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Inhabiting the Solar System

Research Article

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Abstract: The new field of space architecture is introduced. Defined as the "theory and practice of designing and building inhabited environments in outer space," the field synthesizes human space flight systems engineering subjects with the long tradition of making environments that support human living, work, and aspiration. The scope of the field is outlined, and its three principal domains differentiated. The current state of the art is described in terms of executed projects. Foreseeable options for 21st century developments in human space flight provide a framework to tease out potential space architecture opportunities for the next century.

Keywords: Architecture • Space architecture • Human space flight • Space exploration • Offworld • Space tourism • Space manufacturing • Habitation • Habitat • Habitability • System engineering • System architecture • ISS • Moon • Mars • Orbital • Simulator • Analogue • NASA • Commercial space • Passenger travel • Space solar power • Space settlement • Space colonization • Planet • Inner Solar System

1. What is Space Architecture?

Humans have been using permanent materials to make architecture–the willful shaping of the physical human environment–for about ten millennia. But earnest notions of inhabiting outer space awaited the rapid advancement of industrial technologies around the dawn of the 20th century when Verne, Tsiolkosvky, and other visionaries began considering how humankind might travel into space. Just decades later, in 1968, humans left Earth orbit for the first time. Shortly thereafter, architect Maynard Dalton and industrial designer Raymond Loewy designed the interior of NASA's first space station *Skylab*, incidentally establishing the field of space architecture (Figure 1). Long-duration Earth-orbital missions forced the American and Soviet space agencies to address real problems posed by humans living and working–not just camping–in space.

In the last two decades of the 20th century, diverse professionals began to develop principles for space architecture. They compared ideas, published concepts, conducted design studies under contract to NASA and ESA, established educational tracks at universities, and organized technical committees within professional aerospace societies. In 2002 this international community hosted a workshop at which 46 architects, engineers, industrial designers, aerospace managers, technologists, and researchers drafted the *Millennium Charter* [1] to define the scope of the new field. A comprehensive survey of the field is *Out of this World: The New Field of Space Architecture* [2].

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This work was done as a private venture and not in the author's capacity as an employee of the Jet Propulsion Laboratory, California Institute of Technology.

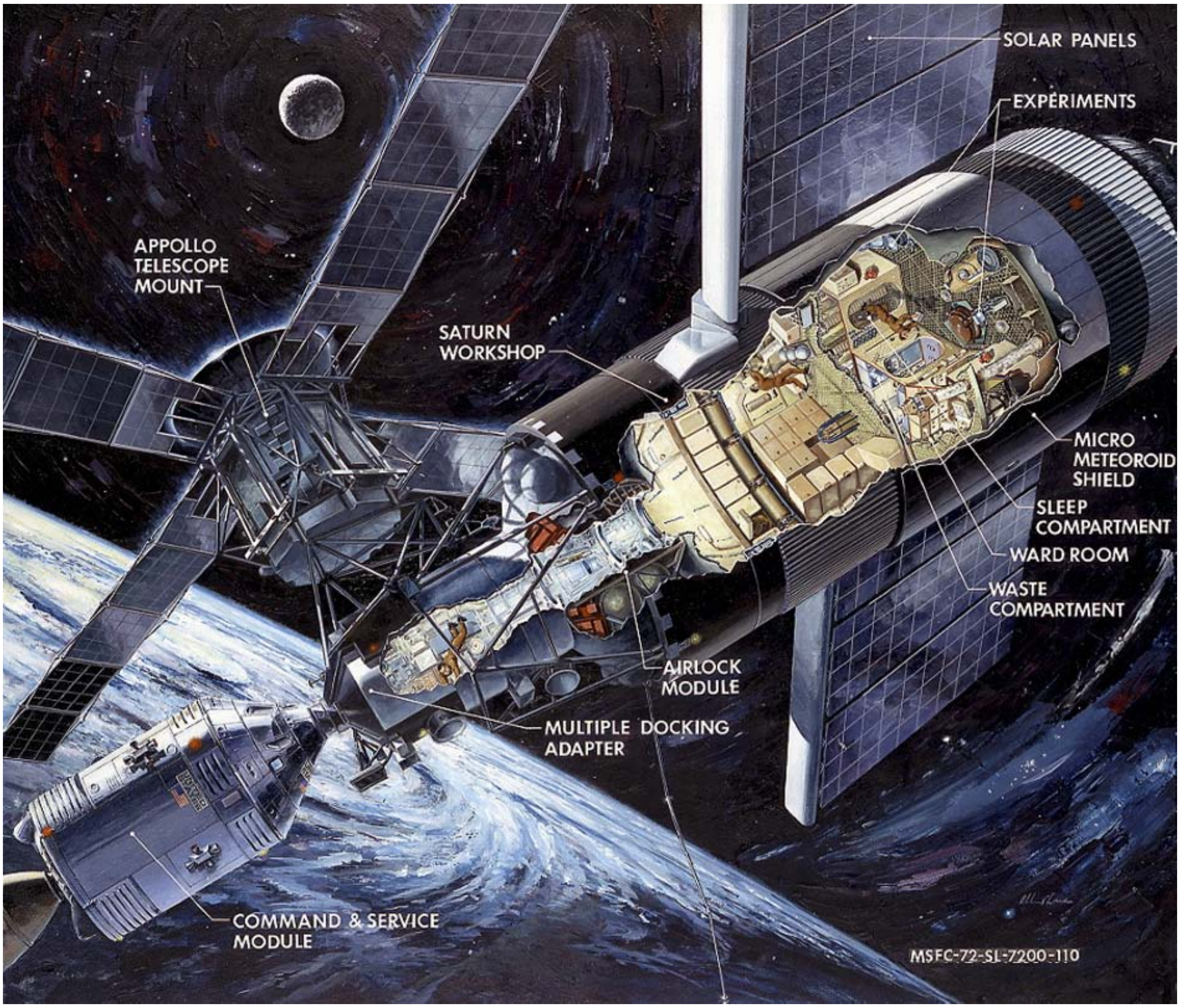

Figure 1. *Skylab* was the progenitor of all contemporary space architecture. Called "a house in space" at the time, it was the first large-volume laboratory designed for sustained living and working in orbit. Credit NASA.

