell
- MM/OD Protection
- Radiation Protection
- Space Environment Protection
- Communications/Video
- Command &Data Handling
- Guidance, Navigation & Control
- Power Management &Distribution
- Active Thermal Control
- Passive Thermal Control
- ECLSS
- Air Revitalization
- Water Distribution
- Waste Recycling
- Biological Science
- Geological/Physical Science

The functional bubble diagram (fig. 4) shows the inter-relationship and proximities with the other habitation functional systems and needs. This functional analysis allows one to better understand the natural grouping of crew quarters, hygiene areas, mission operations, and support systems. Understanding these functional relationships allows the outpost designers to create an outpost based on spatial relationships, crew systems and zone area for work and living areas.

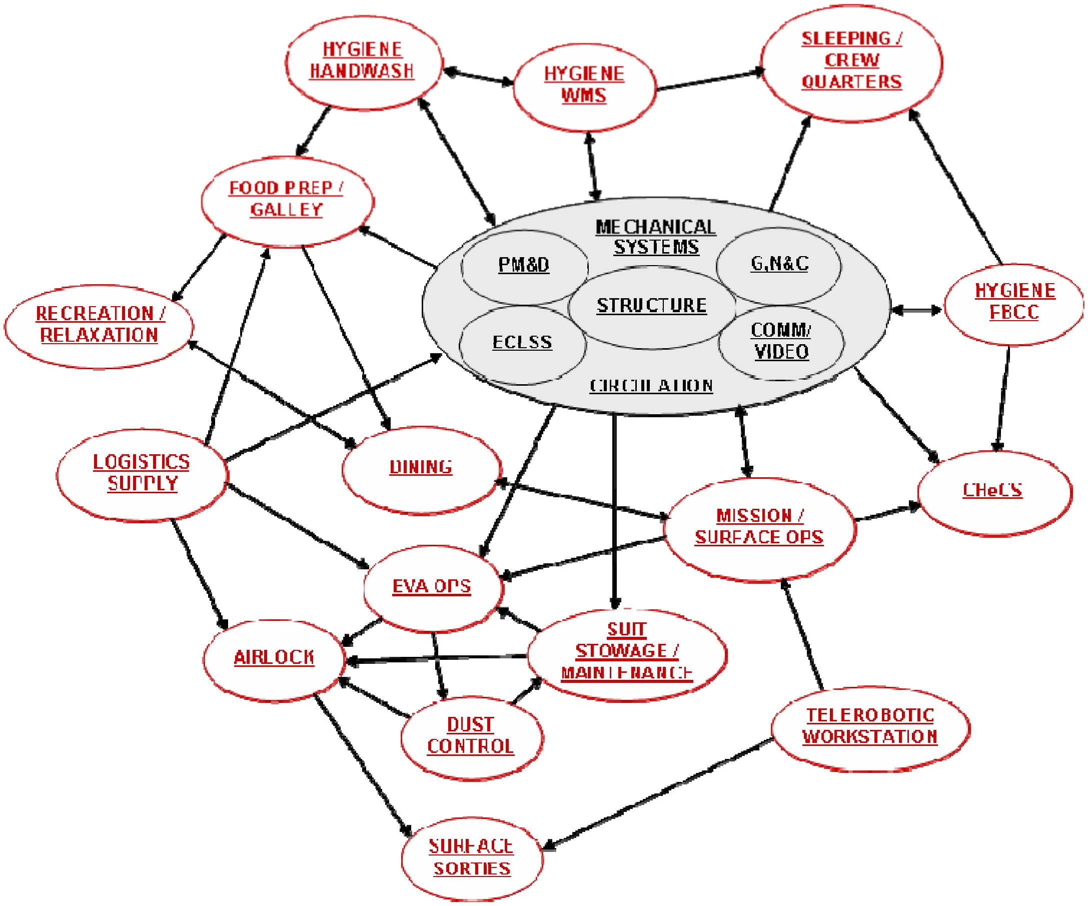

Figure 4: Habitation Functional Bubble Relationship Diagram

Elements of a Space Habitation System

Subsystems

This section discusses the habitation subsystem elements as a system unit and overall design considerations. Figure 5 shows the inter-relationship of the habitation internal and external subsystems. Table 7 describes the typical habitat subsystems.

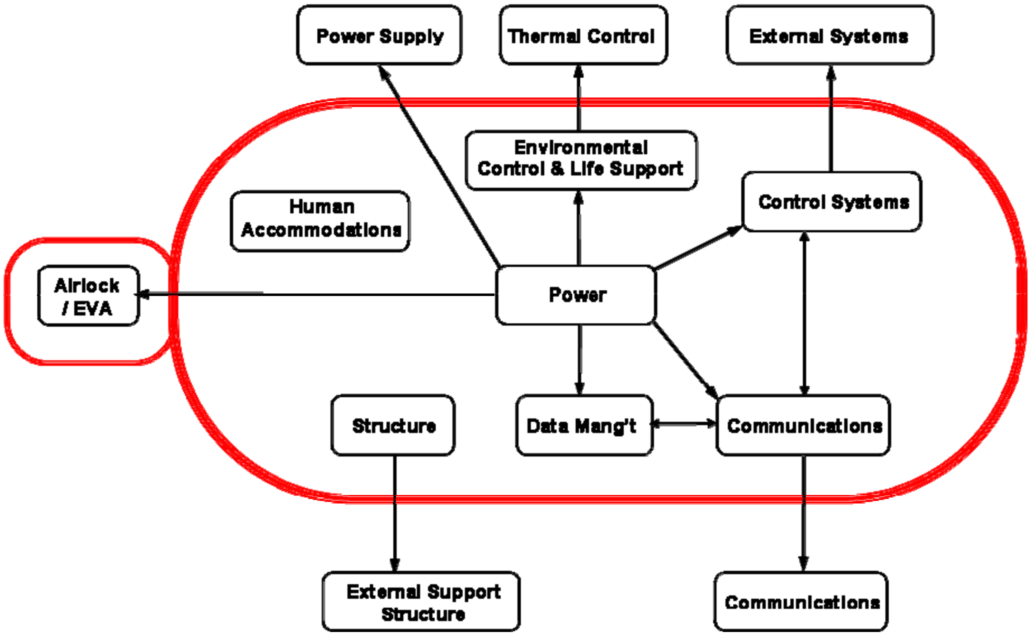

Figure 5: Habitat Functional Diagram

Table 7: 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, and recreation facilities.
Experimentation Equipment	Mission specific science and experimentation equipment.
Stowage	Storage volume for personal and mission related equipment, spares
Radiation Shelter	"Storm shelter" for solar proton events.

Table 8 outlines the typical habitation subsystems and rule-of-thumb mass and volume fractions. These are representative of a medium duration mission.

Table 8: Rule-of-Thumb Habitation Subsystem Breakdown

Habitat System	Mass Fraction (%) (Internal & External Systems)	Volume Fraction (%) (Internal Only)
Structure/Enclosure	20-25	Enclosure
ECLSS	12-15	8-10
TCS	4-5"	1-2
Power	20-25*, **	0.1
DMS / Communications	2-3*	2-3
Internal Audio / Video	0.1	1-2
Crew Accommodations	10-12	50-65
Experimentation Equipment	Varies (10-15)	10-15
Stowage	-Negligible	2-5
Radiation Shelter (if req'd)	10-15	10-15

* Internal & External Systems

** Includes External Solar Arrays, Batteries, Reactants and Tanks

External System Interfaces

The habitation system interfaces with external systems in all applications. The overall space system whether orbital, transfer, or surface provides critical infrastructure support, much like structures on earth provide utility interfaces. The external system must provide a source of power, thermal control in the form of heat radiation, support structure, communications, and other external systems such as experiments, sensors for monitoring the system infrastructure, and an airlock/EVA system.

Table 9 outlines the external systems and general interface requirements.

Table 9: External System Interfaces

Habitat System	Interface Requirements
Structure	Station, vehicle, or surface infrastructure
ECLSS	External water and oxygen tanks
TCS	External thermal radiators for heat dissipation
Power	External power source
DMS/ Communications	External experiment sensors and the communications dish

Space habitat configurations vary according to the design program; but a core group of functions are required in order to satisfy the basic needs of sustaining humans in space. Overall, a space habitat configuration combines all the subsystem required to provide and maintain a living and working environment in space. More specifically the ability to produce power, reject excess heat, water reclamation, air revitalization, maintain crew health, and meet the crew's physical and psychological needs. Table 10 gives some effects and rules of thumb for space habitat configuration drivers. The habitat configuration can vary from a singular open volume space of a short duration spacecraft; to a medium duration facility of a single volume with separated spaces; to the complex and sometimes multiple volume long duration habitats.

Table 10: Space Habitation Design Decision and Key Trades

Configuration Driver	Effect	Rule of Thumb
Habitat Function	Habitat Layout Hab/LAB	Separate Hab & Lab Functions/Activities
Number of Crew	Volume Required	50-90 m3 vol/crew member
Mission Duration	Habitat Size	short, med. & long
Crew mix	Expertise Required	Science, Medical, Operations (2 of each preferred)
Crew gender	Effective cooperation	Mixed gender for short missions, single, couples, or mixed Couples might be preferred for long missions, 6 months or more.
Structure	Alum, Composites, Inflatables	Hard Shell for small vol, short mission. Inflatables for large volume, long missions.
Life Support	Open, partial, closed	% Open
Data Handling & Management	Computers, Automation	Autonomy
Communications	Direct, Relay	Person-to-Person; Person-to-Spacecraft; Spacecraft-to-Ground
Thermal Control	Body Mounted, Separate Structure	Radiators
Power	Generation Source, Storage and Distribution	kg/w
Crew Accommodations	Physiological and Psychological	Free Volume, Private and Social spaces.
Environment Protection	Radiation, Dust	gm/cm3, control
Risk	Level of Redundancy	Fall Op-Fail Safe on Critical

Once the basics of the mission design philosophy and requirements are understood the design team or individual will brainstorm as many design solutions as possible. It is highly recommended to get five to ten people involved with as much diversification as possible. This ensures varying solutions with buy-in from the other disciplines. Everything is looked at and all innovative ideas are put on the design table. Nothing is dismissed nor thrown out as a possible design solution in the brainstorming session. This activity should be as open and receptive as possible to allow for maximum creativity and free-thinking. The following describes several examples of different space habitats designed for various environments.

Orbital Habitats

There are numerous space habitat historical and conceptual examples. Historical and current habitation facilities include Skylab, Spacelab, Salyut 7, Mir and the International Space Station. These space habitats represent an evolution in habitation design and technology. Except for Skylab, space habitats started by providing only the necessities to survive in Low Earth Orbit, not much was understood on the affects of space on humans or how to accommodate them. The ISS habitation facility has culminated all the previous experiences and research on isolation and space effects. This facility now accommodates humans by providing ample free volume per crew member, private space such as crew quarters, separate laboratory facilities, group functions, recreation capability, exercise, and quality hygiene facilities. Not that the previous habitats did not have some form of these, but rather they have been given more importance for the humans’ physiological and psychological well being.

Transfer Habitats

There are also numerous space habitat historical and conceptual examples of space habitats used for transfer of humans from one place to another. Space habitats used during transfer, or space flight, can be as small as the Apollo Service/Command Module to the proposed interplanetary transfer habitats that would be used to go to Mars or to an asteroid. Current space habitat concepts represent an evolution in habitation design and technology. Long-duration space transportation habitats need to provide able free volume per crew member, private space, group functions, recreation capability, exercise, and quality hygiene facilities. Due to the long duration journey to Mars and the zero gravity effects on the human physiology artificial gravity has been proposed as a solution. Creating an induced artificial gravity is a complex engineering solution which also has physiological implications on humans within this environment.

Planetary Habitats

There is only one space habitat that has actually been used on another planetary body, the Apollo Lunar Module. It represented what would be required, as a minimum, to survive on another planet. However, it was very small, cramped and not human accommodation sensitive. Since our lessons learned from Apollo, designers have been designing and proposing many ideas for future space habitats for the Moon and Mars. They range from pre-integrated space station derived modules, to pre-fabricated inflatable structures, to In-Situ Derived and constructed units.

Habitats are categorized into three classifications. Class I is a pre-integrated habitat in that it is entirely manufactured, integrated and ready to operate when delivered to space. Class II is a pre-fabricated habitat and space or surface deployed. Class III is an in-situ derived habitat that its structure is manufactured using local resource available on the Moon or Mars. For example, mining Martian gypsum and making a concrete material used to form habitats. Figure 6 shows the relationship of habitat technology, habitat classifications and time. Currently we are moving towards understanding what class II technologies are and how they will enable future exploration. Table 11 lists the key characteristics of each habitat classification.

- CLASS I: Preintegrated, Hard Shell Module
- CLASS II: Prefabricated, Surface Assembled
- CLASS III: ISRU Derived Structure w/ Integrated Earth components

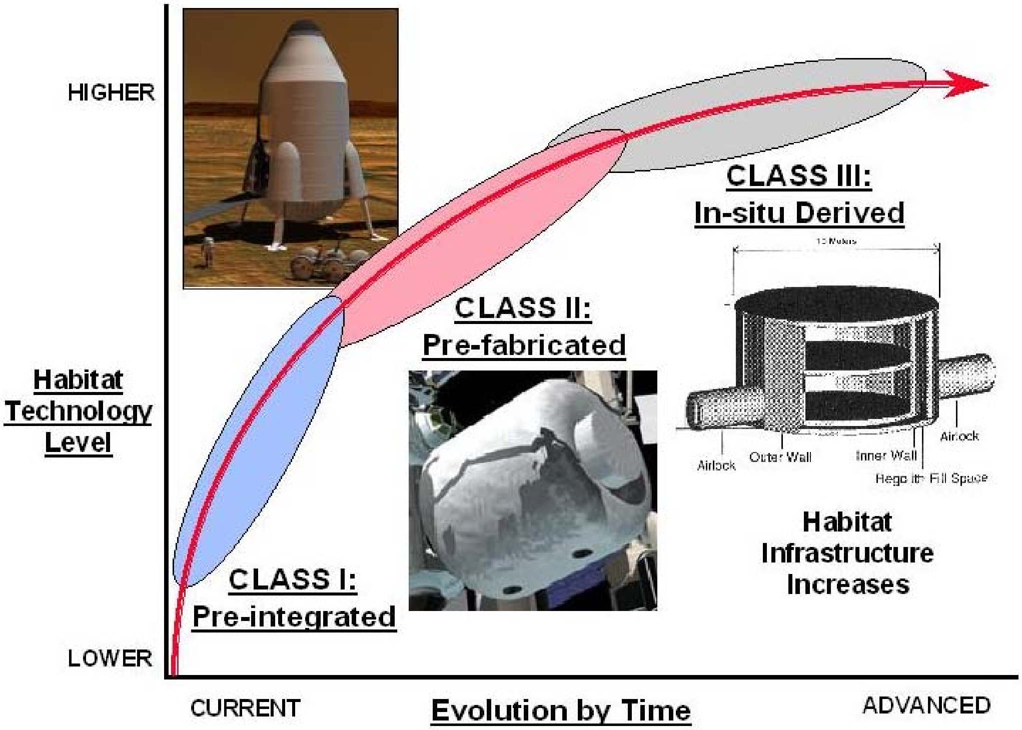

Figure 6: Habitat Classifications

Table 11: Habitat Classification

Habitat Classification	Key Characteristics
CLASS I Pre-integrated	- Earth Manufactured - Earth Constructed - Fully Outfitted and Tested prior to Launch - Space Delivered with Immediate Capability - Limited Volume & Mass - Limited to Launch Vehicle Payload Size Capability - Limited to Launch Vehicle Payload Mass Capability
CLASS II Pre-Fabricated – Space/Surface Assembled	- Earth Manufactured - Requires Space Assembly or Deployment - Requires Robotic and Human Time During Assembly - Partial Integration Capable for Subsystems - Requires some or all Internal Outfitting emplacement - Critical Subsystems are Earth Based and Tested prior to Launch - Requires Assembly prior to Operability • Larger Volumes Capable - Not Restricted to Launch Vehicle Size. - Not Restricted to Launch Mass
CLASS III In-Situ Derived and Constructed	- Manufactured In-Situ with Space Resources - Space Constructed - Requires Manufacturing Capability & 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 Operability - Larger Volumes Capable - Not Restricted to Launch Vehicle Size - Not Restricted to Launch Mass

To accomplish this goal, the following major technical objectives have been identified:

Provide technologies that significantly reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for missions of long duration. Specific goals are to:

- Pre-Integrated Habitats: A composite structure that can be autonomously pre-deployed and operated in LEO, on the Moon or Mars surface. Fully integrated. The capability for A.I. smart hab for failure detection, analysis and self repair.