Space architecture is the theory and practice of designing and building inhabited environments in outer space. Evolved from the tradition of terrestrial architecture, its scope ranges from personal industrial design to urban macro-engineering and from the artistic to the functional–from spoons to highways and from gardens to sewers. The field's core value proposition is that the professional discipline of architecture brings a unique integration of technical responsibility and humanistic sensibility essential for shaping a safe, productive, and ennobling physical human environment in outer space.

The word "architecture" means the act and product of resolving a complex design problem characterized by thousands of parts, mutually conflicting requirements, diverse specialties, and the willful creation of order from chaos. While this essence is shared across all fields that have co-opted the term (e.g., war making, aerospace, computers, and software) it has special resonance wherever the product is meant for human occupation. Training, skills, knowledge, experience, and outlook unique to architects in the building tradition are of vital value as humans expand into space.

Space architecture is more than just aerospace "systems engineering." First, the very few habitable aerospace systems address only primitive habitation needs which will be superseded rapidly as mission purpose, duration, distance, and crew size evolve. Architects are uniquely equipped to address the complex, messy issues of human psychological and sociological needs. Second, unlike analytical disciplines that take problems and systems apart to understand them, architecture is design-directive. It envisions an integrated design solution, from parti through

Table 1. Unprecedented, wide range of specialties coordinated by space architecture.

Scope	Traditional Terrestrial Disciplines	+ Additional Subjects for Space
Architecture	Human activity analysis & programming	Mission operations planning
	Psychology & sociology	Psychology of remote isolation and sensory deprivation
	Comparative historical analysis	
	Abstract & representational modeling	
	Structural engineering	Aerospace structures & mechanisms, including pressure containment and vacuum tribology
	Materials development & testing	Aerospace materials and space environments
	Environmental control engineering	Life support systems
	Design for sustainability	
	Site engineering	Planetology including alien engineering geology, weather, atmospheres, chemical environments, diurnal cycles, and gravity
	Landscaping	
	Construction engineering, safety, and quality inspection	
	Interior design	
	Color and lighting design	
	Firesafety	
	Power generation, management & distribution	
	Acoustic engineering	Vibration & noise control
	Environmental impact and wilderness management	
	Furniture design	
	Industrial design	
	Art	
	Economics & finance	
	Negotiation & contracting	
	Construction management	Aerospace project management
	No terrestrial equivalent	Astrodynamics; attitude control; and guidance, navigation, and control
		Propulsion, launch, and landing
		Vacuum thermal management
		Command & data handling
		Autonomy
		Reliability, safety, and mission assurance
Urban planning	Potable water supply & distribution	Advanced, closed, and biologically-based life support systems
	Waste management	Material recycling
	Agriculture & processing	Biomass production
	Power production & distribution	
	Industrial production	Space mining and *in situ* resource utilization
	Mass transit and industrial transportation	
	Material supply & distribution	
	Commerce	
	Crime & law enforcement	
	Environmental protection	
	Communication networks & media	
	Public recreation & spectator events	
	Parks management	
	Public health management	
	Death accommodation	
	Defense	
	Urban growth	

detail, and then creatively guides supporting analyses to achieve that vision. Third, while aerospace systems architects are typically most active in the conceptual phase, terrestrial architects typically lead the complete unfolding and realization of their designs.

We should anticipate that in the second half of the 21st century, with large numbers of people traveling, working, and living in space, the technically challenging issues that dominate design and operation of habitable space systems today will have been largely solved and reduced to practice. As a result, and as spacefaring populations grow, more atavistic human needs will come to the fore. Aerospace engineering disciplines will blend into the panoply of subjects architects have historically coordinated. The wide range of disciplines space architecture coordinates both includes and exceeds those already known to terrestrial architecture (Table 1).

The lure of space is strong for designers of the human environment. For the first time in human history, we are reaching, and therefore must learn to live and thrive in, environments so alien that our very weight is reduced or canceled. Different gravity levels, lack of air, strange lighting, extreme temperatures, killing radiation, hardscrabble material resources, vast distances, and psychological remoteness characterize places in space. For space architects, this is more inspiring than discovering a new continent.

Space Architecture has three physical domains: **Terrestrial** (space-support facilities on Earth); **Orbital** (locations near Earth or other natural bodies, or in "free space" orbiting the sun); and **Planet-Surface** (on and under the surface of the Moon, Mars, or asteroids).

2. Terrestrial Space Architecture

Not all "space architecture" is in space. Terrestrial space architecture comprises three types: simulators and analogues, research and test facilities that approximate specific space mission conditions; support infrastructure, the Earth-based segment of space missions; and "spin-off" architecture that uses space technologies and perspectives to benefit life on Earth directly.

2.1. Simulators and Analogues

Space architecture learns vital lessons from extreme terrestrial environments that depend on high technology and drive psychological stress. Two prime sources of this learning are space mission simulators and analogue environments like polar research stations and submarine facilities. Since the 1970s European, American, and Russian investigators have studied system and human performance in a series of mission simulation campaigns that emulate various aspects of long, deep-space missions [3].

Antarctica is the most versatile terrestrial analogue environment for space exploration missions. Approaches for deploying inflatable shelters, and monitoring and controlling habitat systems remotely, have been tested at McMurdo Station rapidly and at minimal cost [4]. Such technology demonstrations inform both the development of lunar habitat concepts and new types of Antarctic remote science stations. The contemporary state of the art in Antarctic science research station design (e.g., the British *Halley VI* and Spanish *Juan Carlos I* stations) provide direct analogues for lunar science bases (Figure 2): complex, functionally integrated base modules fabricated remotely; shipped with choreographed logistics to Antarctica; assembled, verified, and commissioned during short seasonal "missions;" and expected to operate reliably for many years [5].