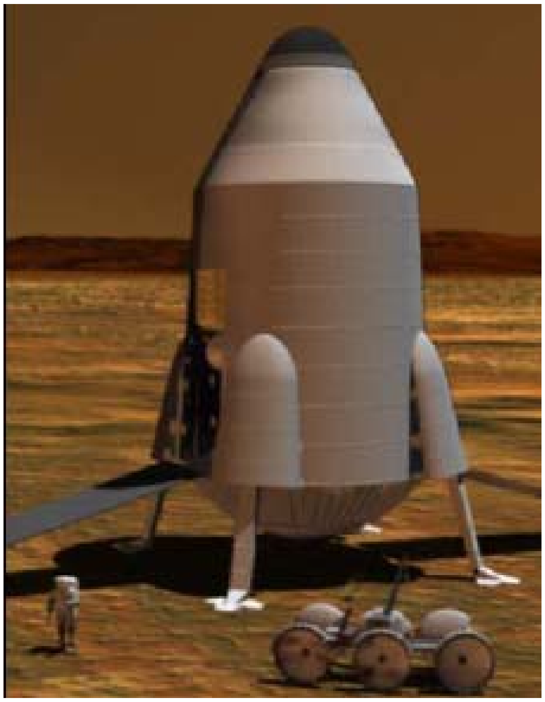

Figure 7: Pre-integrated monolithic hab unit

- Pre-Fabricated Habitats: <u>Inflatable structures</u> that can be autonomously pre-deployed and operated on the Moon and Mars surface. Partially integrated and flexible. The capability for A.I. smart hab for failure detection, analysis and self repair.

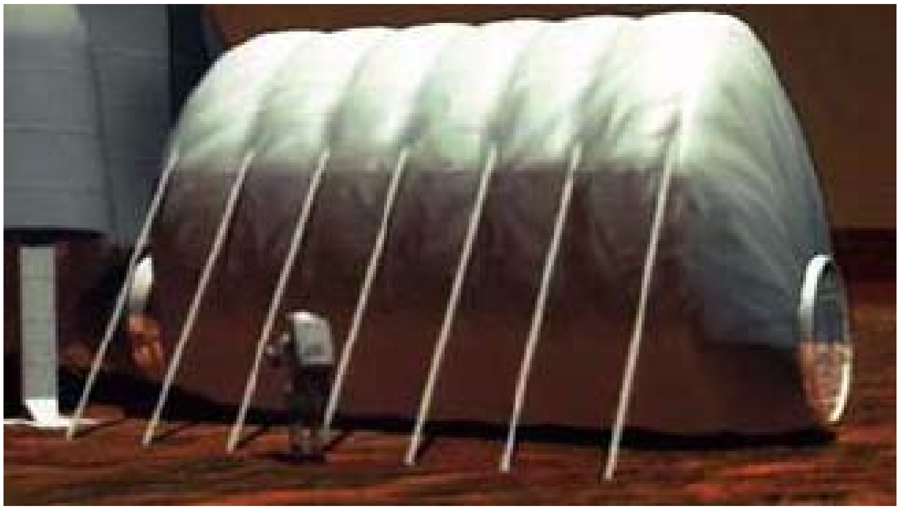

Figure 8: Pre-fabricated surface deployed hab unit

- ISRU-Derived Habitats: An <u>ISRU-derived structure</u> that is manufactured using indigenous resources and constructed autonomously. It is autonomously operated and maintained utilizing A.I. and V.R. The capability for A.I. for failure detection, analysis and self-repair.

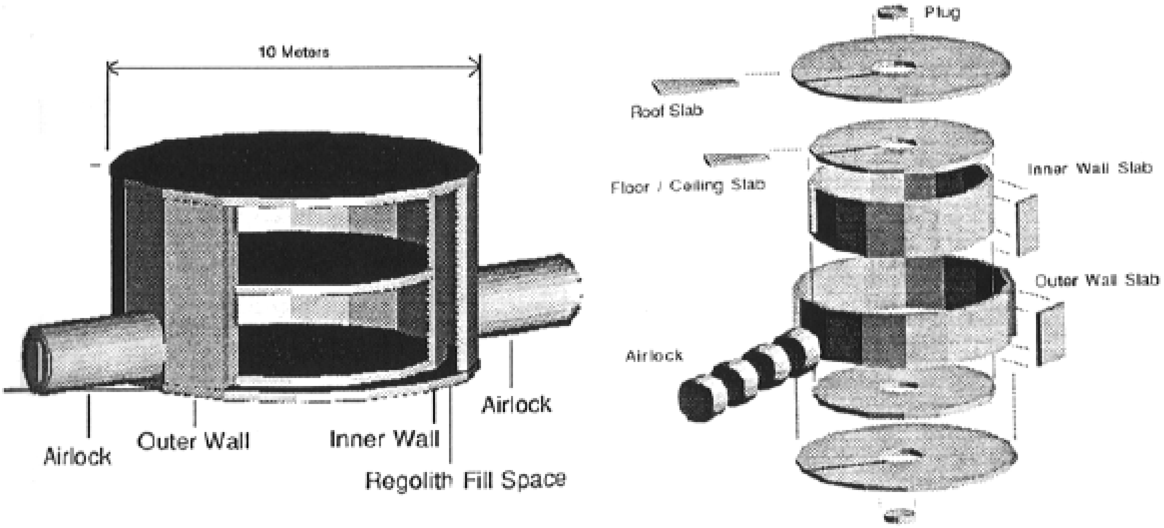

Figure 9: ISRU-derived habitat unit concept

Surface Outposts

Once the basic habitation driving requirements, environmental constraints, and design guidelines are understood surface outpost strategies can be explored. There are numerous outpost strategies to achieve the desired lunar architecture end-state. If the country's desires were to perform lunar sortie mission only then perhaps the lunar strategy would be similar to Apollo in which the crew would stay and live in a habitat on the lander for a few days. If the desire was to build an outpost for lunar stay times of a few months, then perhaps pre-integrated Class 1 or Class 2, or perhaps a hybrid of the two would be the preferred solution. However, if the desired end-state of a lunar architecture is to create a permanent sustained presence that would lead to colonization, then perhaps the Class 2 with evolution to a Class 3 or combination there of would be the preferred solution. The configuration of the outpost is influenced by the environmental site, transportation system, state of the technology, and desired end-station condition or out come. Table 12 describes some of the outpost design aspects and the issues facing the mission planners, architects and engineers.

Table 12: Surface Outpost Design Option Generation

Design Approach or Aspect	Issues	Options
Habitat Size / Volume	• What is the required volume? Will it package in the launch vehicle? If not, what are the alternatives?	• Hard-shell vs. Inflatable
Habitat Weight	• Account for all external and internal subsystems and interfaces.	• Single Module vs. Multiple Modules
Life Support System	• What is the required or desired level of self-sufficiency, if any? Technology readiness?	• Open Loop vs. Closed Loop systems
Degree of Integration	• Is the habitat fully integrated or does it require some level of preparation activity?	• Preintegrated vs. Assembly required
Power Supply Approach	• Options include batteries, fuel cells, solar arrays, solar dynamic, and nuclear.	• Resupply vs. Long Life Systems vs. In Situ Resource utilization
Communications Approach	• Options include direct or indirect through a relay such as a satellite(s). Delay times.	• Ground control vs. Astronaut control, vs. Autonomous systems
Thermal Control Approach	• Options include passive and active systems.	• Mass vs. Power vs. In Situ Resources
Crew Accommodations	• Options include tolerable (austere), performance level, and optimum for comfort.	• Short missions & small volumes vs. Longer missions & larger volumes
Risk Approach	• Level of Safety. Options include protection from radiation, orbital debris, micrometeoroids, and dust. Health Care.	• Short vs. Long Duration

Once a site for the surface outpost has been selected, we must determine the specific capability desired of each of the various hardware elements. Ultimately these will all flow from the mission objectives. However, we can easily see that a single top-level design concept can accommodate virtually all mission objectives.

Consider a mission that is constrained by cost, as virtually any realistic mission would be. This mission would conclude that in-situ resource utilization (ISRU) is a required capability for the surface base. Without the ability to generate resources for the crew, (oxygen, water, food from plants, and the equipment, fuel), all of these resources would have to be brought from Earth. Bringing them from Earth would ultimately require the use of additional launch vehicles, unless the payload mass is compromised, and this contradicts the requirement to minimize cost. Consequently, some area or zone of the landing site must be dedicated to ISRU.

ISRU, in turn, will require large amounts of power to accommodate the necessary mining operations and processing capability. This implies that the site must also provide a significant power generation capability. A power generation zone which utilizes solar arrays, a prime candidate, must be physically separated from the ISRU zone or dust from the mining operations will contaminate the arrays and reduce power. The combination of the ISRU equipment and the power generation equipment could not possibly be carried on any single landing vehicle, so multiple launches and landings will be required. These in turn drive the need for a dedicated launch/landing facility to minimize risk to the crew and to minimize the possibility of contaminating the power generation zone or ISRU zone. The launch and landing zone is therefore a third capability desired of the surface base.

To this point we have not yet discussed the scientific or commercial objectives of the mission that are providing the purpose in being on the surface in the first place. The presence of sensitive scientific or commercial equipment will again force these operations to be isolated to a dedicated zone.

Finally, the human occupants must also be accommodated. Because they will be forced to visit each zone periodically, for maintenance if nothing else, it makes sense to have the habitation zone centrally located. The result is a concept that is illustrated in figure 10. The surface outpost must be planned/zoned and physically separated according to function. This surface outpost concept provides the capability to: i) utilize in-situ resources, ii) generate large amounts of power, iii) launch and land safely, iv) perform the required scientific or commercial operations, and v) provide a safe haven for humans.

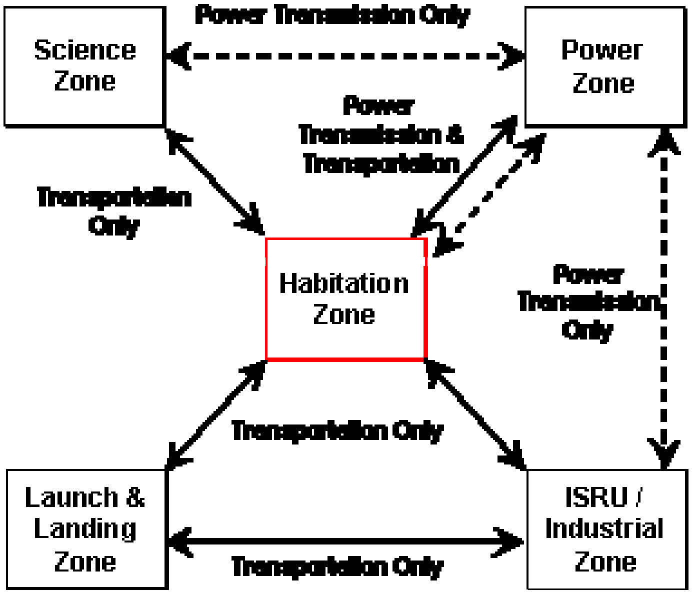

Figure 10: Surface Outpost Organization and Layout

Launch and Landing Zone

The launch and landing facilities are the first elements that the mission will encounter. If they are substandard, the mission can fail before the surface base is even established. The location depends on the site topography and flight path. Approach and take off should not cross over the habitation zone and should strive to avoid the power, ISRU, and science and industry zones as well (fig 6). Ideally, the surface should be naturally hardened – rock is preferred to dust. However, this type of natural hardening is usually associated with less than smooth surfaces so it may be necessary to first locate a flattened area, and then harden it via paving or berming. This site should also evolve to hold fueling equipment, once the ISRU capability has been established, and is a candidate to host the GN&C equipment as well.

Habitation Zone

The habitation zone facilities keep the crew alive and are the focal point for the surface base. All supporting facilities that don't have a reason to be located elsewhere should be here: habitats, laboratories, maintenance facilities, etc. On early missions the habitation zone and launch & landing zone may be co-located, but the habitation zone should be moved to a different location over time. One rule of thumb is that the zones should be separated before allowing additional landings to occur while there are already people in the habitation zone. This will prevent any possible landing failure from damaging the habitation zone and its occupants.

The habitation zone and its capabilities are closely tied to the landing vehicle capabilities. Since each element must ultimately be brought from the launch & landing zone, the habitation zone elements must be designed to be separate but integratable. The capability to act as separate units also provides an additional margin of safety in the event of pressurization failures of any single element.

Power Generation Zone

The power generation facilities should be located as close as possible to the other zones to reduce transmission losses. However, this must be balanced by contamination concerns, if solar arrays are present, or safety concerns, if nuclear facilities are present. Nuclear materials should be located several hundred meters away at a minimum. Solar arrays should be located sufficiently far away so that dust transport from other areas is not a concern. Obviously, dust transport on the Moon is aided by the lower gravitational pull on the surface while dust transport on Mars is aided by surface winds.

Science and Industry Zone

These are facilities that enable us to achieve the mission objectives. To prevent contamination the site should dedicate an area for geological and science exploration that will not be disturbed by other base activities.

In-Situ Resource Utilization Zone

These are the facilities that help us live off the land. If oxygen is produced it can be used to re-supply the habitation breathing supply and lander fuel supplies. The nature of the equipment located here will ultimately be determined by the in-situ resources being sought, but will probably include typical mining equipment and cryogenic storage equipment. Because ISRU operations are prone to produce dust, this operation should be conducted at a distance from the other zones, or should make use of the site topography for shielding.

Surface Outpost / Base Evolution

After the exploration sortie mission phase of a planetary body, such as the Moon or Mars, development of a surface outpost or surface base may begin. The establishment of an outpost and then subsequently a base requires a master planning philosophical decision to either develop a centralized base or a distributed series of smaller outposts. Each has advantages and disadvantages based on the long-term objectives of planetary settlement. Much can be learned from the urban planning principles practiced for hundreds of years on Earth. However, this philosophical discussion is for another time. The initial surface base is often referred to as an “outpost.” It consists of the capabilities to support humans while living and working on that planet’s surface. This includes capabilities such as a habitat, laboratory, airlock, surface mobility, power generation, heat rejection, environmental protection, launch and landing, and communications. These capabilities may be the bare minimum required to ensure mission success or may be enhanced for improved performance capabilities. Other capabilities will be added as required by the mission objectives. As the surface activities increase, so will the surface infrastructure that will be required to support a mature surface base. Table 13 highlights the surface outpost phases and their key features.

Table 13: Surface Outpost Development Phases

Surface Base Phase	Key Features	Component
Surface Exploration Sorties	• Visit multiple locations • Surface exploration and mapping • Surface science and experiments • Robotic and human missions	• Orbiters, surveyors • 1-4 Robotic surface rovers • Field-deployed measurement stations • 2-4 crew, 2-7 days surface

Base Planning	• Site Characterization • Site Planning • Site Visit & Exploration	• Robotic Surveying Rovers • Robotic Surveying Equipment Robotic Soil / ISRU Equipment • 2-4 Crew, 2-7 days Surface
Surface Research Outpost	• Initial Habitat & Laboratory • Surface Science & Experiments • ISRU Pilot Plant • Short to Medium Mission Duration • Few Crew • Airlock • CELSS Experiments and Chambers • Surface Transportation Capability	• Pre-Integrated Modules • Initial Life Science & Surface Experiments • Produce kg(s) of useful resource: i.e. Oxygen • 6 - 28 days Surface • 2 - 6 Crew • Integrated Surface Airlock • Initial Life Science Experiments • Short-range: < 10 km
Initial Outpost	• Medium Mission Duration • Surface Science & Experiments • Construction & Resource Development • ISRU Production Plant • Several Crew • Block II Habitat • Separate Laboratory • Airlocks/ EVA Maintenance • Launch & Landing Facility • Power Generation Facility • Food Growth Capability • Surface Transportation Capability	• 28 - 180 days Surface • Remote Sensors, Experiments • Robotic Mining/Construction Equipment • Production Rate: 10s-100s kgs • 6 - 12 crew • Pre-Fabricated Large Shells • Pre-Integrated Module, Separated • Separate Surface Airlock & EVA Support Maintenance Facility • Dedicated Landing Area, Some Surface Preparation • PVA/RFC: 10s-100 kWe • Dedicated Chamber: <50% • Medium-range: 10 - 100 km
Resource Production & Utilization	• Medium Scale Resource Commodity Production • Export Resource • Establish Market & Return on Investment • Large Scale Power Generation • Mining Capability • Food Growth Capability	• Transportation Refueling Capability, Material Processing • Produce Fuel, Power, Raw Material • Deliver Fuel, Power, Raw Material to Orbit/Customer • 100s - 1000s kWe • Soil: 10s Tons Processing, Tunneling • Dedicated Chambers: <80%