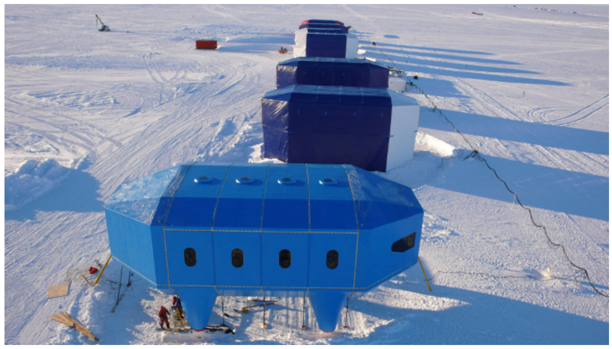

Figure 2. British *Halley VI* Antarctic research station offers a useful analogue for many characteristics of space architecture: remotely-fabricated, complex, and reliable modules; shipped to the site with a choreographed logistics campaign; assembled, verified, and commissioned in situ during short "missions"; and operated without ready resupply. Credit [5].

2.2. Support Infrastructure

Space architecture depends on Earth-based facilities for key functions: prototyping, manufacture, and test; logistics and launch support; and control and communications. Installations that interface physically with space flight systems require special architectural consideration and provide near-term opportunities for space architects. Current examples include a European Space Agency facility (Figure 3) to support developmental testing of the robotic ExoMars rover and enhance public engagement in space exploration [6] and the expansion and adaptation of airports to host commercial spaceports [7], accommodating their unique considerations for ascent and landing, range safety and ground support.

2.3. Spin-off Architecture

Learning how to meet the extreme requirements found in space architecture can teach us techniques for directly improving the quality of life on Earth (Figure 4). In space, the stuff of life cannot be taken for granted. This fosters a "spaceman" mentality where the habitable world is a closed, tightly coupled system that values everything needed and reveals immediately the ramifications of everything done. This approach transcends a "cowboy" state of mind where the world appears limitless and insensitive to human actions [8].

3. Architecture in Space

In-space architecture is divided coarsely into three types: Class I (launched intact, with systems already integrated and verified); Class II (constructed or assembled in space and verified there, using parts and subsystems manufactured and tested on Earth); Class III (fabricated and constructed in situ from local materials, then verified and outfitted with systems imported from Earth) [9]. Beginning with the International Space Station (ISS) most projects are really hybrids: the ISS flight system was fully integrated for the first time on orbit.

Architecture in space starts with conditions imposed by its natural environments: as axiomatic as gravity and weather are on Earth, applying at all scales, and constraining the design options available. This section collects and summarizes some architectural implications of the most salient conditions; detailed explanations are in [10–14].

Gravity Level

There are four applicable gravity conditions: microgravity (all orbits); ultra-low gravity (asteroids); 1/6 Earth-normal (the Moon); and 3/8 Earth-normal (Mars). Objects in orbit are in continuous free-fall. The human body takes on a neutral posture, with all joints slightly bent; the spine stretches; fluid collects in the upper body; taste and smell are diminished due to nasal congestion; physical and chemical deconditioning occur over time.

Behavior of fluids is dominated by surface tension; behavior of solids is dominated by friction, electrostatic, electromagnetic, and elastic forces. Dust and objects drift on air currents if inside or orbit individually if outside. There are no fixed locations in orbit. The lower the orbit altitude the more quickly its characteristics propagate; separate objects end up in non-coplanar orbits, eventually enabling head-on encounters at up to 14 km/s. The only zero-energy way to keep objects together is to link them mechanically. In LEO, continuous application of torque is required to maintain the attitude of an object whose inertial axes are neither parallel nor normal to the nadir vector.

Weightlessness can theoretically be compensated by a rotating flight system; centripetal acceleration induces pseudoweight, but no human-scale system has yet been developed or flown to do this. Rotating systems containing fluids settle naturally into the lowest-energy state (rotation about the axis of maximum moment of inertia) so pancakes are stable while spindles are not. The rotation axis remains fixed in inertial space unless acted upon by an external torque. Out-of-plane motions within the rotating system generate Coriolis accelerations, which cause vestibular disturbances in animals if the ratio of rotation rate to radius is high. Trajectories of objects thrown inside rotating systems appear counter-intuitively curved when viewed within the rotating frame of reference.

Asteroidal hypogravity is low enough to be negligible for gross motions but significant enough to settle particles. Mars' moon Phobos (at $>$ 20 km long, a very large asteroidal body) has enough gravity to preclude jumping to escape velocity, but a baseball pitcher could throw a ball to escape. Lunar surface gravity is enough to aid construction and operations; gravity anchoring of equipment and structures is less effective than on Earth, but lighter structural members can be used for familiar spans, and unprecedented spans are possible.

Human locomotion in lunar gravity is quite different from familiar Earth locomotion. Walking and running gaits, motion postures, and traction are all affected. Indoor walking may require 2.5 m headroom clearance, with comparable modifications of riser/tread ratios and dimensions for stairs and ladders, workstation design, and corridor and door heights. Whether 1/6 g avoids physiological deconditioning is unknown.

Mars gravity is over twice as strong, so dead loading is 2.25 times the lunar case for the same equipment. Mars' greater gravity retains enough atmosphere for landing vehicles to use heat shields and aerodynamic decelerators, which limits allowable payload dimensions. Whether 3/8 g avoids physiological deconditioning is unknown.

Vacuum and Pressure

In space the typical vacuum exceeds by several orders of magnitude the quality of vacuum attainable in laboratories on Earth, which poses severe structural, thermal, and operational conditions for architecture. LEO imposes a unique exception: the Earth's exosphere is rich in reactive monatomic oxygen. Extremely erosive to ram flux surfaces, this forces use of special materials and coatings.

Habitats containing Earth-normal atmosphere experience 70-100 kPa (10-15 psi) across their entire enclosing surfaces. This structural challenge constrains the size of Class I structures and the complexity of Class II structures. The external vacuum is lethal, but not instantly. The joints of inflated spacesuits are hard to bend and therefore cause fatigue.