Surface Base	• Underground Facilities • Established Space Transportation Hub • Pressurized Ground Transportation • Food Growth on a Large Scale • Long to Permanent Stays • Community Size	• ISRU-Derived Structures, Tunneling • Centralized Surface Space Port • Pressurized Surface or Underground Rail System • > 180 days Surface • > 50 People
Industrialization	• Commercialization of Exports • Manufacturing Facilities	• Produce & Deliver Exports • Pressurized Processing Plants
Sustained Human Presence	• Economically Independent • Logistically Independent • Social Structure of a large Community • Sustained Large Scale Food Growth	• Sustained Export Capability • Produce/Repair Equipment • Local Government and Social Structure • Bio-Dome(s) Facilities: Horticulture, Agriculture & Aquaculture Capability

A mature surface base's capabilities include inhabiting tens of humans for long durations, large-scale power generation, surface transportation, a space transportation hub, and the ability to utilize the local resources to support the economic viability of the base. Once surface resources are being developed for use, they can be exported for use in space and at low-Earth orbit. Other businesses, such as entertainment and tourism in the form of resorts and hotels, will develop in conjunction with ISRU. Manufacturing facilities will be established that will lead to settlement of the planet. The surface base will now have grown into a settlement that will operate independently of Earth. At this point of surface base growth there will be a sustained presence at this location thus making humans an interplanetary society.

The first step in any planetary development program is the global mapping of the planet with relatively high-resolution imagery and remote sensing measurements to determine the chemical and mineralogical variability of the soil. Precise gravity mapping of the planet, as well as more detailed research on seismology and soil properties is required. Furthermore, Base Planning should include work on understanding the technologies necessary to exploit lunar resources. Robotic exploration of the lunar surface may also have to take place in order to obtain site-related data. The objectives are the definition of a site for an initial base and of the activities that would be carried out there. Concurrently this phase of the planetary program will see the development of transportation systems capable of supporting the base development.

The next phase of development will include disposable landers. A major problem of many base concepts is the functional gap between landers and the actual base. Disposable landers are generally limited in size due to payload constraints. Thus, lander stay times are usually limited to a few days or a week. Yet, construction of a permanent base will require many hours of productive automation and robotic construction time.

The Initial Outpost should provide the capability to support lunar base construction by housing initial lunar crews for several weeks. This outpost should have a small, self-contained, crew-tended facility that can be set down on the surface and activated with minimum effort. Its primary function would be to support surface EVA for science and base support activities. Also, initial science facilities and pilot plants are installed during this phase. A number of these outposts can be distributed across the planet to support a broader exploration strategy. Temporary visits at such base outposts may also be very useful, for example, for the regular maintenance of an astronomical facility. At an advanced stage, these outposts may also serve as lifeboats for base crews.

The establishment of a permanently occupied, operational base will provide a limited research laboratory for science, materials processing, and surface operations. If science and astronomy were to be the focus, especially local geological exploration, the establishment of small astronomical observatories, and the emplacement of automated instruments could be carried out. If production were to be the focus, pilot plants for resource extraction could be set up, and the study of the production of resources from indigenous materials will be initiated. If self-sufficiency were to be the focus, the emphasis at this stage could be on agricultural experiments utilizing planetary soil as substrate and recycling water, oxygen, and carbon dioxide.

Settlement includes the expansion of the base facilities. Intensive research and development could be conducted. This phase would be accompanied by a greater access to power, better mobility in and away from the base, and more diversified research capability. Still, depending on the long-term priorities, there may be a different focus. A science-oriented base might emphasize long-range traverses for paleontological studies (Mars) or extension of observational capability with larger telescopes. A production-oriented base might emphasize the development of highly automated systems to produce and transfer liquid oxygen for use in transportation systems. After these surface base phases, a truly permanent human presence could be envisioned.

A surface outpost is comprised of numerous surface systems that work together to provide the capabilities to support mission, crew and scientific objectives. Figure 11 shows the different surface systems that comprise an outpost or base. As missions vary so do the systems required to support the crew to meet the mission objectives. At a minimum, there is a core infrastructure of external systems required to support human presence on the Moon and Mars. This minimum surface system infrastructure is comprised of a habitat, a laboratory, radiation shielding, airlock, EVA systems, life support system, power supply system, thermal control system (heat rejection), communication system, (crew consumables, and health maintenance - these are part of the life support system). However, additional infrastructure may be required such as a dedicated laboratory facility, additional airlocks, logistics resupply, surface transportation, construction support equipment, mining and ISRU equipment. There are many different concepts of these systems that include mass, volume and power needs.

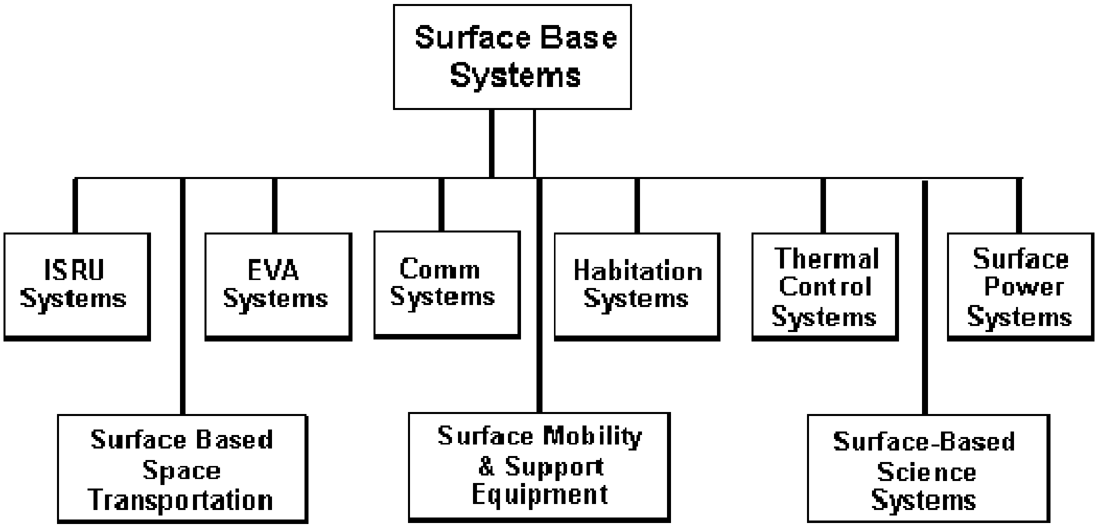

Figure 11: Surface Outpost / Base Systems.

Habitation Strategies

Space and planetary habitats are pressure vessels which provide the living quarters and support systems needed by human crews engaged in space exploration. Structures, materials research, and technology development is required for the very lightweight and comfortable habitats needed for the months of transport to Mars and for the months, and possibly years, which humans will spend on the surface of the Moon or Mars in carrying out exploration and development activities. Such habitat technology also has the potential for being important in opening up the possibilities for near Earth orbital platforms for commercial usage. Major technology interests are in advanced lightweight materials, in use of inflatable design techniques, and in techniques for providing protection from micro-meteoroids, orbital debris, and radiation protection.

The goal of Advanced Habitats is to provide living and working pressurized elements to support self-sufficiency for human beings to carry out research and exploration productively in space (low Earth Orbit) for benefits on Earth, to open the door for planetary explorations, and to create self-sufficient bases on other planetary bodies.

Habitation strategies for a surface outpost include unloading the habitat(s) and emplacing them on the surface; leaving the habitat(s) on the lander thus becoming the initial outpost; and designing the habitat(s) to be mobile. Of course a combination of all three approaches could be employed as well. Unloading the habitats has some desirable features such as being close to the surface, being accessible for maintenance and repair, the capability to ad in-situ materials to protect from radiation, and the ability to dock a pressurized rover to the habitats. Of course they also may need to be segmented into smaller manageable units so they can be unloaded, transported, and emplaced on the surface. Leaving the habitat on the lander has desirable the features of being fully integrated, checked-out on Earth, and sent knowing it is ready to be activated and moved into by the crew. Also, the habitat-lander may be able to provide a larger open volume which is desirable for long-duration missions. On the other hand, there are considerations such as the limitations of the lander, how big they can be, and how to bring two units (a hab and a lab) together for connection. Other considerations are how to protect the habitat from radiation when it is several meters on top of the lander, accessibility for maintenance and repair, and how to segment the internal volume so incase of a pressure breach the entire habitat volume is not lost. Mobile habitats provide the capability to perform more exploration and move the outpost from site to site. In this case the mobile habitat has size limitations depending on the mobility system. There are risks associated with moving the habitat of which a few are ensuring the structural integrity of the pressure shell while it is moving about the surface, the risk of getting stuck or impassable terrains—to mention a few. When determining which habitation strategy to pursue considerations of the mission objectives, risk, cost and safety of the crew are required. After which each strategy should be traded-off to determine which approach best satisfies the requirements and performance challenges. Depending on the campaign objectives one or a combination of habitat strategies may be used or phased as the outpost matures.