In a vacuum waste heat can be rejected only radiatively, or by evaporating fluid sacrificially. Sound is conducted and reverberates throughout a system until dissipated within the structure and its contents, because

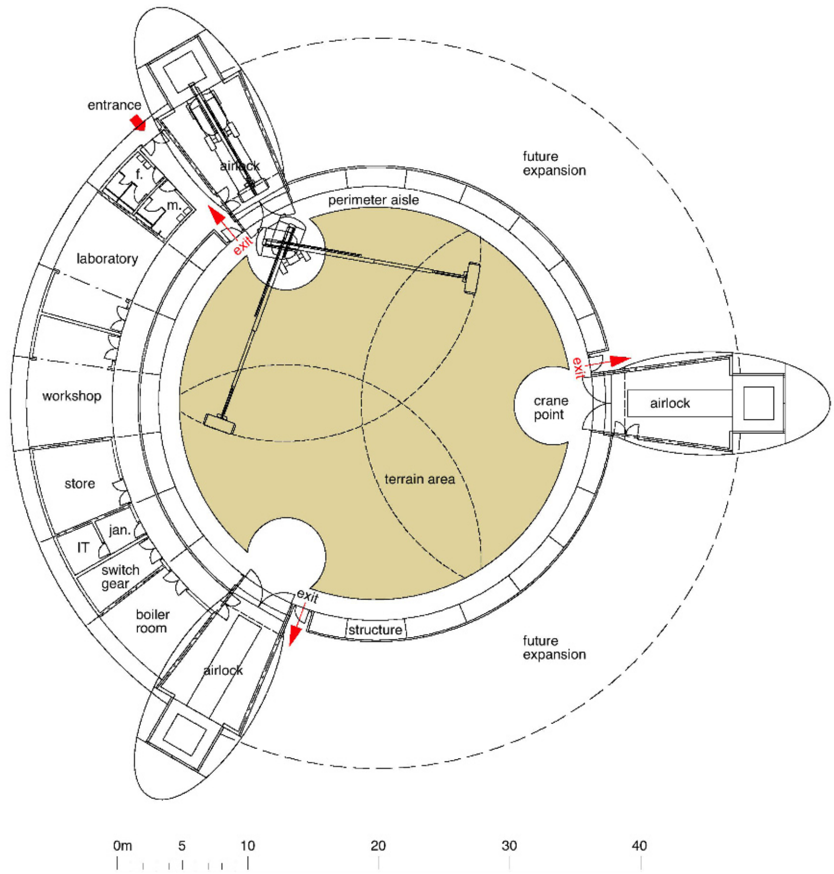

Figure 3. Terrestrial support facilities, like this ESA planetary surface simulator project and airports being modified into commercial spaceports, provide the architectural link between space missions and the Earth, as well as near-term work for space architects. Credit [6].

acoustic waves cannot dissipate directly into vacuum. All spacecraft gradually leak atmosphere. The vacuum near spacecraft is "dirtier" than in the wake of a ram shield or in free space. The desiccated vacuum environment on the Moon may allow in situ manufactured glass to approach its theoretical strength.

Radiation

Four types of space radiation are applicable to space architecture: high-energy galactic cosmic rays (GCR), an isotropic flux of protons, alpha particles, and heavier nuclei; solar flares (solar proton events, SPE), a wind of high-energy protons with fluxes up to 100/cm^2/s resulting from explosions in the sun's chromosphere; Earth's van Allen belts, zones of high-energy solar-wind electrons and protons trapped by the geomagnetic field; and radiation emitted by nuclear power sources.

GCR fluence increases linearly with time; mitigation options other than high-mass shielding are undeveloped. LEO locations are generally shielded from SPE and other solar wind particles by the geomagnetic field. Extended presence at GEO (in the outer edge of the outer van Allen belt) or beyond Earth orbit requires storm-shelter shielding rich in hydrogen, such as water or polyethylene. Protection from nuclear materials requires specialized (*e.g.*, LiH and tungsten) shielding and geometrical separation. Today, LEO residence time totaling a few dozen months yields lifetime exposures of the same order as permitted for radiation workers.

Asteroidal and lunar surfaces are bombarded by the same radiation as high Earth orbits, albeit only from the overhead hemisphere. Habitable lunar-base structures intended for long occupancy require heavy radiation shielding. Some scenarios use water jackets for this purpose, requiring the water to be brought from Earth. Regolith (granular dirt and dust) blankets have also been proposed but the required thickness is unverified. The use of dusty native material introduces design and operational complexities so regolith sheltering schemes and operations

Figure 4. Desert Seal's space insulation system, photovoltaic-powered fan, and aerodynamic configuration harness local conditions to create a habitable single-person sleeping environment. Credit [8].

scenarios must be designed in from the start [15]. Mars' atmosphere provides an uncharacterized level of attenuation; the need for long-term regolith shielding there is unknown.

Illumination and Temperature

LEO architecture is exposed to 1389 W/m^2 of unfiltered solar spectrum, including ultraviolet (UV) wavelengths that can embrittle or degrade materials, blind sensors including retinas, burn tissues and cells, and induce thymine-dimer DNA damage. Systems require UV-tolerant materials and coatings and UV filters for sensors, visors, and windows. View factors for different purposes–sun, Earth, cold space, astronomical objects in dark sky, nearby hardware, clean vacuum, beamed-power sources, oxygen ram flux, debris flux maxima–are generally mutually incompatible and change with time.

Influenced by many factors, temperatures in LEO can vary hundreds of degrees depending on whether surfaces face the sun, the Earth, each other, or deep space. Terminator passage (up to 32 times per day) is the dominant periodic constraint. Space-system designs must include a combination of clever configurations, tolerant materials, passive shields, heat pipes, or active cooling loops to redistribute heat, heaters/radiators to add/reject heat, and "barbecue" rotation to even out the heat load.

Without intervening air, the view of space objects is clear, limited only by diffraction and glare. The Earth view varies constantly because of Earth's rotation and weather, and is beautiful and poignant; spacefarers report never tiring of it.

The lunar synodic period is 29.53 Earth days; at the lunar equator, this means almost 15 days of daylight and 15 days of darkness. Sunlight is unattenuated except where reflected by local surfaces; contrast is extreme. The near side is illuminated at night by Earthshine; the full Earth is roughly 50 times brighter than is a full Moon viewed from Earth. Lunar surface temperatures change drastically from high noon to predawn, e.g., 111°C to -171°C. Temperatures decrease rapidly as sunset approaches, falling about 5 K per hour. Hard vacuum between grains of lunar regolith makes it a very poor thermal conductor. Radiation of low-grade heat (*e.g.*, from electronics, people, and lights) to space is challenging during the lunar day because of the high surrounding ground temperature and overhead sun.

Mars receives less than half the specific solar flux that the Moon (or Earth) does because of its greater distance from the Sun; its elliptical orbit causes 39% annual insolation variation. The surface temperature varies between about -120°C and -25°C daily (Mars' diurnal cycle, the sol, is 1.03 Earth days long) and rarely exceeds the freezing point of water. Together, the shorter diurnal cycle and moderating atmosphere make Mars a more hospitable place than the Moon.

High-Velocity Impacts

The LEO orbital debris environment is increasingly problematic for architecture there. Relative velocities as high as 14 km/s make even paint flecks hazardous. The flux probability peaks at incoming angles roughly 45 deg to starboard and port off the bow. Risk is proportional to the area exposed to the flux. Shielding is practical only for particles of $\sim$1 cm size or smaller. Critical structures are wrapped in thick Whipple bumpers comprising many energy-dissipating layers. Shielding space suits, windows, sensors, radiators, and solar arrays during use is not practical at all. Natural micrometeoroids may have velocities as high as 20 m/s. Surface degradation and pitting occur, but the impact cross-section for catastrophic collision is low. Micrometeoroids bombard the lunar surface as well; the Mars surface is shielded by its atmosphere.

Dust

Lunar regolith clumps together macroscopically like damp beach sand. Fifty percent consists of dust finer than 70 µm (too fine to be resolved by the unaided eye). This extremely penetrating and abrasive dust sticks electrostatically to objects that touch it. Pressure seals and life-support equipment are subject to contamination, and sensitive photovoltaics, optics, and thermal radiators are prone to degradation. Putative toxicity of the inhaled dust drives the design of future space suits and airlocks. Dust-removal technologies under development are not yet tested in the lunar environment.

Mars' tenuous CO_2 atmosphere (average surface pressure ~0.7% of Earth sea-level) varies greatly seasonally and with surface elevation. Direct wind loading is not a problem, but the high wind speeds (of order 100 m/s) loft surface fines to relatively high erosive and penetrating capability. Local dust storms and occasional global, long-lived dust storms are unavoidable. So unlike on the Moon, contamination cannot be minimized by locating components above surface activity. Experience with solar-powered rovers demonstrates that occasional, random dust devils tend to clear accumulated dust from photovoltaic and radiator surfaces. Dust health effects are unknown.

Prevalence and behavior of asteroidal dust are almost unknown. However, early models indicate that hypogravity allows even boot-kick disturbances to loft granular particles into obscuring clouds that settle over several hours, potentially complicating surface operations.

Substrate Mechanics

Lunar regolith formed over billions of years, as meteoroid bombardment pulverized the rocks and mixed and settled the resulting fragments. Regolith depth ranges generally from 2-30 m, 5-10 m in mare regions. The bulk density is very low (0.8–1.0 mt/m^3) in the upper few millimeters, but increases to 1.4-2.2 mt/m^3 at and below ~ 3 m. Just below the surface, lunar regolith is more cohesive (0.1-1.0 kN/m^2) than most terrestrial soils, and has extremely high relative densities approaching 100% just a couple of meters down. Excavation of native material is difficult, but undisturbed subsurface layers of material might provide excellent foundation substrate; once disturbed, no amount of compaction can regain the native relative density. Moonquakes are negligible.

Mars regolith mechanical properties have been observed from concrete-hard and sticky-clumpy with admixed ice (*Phoenix* northern-latitude site), to exposed-bedrock, rocky sand, and soft deposits that can trap wheeled vehicles (*Spirit* and *Opportunity* rovers). Speculation that chemical reactions in Martian soil would be detrimental to some materials, including polymers, did not prevent the *Spirit* and *Opportunity* rovers from far outliving their design lives. Sand-dune mobility has been observed on the surface, and permafrost is inferred over widespread regions, so simple foundation pads (as would be possible on the Moon) might be impractical. Surface frost is common at dawn. The Martian poles are particularly active regions seasonally; massive alternating freezing and sublimation of CO_2 ice would be problematic for permanent structures located there.

Asteroid structures are expected to vary widely: some solid metal, some rock and regolith, some "rubble piles" barely bound by weak gravity, and some "fairy castles" based on fragile adhesion. Anchoring schemes have not been engineered, let alone tested.

Material Combinations for Class III Structures

Lunar rocks and regolith are >98% oxygen, silicon, magnesium, iron, calcium, aluminum, and titanium. Iron is abundant (9-14%) in mare regions; titanium is available at 1-6.5%. Aluminum is found in lunar highlands at 9-18%. From these major elements many structural material combinations are possible; shipping additives from Earth for in situ fabrication of structural materials opens a great range of options. Lighter elements required for organic materials and biomass (especially nitrogen and carbon) are notably deficient on the Moon. Hydrogen is somewhat enriched in regolith compared to the other volatiles, and ore-like concentrations are now thought to be potentially available in permanently shadowed polar craters at the poles. Glasses are found naturally and can be made from available CaO and SiO_2. Structural components can also be made directly from sieved native basalt, by casting and sintering.

Mars also comprises largely silicate rocks and regolith. The availability of water makes conventional concrete a more promising option than on the Moon. Circumstantial evidence may anticipate the presence of ore bodies: volcanic origins, water-altered minerals, and widespread permafrost and even ice deposits just under the surface. Organic polymers and related materials could ultimately be made there from lighter elements. Mars' supply of elements appears well balanced for human uses. It should become possible eventually to make anything there that can be made on Earth, including outfitting equipment, consumables, and biomass. In environment and resources, Mars is the most hospitable planet after Earth.

Although there are many sub-types, asteroids can be considered either stony (made of silicate rock); carbonaceous or icy (rich in volatile elements); or metallic (iron-nickel alloys). Stony asteroids would be most like lunar and Mars rock; carbonaceous materials could conceivably be used for life support and propellant; and metallic asteroids are essentially concentrated ore bodies. Orbital mechanics makes large-scale utilization of asteroidal materials generally impractical.

Forward and Back Contamination at Mars

Mars has an additional, unique constraint. It might have once harbored native life, and conceivably still could in protected microclimates. Back contamination would expose humans or the Earth to putative Mars organisms; forward contamination would introduce Earth life or life-signature chemistry into a putative Mars ecosphere. Concluding that Mars is barren can only follow detailed, global exploration most likely involving human field work. Thus paradoxically, we will probably remain uncertain about the possibility of contaminating a Martian ecology until the human operations that might contaminate it occur. Precluding such contamination therefore becomes one of the most significant design challenges for Mars architecture [16].