Figure 12 is an example of a Class 1 habitat that would be unloaded and used for short-duration outpost architecture. By pre-integrating the critical and required subsystems, these subsystems can be checked-out on the ground, verified operational, and packaged for launch. Upon reaching the habitat's final destination the use of habitat autonomy techniques can be used to start up the habitat prior to the crew's arrival. This minimal sized Hab unit has the basics to sustain a crew, such as minimum stowage, a minimal food warming capability, a minimum waste management toilet, hygiene capability, and deployable hammocks to provide a temporary sleeping capability. However, a long-duration stay outpost requires additional private crew quarters, more ECLS and consumables to provide the required long-duration functionally such as food and spares stowage, medical care, life support sustainability, EVA operations, science operation, and mission operations.

The habitat units can be delivered on smaller landers and deployed to the desired outpost site location. Each unit will mate to the main utility / logistics module. The utility / logistics module becomes the backbone of the outpost. Individually, each unit could be used to provide minimal functionality, such as crew support, for a few days. However, all the units are required to provide a minimum outpost volume for medium duration missions. Additional units will be required to sustain 4-crew for 6-month surface campaigns. The functional needs for an outpost can be divided into four achievable segments. They are the Crew Operations, EVA Operations, Mission Operations, Science Operations, and Logistics Operations (fig 12). The Crew Operations unit includes basic crew accommodations such as sleeping, eating, hygiene and stowage. The EVA Operations unit includes additional EVA capability beyond the suit-port airlock function such as redundant airlock(s), suit maintenance, spares stowage, and suit stowage. The Logistics Operations unit includes the enhanced accommodations for 180 days such as closed loop life support systems hardware, consumable stowage, spares stowage, interconnection to the other Hab units, and a common interface mechanism for future growth and mating to a pressurized rover. The Mission & Science Operations unit includes enhanced outpost autonomy such as an IVA glove box, life support, and medical operations.

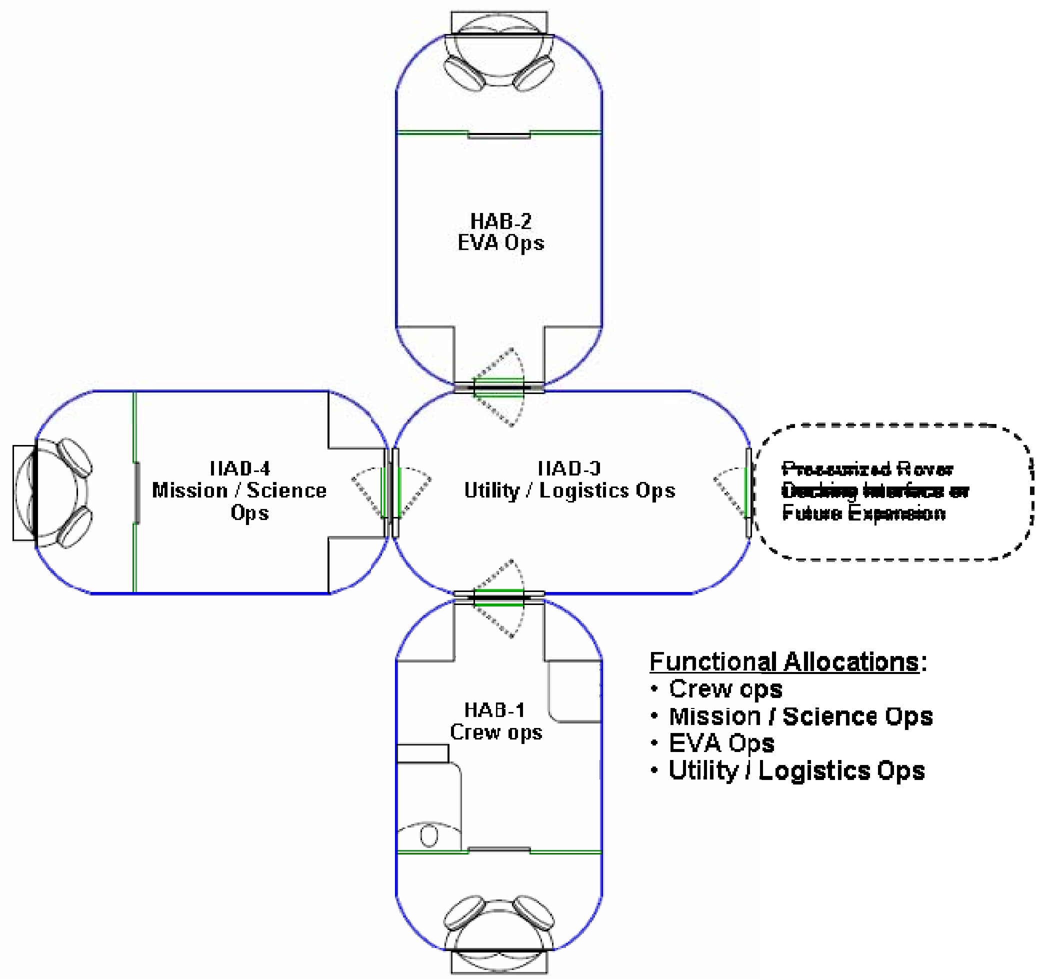

Figure 12: Notional Lunar Outpost Configuration using small hab units

Figure 13 is an example of a Class 2 large monolithic inflatable habitat that would be prefabricated on Earth, packaged on the lander, and then unloaded to be used for a long-duration mature base. The Habitation Complex consists of an Initial Habitat Module, the Inflatable Habitat, two Interconnect Nodes, two external Airlocks, two Service Modules, a Logistics Module and ISRU-Derived Radiation Shielding. This inflatable habitat will provide a living and working environment for a crew of 12. This master plan emphasizes a mature base with an ISRU Production Plant to the East, a Nuclear Power Facility to the North, science exploration to the West, a Launch and Landing Facility to the South, and the Habitation Complex at the center of the base, figure 13. Although this lunar base concept is far into the future; it is necessary to understand the base infrastructure and utility capability required for planned growth.