3.1. State of Practice for Orbital Architecture

For the half century that spaceships have ventured into orbit, habitat form has been dominated by the geometry of rocket flight: ascent and re-entry forces and aerothermodynamics; adaptation of rocket upper stages; and modules that fit into payload shrouds. With the singular exception of actual flight cabins built into airplane-shaped vehicles (*e.g.*, the Shuttle and the new generation of commercial sub-orbital vehicles), these modules are symmetrical about the launch thrust axis, whether conical (Apollo, its predecessors, and Orion), spherical (Soyuz and Shenzou), or cylindrical. Larger volumes are contrived by in-space clustering and interconnection of modules.

ISS is the premier contemporary example of orbital architecture. In the 1980s many alternative interior architectures were studied extensively before the archetype was set for what became the American, European, and Japanese elements (Figures 5 and 6) [17]. Now assembled and hosting six permanently, ISS comprises five basic module types: (1) operations and laboratory modules with equipment installed permanently around the perimeter (*e.g.*, Zarya); (2) laboratory modules with interchangeable racks lining a rectangular lumen (Columbus, Kibo, and Destiny); (3) interconnecting nodes; (4) logistics modules that act as supply/disposal closets (MPLM, HTV, ATV, Progress); and (5) crew return capsules (Soyuz) and airlocks [18].

Budget limitations canceled plans for a dedicated ISS Habitation Module, but operational experience allowed compensating the loss with a sophisticated Crew Quarters design retrofitted into the Harmony connecting node (Figure 7) [19]. Alternative, kit-of-parts solutions compatible with ISS rack structures have been proposed for this most personal architectural space (Figure 8) [20].

By synthesizing the Russian and American experience base, then folding in European and Japanese participation, ISS now provides foundational realism for all next-generation concepts. Enormous learning has resulted from its international design, fabrication, assembly, verification, commissioning, and operation including maintenance. The keystone nature of ISS for subsequent orbital architecture cannot be overstated.

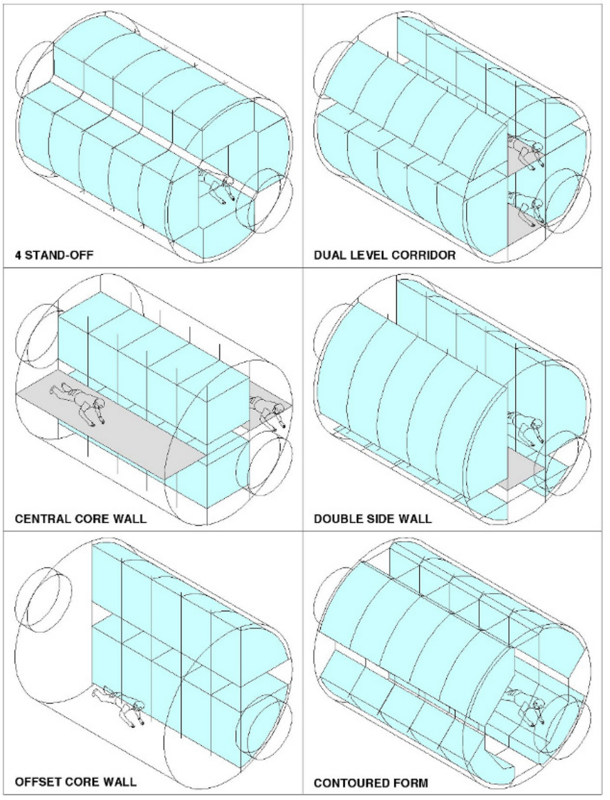

Figure 5. Six fundamental ways to package on-orbit functions into a Shuttle-payload-bay-sized module were analyzed extensively before NASA settled on the upper-left architecture option. Credit [17].

3.2. Orbital Architectural Form in the Future

For decades NASA has considered expandable “inflatable” modules to be the next step in space habitation system technology, decoupling the usable volume attainable on orbit from the “mold line” of the rocket that gets it there. TransHab (Figure 9) was a major step forward in the development of space-rated inflatables. Developed by a NASA tiger team in the early 1990s for Mars mission applications [21], TransHab almost made it onto the ISS instead, and then found a third life as the basis of commercial modules currently under development and demonstration by Bigelow Aerospace (Figure 10) [22]. TransHab’s larger size opens possibilities for new human environments and missions, including those consistent with the emerging high-end tourism market (Figure 11) [23]. Full use of microgravity three-dimensionality will allow a startling combination of compactness and spaciousness.

Detailed knowledge of how to assemble a large, complex system in Earth orbit, and modify its configuration

Figure 6. The Destiny laboratory module is the archetype for most ISS elements: four banks of relocatable, hatch-sized equipment racks, supported and fed by four hidden utilities chases, surround a rectangular free volume. Credit NASA.

Figure 7. ISS Crew Quarters, fit into specialized racks assembled on orbit, provide air circulation, temperature control, acoustic and visual privacy, and provisions for telecommunications, personal items, and safety systems. Credit NASA.

over time even as it is continuously used, paves the way for deep-space human exploration as well as more elaborate Earth-orbital applications including eventual large-scale commercial development.

Module architectures for multiyear, deep-space (*e.g.,* Mars-class) missions must reconcile all that is being learned from ISS with three additional sets of unrelenting drivers: (1) technologies and systems that can protect humans reliably from the lethal deep-space environment for years without rescue or resupply; (2) a designed environment that promotes psychological and sociological health in the most remote state humans will ever have encountered; (3) integration into a complex, tightly coupled space mission and transportation system (Figure 12).