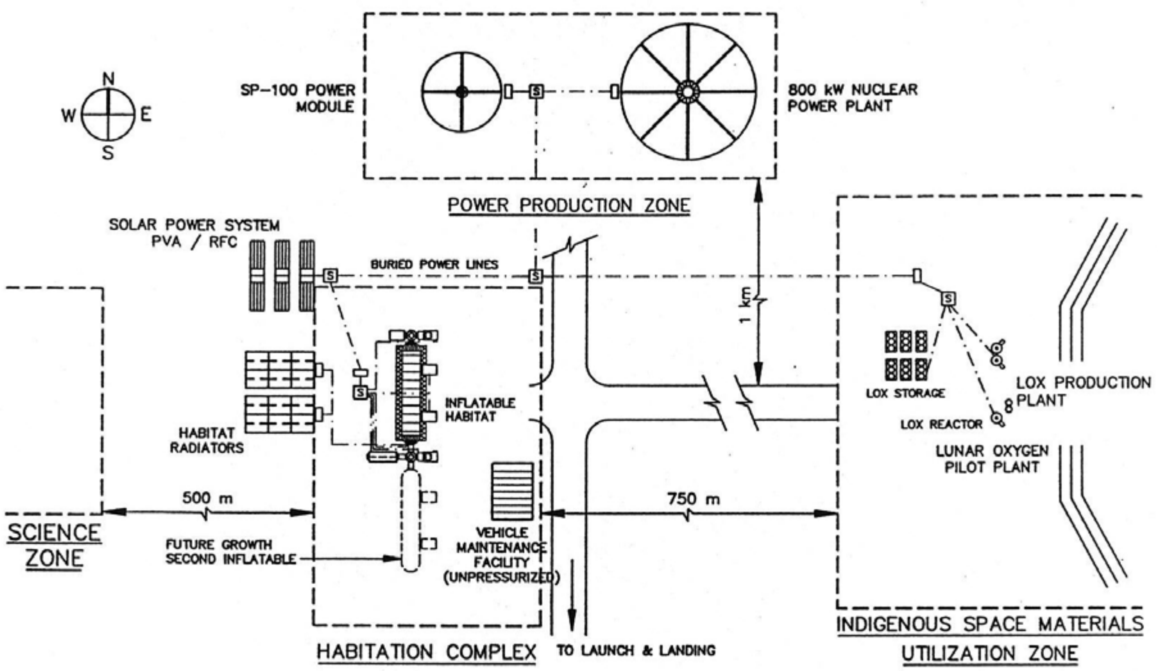

Figure 13: Notional Mature Lunar Base Master Plan

Figure 14: Notional Mature Lunar Base using an inflatable habitat

The habitat integrated into a lander takes on the persona of form and function. In this case it is the lander function dictating what form the habitat is to be or can be. One option is to use a large monolithic hard shell on top of the lander. Another is that the habitat is the lander with an integrated landing system, engines, and propellant tanks. Yet another is that the lander transforms into the surface habitat by use of an expandable structure. Each has their respective desirable features. Figure 15 is an example of an integrated habitat-lander.

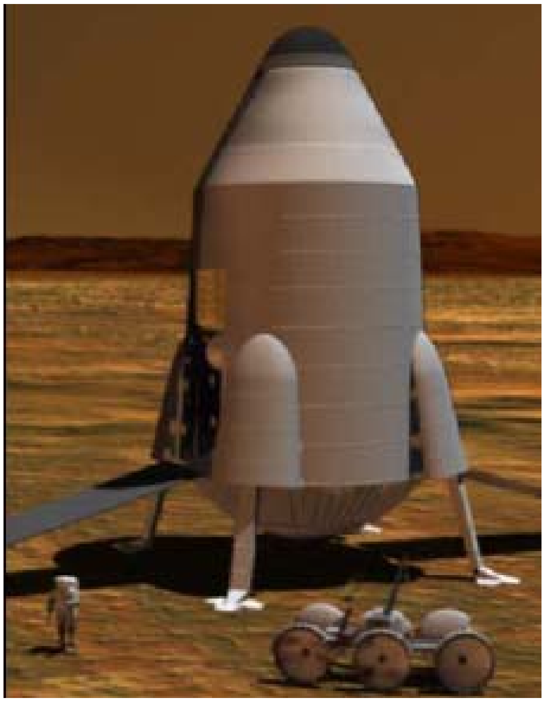

Figure 15: Pre-integrated monolithic habitat-lander

The mobile habitat can take on the form of several large pressurized rovers or an integrated habitat-lander that has integrated mobility. As previously mentioned this approach may be desirable to maximize the exploration of a planetary body. Figure 16 is an example of what a mobile habitat-lander might look like. This concept is based off the idea of a horizontally oriented lander with the habitat under-slung and deployable landing legs with mobility systems pre-integrated. Of course each concept has to be designed and tailored to meet the mission objectives, requirements and performance constraints.

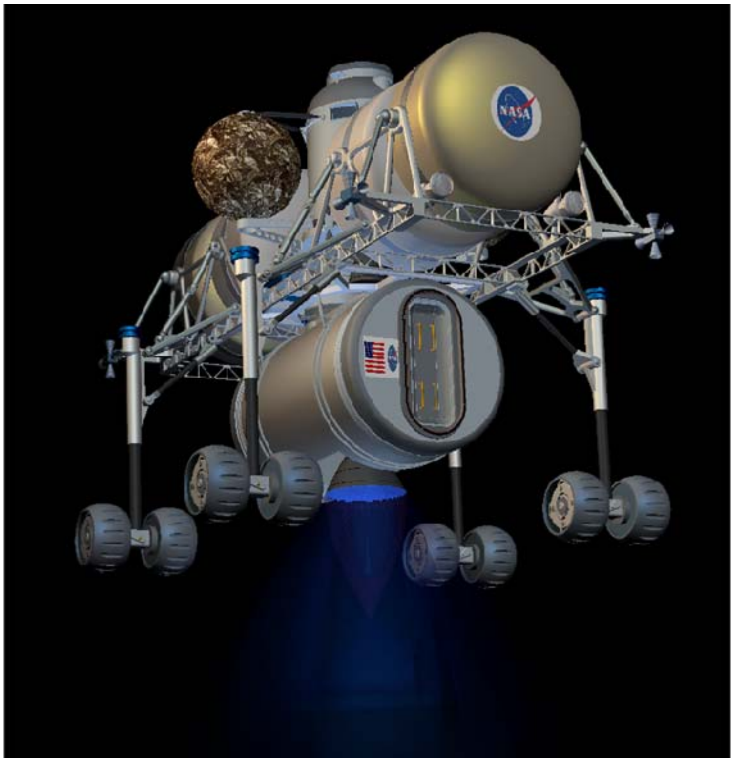

Figure 16: Pre-integrated mobile hab unit

Humans will move from the confines of our planet Earth, and in doing so will establish new foot holds on distant places in LEO, the moon, or Mars. When human take that step space architecture and engineering will be helping to plan, prototype, build, test and prepare to make their journey habitable. Humans can endure much, but our desire is to live and work in harmony with our environment. NASA has long been a leader in research and development of new technologies for space activities. Many of which have spun off to benefit human kind and Earth. Prime examples are computers, medicine, recycling and there are many, many more.

Challenges

One of the primary challenges facing architects of future habitats on other planetary surfaces is providing the same safe environment for astronauts we have come to expect in our transportation vehicles and Earth orbit space stations. While we have analog experience in extreme environments on Earth and operational lessons learned on ISS, we really face a new set of technical challenges to solve for habitats on the moon and Mars.

The same drivers of mass, volume and power will apply. In the area of mass - materials research and technology development of structures is required for the very lightweight and robust habitats needed for the months of transport to Mars and for the months, and possibly years, which humans will spend on the surface of the Moon or Mars in carrying out exploration and development activities. Such habitat technology also has the potential for being important in opening up the possibilities for near Earth orbital platforms for commercial usage. Major technology interests are in advanced lightweight materials, in use of inflatable design techniques, and in techniques using these materials to provide protection from micrometeoroids and secondary ejecta. Space and planetary habitation, pressure structures and unpressurized shelters are being sought out for innovative structural solutions that would combine high strength and light-weight materials, along with the reliability, durability, repairability, radiation protection, packaging efficiency and life-cycle cost effectiveness that is also needed.

In the area of volume, development of materials that have the ability to be packaged for transport within the volume constraints of the transportation system and then expanded once on the surface, along with them being light weight adds to the inherent packaging efficiency. Another major challenge is determining the standards and requirements for “internal volume” needed for crew habitation while making sure it is based on true analog experience. This should also be done with an eye towards the resulting “floor area”. Providing a requisite volume for crewmembers will not be enough. Providing an effective layout that may have to accommodate shared operations will be just as important.

Advances in material developments and manufacturing techniques have lead to the emergence of inflatable structures use in space. Whereas tensile fabric structures have been used on Earth for thousands of years, their use as human space habitats is in its infancy. Inflatable structures are gaining momentum as continued development and testing matures its uses for space. The ability of the structure to “self-heal,” the emplacement, erection, deployment or manufacturing of habitats in space or on the Moon and Mars are considered needed technologies for the evolution of humans into space and the eventual settlement on Mars. Integration of sensors, circuitry and automated components to enable self-deployment and “smart” structures are considered necessary to allow a habitat to operate autonomously.

Pre-Integrated habitats are commonly an aluminum or composite structure that can be autonomously pre-deployed and operated in LEO, on the Moon, or Mars surface. They are fully integrated and have the capability for Integrated Systems Health Management (ISHM) smart habitat systems for failure detection, analysis and self-repair. Pre-fabricated habitats are constructible or deployed habitats such as an Inflatable structure that can be autonomously pre-deployed and operated on the Moon and Mars surface. They are partially integrated and flexible and also have the capability for ISHM smart habitat systems for failure detection, analysis and self-repair. ISRU-Derived habitats are based ISRU-derived structures that are manufactured using indigenous resources and constructed autonomously. It is autonomously operated and maintained utilizing artificial intelligence and ISHM. It will have capability for ISHM smart habitat systems for failure detection, analysis and self-repair. As advanced habitats evolve from current pre-integrated habitat modules to future ISRU-derived structures, so does the level of technology investment required to achieves these systems. Pre-integrated habitats have a high level of technology maturation and thus a lower technology investment is required compared to ISRU-derived habitats.

Space and planetary habitation, pressure structures and unpressurized shelters need innovative structural solutions that combine high-strength and light-weight materials, along with the reliability, durability, repairability, radiation protection, packaging efficiency and life-cycle cost effectiveness. 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 concepts, technologies and techniques have been proposed over the years that allow the delivery of deployable habitats to space and planet surfaces, or the manufacturing and construction of habitats on planet surfaces. Many new and exciting break-through in biotechnology have opened up exciting possibilities. The use of biotechnology combined with a fabric or matrix structure could someday produce a self-healing property analogous to our human skin.

In the future, numerous technologies will be researching methods and techniques for fully integrated inflatable “skin” and sensors/circuitry that enables “smart” structures that autonomously detect, analyze, and correct (repair) structural failure. Manufacturing methods of integrating miniaturization technology into the habitat skins, thus reducing weight and increasing self-autonomy are considered desirable. Technologies of this nature will be required far into the future to develop large planetary bases and support infrastructure such as inflatable greenhouses.

NASA is researching methods and techniques for fully integrated inflatable “skin” and sensors/circuitry that enables “smart” structures that autonomously detect, analyze, and correct (repair) structural failure. Manufacturing methods of integrating miniaturization technology into the habitat skins, thus reducing weight and increasing self-autonomy are being considered. Technologies of this nature will be required to develop large planetary bases as shown in figure 17.

Therefore the following are recommend areas of focus:

- Develop composite structures that can be deployed and operated in space and on planetary bodies for 10-20 year life time.
- Develop inflatable structures that can be packaged, deployed and operated in space and on planetary bodies for 10-20 year life time.
- Develop ISRU-derived structures, manufacturing processes and construction techniques that can be packaged, deployed and operated in space and on planetary bodies for 10-20 year life time.
- Integrate diagnostic and habitat health monitoring through out the habitat.

- Integrated self-repairing skins for habitat structures.
- Integrated design techniques that incorporate advanced systems into the habitat skin/structure and incorporates techniques to adjust resources within the habitat to automatically protect the crew based on the sensed environmental conditions.

Figure 17: Artist Concept of a mature Lunar Base

Another major challenge habitat designers will face is the environment present on the planetary body. Addressing space radiation is a major environmental challenge for the habitat designer because there is a lack of data to determine the effects it will have on the human body or the maximum allowable dose that should be permitted for long-term missions of 6 months or more. Comparisons are made to terrestrial and low-earth-orbit radiation experience, but space radiation as encountered outside the protective electromagnetic and atmospheric shield of our planet is not the same. There are two types of radiation that are of primary concern, solar particle events (SPE) from the solar flares generated by our sun, and galactic cosmic rays (GCR) from unknown sources beyond our solar system. Of these two types the SPE can be the most intense, which has led to shelter designs for the protection of crew during a solar flare. GCR is continuous background radiation at a lower level that is of more concern for long-term missions.

A variety of materials and material thicknesses have been considered for shielding space habitats. In general, it has been found that the greatest benefit can be derived from the first 5 to 10g/cm^2 of material for both SPE and GCR shielding, and that non-metallic materials are best for GCR shielding. This has led to a general rule of thumb for water wall enclosures 10cm thick along outside walls, and less where other equipment is in place that can provide protection for the crew. Water is often selected as the primary SPE shelter shield because it is an important resource for other systems and contingency operations. In other words, the water is going to be there in tanks, so why not make it conform to a usable shield shape. Long-term protection for GCR is more complex, and may require shielding thicknesses measured in meters. So, in-situ materials are often considered for long-term missions where part of the build-up strategy would be to bury the habitats below a meter or more of locally mined material.

Location of the shelter within the habitat is an important consideration too, and so the crew sleeping quarters are often selected since the duration of an SPE could be more than a day in length, and this is one location where the crew will spend at least 8 hours a day anyway. For GCR protection, the entire habitat would need to be shielded to provide protection for long-term missions. Integrating the radiation protection system into the habitat design and the mission operations can be challenging. In general, all habitats should have a SPE storm shelter to protect the crew during solar flares. Water, being a leading candidate for the shelter material, should be integrated into the system for dual use where feasible. And, for long-term missions a strategy should be developed to incorporate in-situ materials added over the structure over time to build up the protection needed from GCR.

Summary

The probable evolutionary path of space architecture and habitation is hard to predict. Through the efforts of dedicated women and men, the future of space architecture and human space flight looks promising. Advanced Habitation efforts throughout the NASA centers, within industry and academia, around the country, and around the world are working on research and designs to make space travel safer, more habitable, and hospitable for humans. In the near future space architects and engineers will not only help shape the vehicles that get us there, but also the built environment we bring with us to live there. This will have to be done with a clear understanding, respect and appreciation of the natural environment we will have to operate in. Much like our approach to sustainable architecture within our built environment on Earth, we will have to incorporate design features and technologies that enable sustainable space architecture on other planetary bodies.

History has taught us that architects and engineers have shaped our built environment; and they will continue to do so on Earth and in space. Ground-breaking design and technology work by architects and engineers in the aerospace community are laying the foundation for human space flight by which many will follow for years to come. Whereas the many Architectural-Engineering teams have made incredible strides in advanced habitation, there remains a great deal of work to be done on Earth and in space to enable humans to live and work for long durations in low Earth orbit and beyond.

References

1. Capps, Stephen D; Fowler, Robert & Appleby, Matthew. 1991. Induced Gravity Mars Transportation Systems. Space Manufacturing 8, pp. 126-13 1. Proceedings of the Tenth Princeton/AIAA/SSI Conference, May 15-18, 199 1. Published by the AIAA.
2. Clark, Bryant & Graybiel, Ashton. February 196 1. Human performance during adaptation to stress in the Pensacola Slow Rotation Room. Aerospace Medicine, Vol. 32. pp. 93-106.
3. Graybiel, Ashton & Knepton, James. November 1972. Direction-specific adaptation effects acquired in a slow rotation room. Aerospace Medicine, Vol. 43. pp. II 79-1189.
4. Hewes, Donald E. & Spady, Amos A. March 1964. Evaluation of a gravity-simulation technique for studies of human self-locomotion in lunar environment. NASA Technical Note D-2176. NASA/Langley Research Center.
5. Hewes, Donald E. & Spady, Amos A. & Harris, Randall L. Jane 1966. Comparative measurements of man's walking and running gaits in earth and simulated lunar gravity. NASA Technical Note D-3363. NASA/Langley Research Center.
6. Human-Systems Integration Standards, CxP 70024, CxP 01000, 2007
7. Kennedy, K. and Capps, S., “Designing Space Habitation,” SPACE 2000: 7th International Conference and Exposition on Engineering, Construction, Operations, and Business in Space, ASCE, March 2000
8. Loret, Benjamin J. May 1963. Optimization of spare vehicle design with respect to artificial gravity.
9. Margaria, R. and Cavagna, C. A. December 1964. Human locomotion in sub-gravity. Aerospace Medicine, vol. 35, No. 12. pp. 1140-1146.
10. NASA Procedural Requirements (NPR 7123.1), NASA Systems Engineering Processes and Requirements
11. NASA’s Exploration Systems Architecture Study, NASA, Nov. 2005
12. Nicogassian, Amauld E. & Parker, James F. Jr. 1982. Space Physiology and Medicine. NASA SP-447. U.S. Government Printing Office, Washington, D.C.
13. O'Laughlin, T.W.; Brady, J.F. & Knewsom, B.D. May 1968. Reach effectiveness in a rotating environment. Aerospace Medicine, Vol. 39. pp. *505-508.*
14. Reason, James T. & Graybiel, Ashton. January 1970. Progressive adaptation to coriolis accelerations associated with I rpm increments in the velocity of the Slow Rotation Room. Aerospace Medicine, Vol. 41. pp. 73-79.
15. Spady, Amos A. & Krasnow, William D. July 1966. Exploratory study of man's self-locomotion capabilities with a space suit in lunar gravity. NASA Technical Note D-2641. NASA/Langley Research Center.