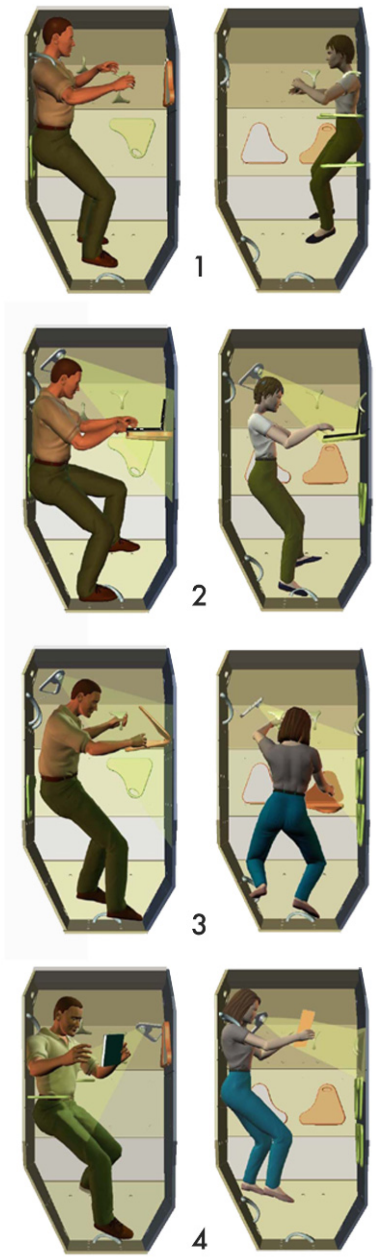

Figure 8. Concept for retrofitting ISS Crew Quarters accommodates various activities and anthropometric range with a simple kit of parts, easily adjusted. Credit [20].

Multiple criteria must be comprehensively measured and scored over thousands of options [24].

Rotation-induced acceleration is the only practical way to compensate orbital weightlessness. Yet occupying a rotating system is perceptually quite different from

Figure 9. TransHab developed a Class II structure system allowing a habitat to be system-verified before launch, volume-expanded after launch, shielded from debris impact, and insulated against temperature extremes. Credit NASA.

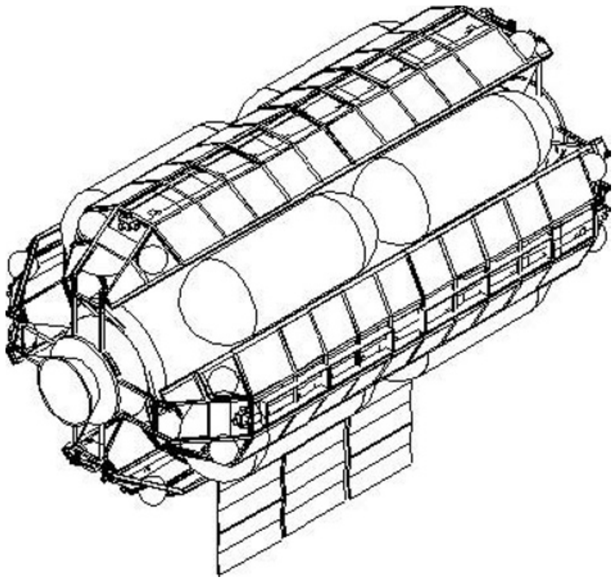

Figure 10. NASA licensing allowed the TransHab module technology to be used for private development of integrated modules for commercial customers. Credit [22].

experiencing planet-gravity weight. Without orbital centrifuge studies of physiological response, it cannot be known whether partial weight (*e.g.*, lunar at 1/6 Earth-normal acceleration; or Mars at 3/8 Earth-normal) precludes the debilitating deconditioning caused by extended microgravity. Best-available contemporary design guidelines for conceptual systems are synthesized from multiple analyses (Figure 13) and visualized with simple simulators [25–27].

Given market growth for leisure (*e.g.*, resort vacations in Earth orbit) and business (*e.g.*, construction and operation of space solar power satellites) space passenger travel, orbital architecture could conceivably grow into bona fide orbital urbanism, supporting large permanent and transient populations with a full range of services for work, living, recreation, and human fulfillment. Despite their large scale, the form of eventual space cities will remain subject to a pattern language discernible now, arising from the fundamental orbital environmental constraints (Figure 14) [28].

3.3. Planet-Surface Architecture

There is no precedent for planet-surface architecture. Images of planetary bases have been with us practically since the dawn of the space age (Figure 15) [29]. But what can they really be like, and how could their architecture evolve? Three place-types are accessible to humans in this century: the Moon, Mars, and thousands of asteroids (in Earth-like orbits, at the Sun-Earth Lagrange Points L4 and L5, the two moons of Mars, and ultimately those in the Main Belt). Almost all asteroids have ultra-low gravity, so asteroidal architecture would be a hybrid of orbital and planet-surface types and is thus not treated here.

Outposts

Planetary outposts will be the first human beachheads on other worlds. A reasonable evolution begins with short sortie missions, then "campsites" that might incorporate lander vehicles into the outpost architecture as re-used assets are gradually built up. Recently NASA investigated lunar surface architecture concepts incorporating the best science and technology known at the beginning of the 21st century (Figure 16): possible polar ice deposits; high-efficiency solar power; amphibious, multi-terrain mobility; and expandable habitat designs [30]. These approaches highlight compactness, pre-integration, and adaptable modularity appropriate for early planetary exploration.

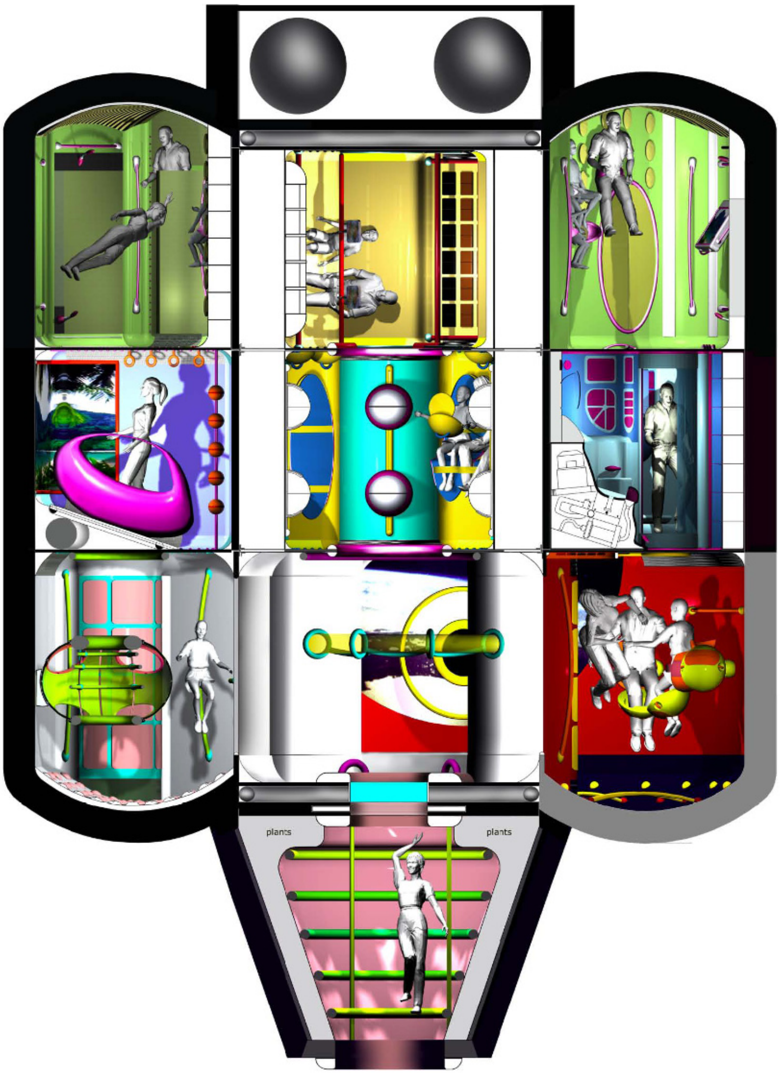

Figure 11. TransHab's expanded volume, if fully exploited for the three-dimensionality allowed by microgravity, can be packed with a dazzling variety of functions and spaces to support a dozen-person luxury hotel module. This section shows double staterooms, multiple socializing spaces, storm shelter, media theater, and circulation passages. Credit [23].

One of the toughest challenges facing planet surface architects is enabling routine access between a clean interior and a native exterior pervaded by hazardous, possibly toxic dust. Airlock design must balance many mutually conflicting issues (Figure 17): suit design, airlock volume, cycle time, routine and contingency operations, dust control, maintenance access, and system integrity in harsh planetary environments [31].

Mobile architecture will enable comprehensive human exploration of large planets; the Moon has as much surface area as Africa and Mars has as much as all of Earth's continents combined. All the challenges of planet surface architecture—including radiation shielding, power, and thermal rejection—are intensified in mobile habitats that must carry everything with them or rely on cached supplies. Concepts range from dividing functions among a "flotilla" of slow-moving modules (Figure 18) [32] to self-contained, unitary mobile laboratories optimized for fast coverage of large distances (Figure 19) [33].

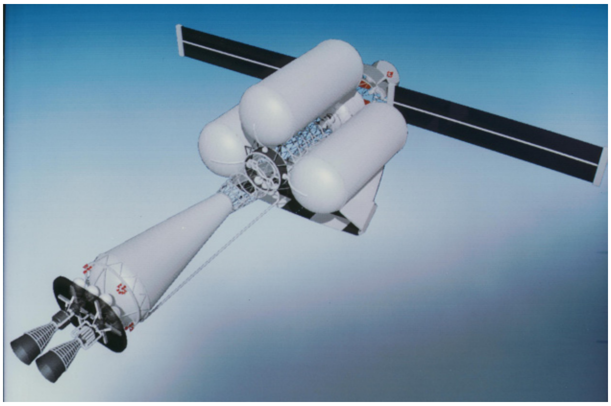

Figure 12. Mars-class deep-space habitat designs must synthesize hundreds of competing requirements for both weightless and surface applications, all living functions for small crews on unprecedented remote missions, radiation shielding, food supply, reliable life support, and integration into mass-limited flight systems for transit and Mars landing. A habitat system sized for six is the small white cylinder embedded toward the front of this Mars mission vehicle configuration based on nuclear thermal propulsion. Credit [24].

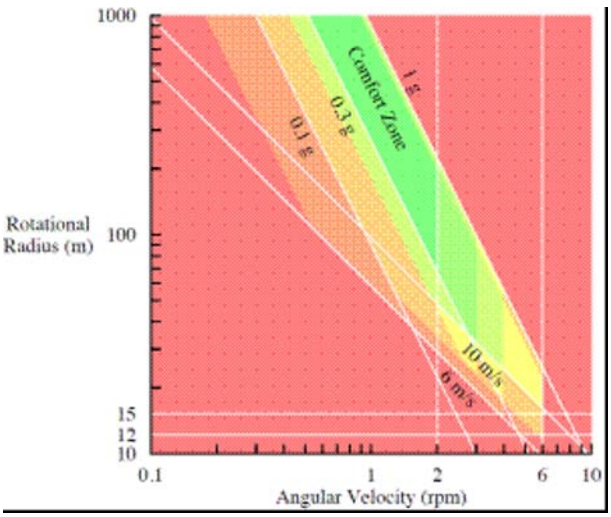

Figure 13. Artificial gravity "comfort chart" is composited from five seminal but disparate, extrapolative analyses of human tolerance of rotation. The green zone represents the range of gravity level, spin radius, and angular velocity that multiple researchers agree is acceptable. Credit [27].

Planetary Bases and Settlements

How might outposts grow into larger permanent bases, and what architectural elements could enable this? Are there formal possibilities other than warrens of interconnected modules? How would habitable elements integrate into a total base architecture? And what would change as a base evolves into a settlement? This article can include only a few examples to hint at the possibilities.

Advanced concepts address ways to achieve spacious habitable environments, large-scale construction, and fabrication using native materials. Cylinders and spheres, while natural for containing atmospheric pressure, are not efficient volumes for use in gravity conditions, i.e., on the Moon or Mars. Concepts have been proposed for laterally-extensive, "tied pillow" inflatable structures, and for membrane structures that take almost-flat-floor geometries when inflated (Figure 20) [34].

Robotic mechanisms that self-assemble to become habitable structures may offer solutions for building and reconfiguring large structures [35]. Mass-produced product lines of functional panel elements may enable automated expansion and reconfiguration of planetary base stationary and mobile elements (Figure 21).

Evolving from a planetary base to genuine settlement would take space architecture to a new level involving the use of local materials and development of techniques for in situ fabrication, construction, verification, and outfitting (Figure 22) [36]. Such concepts provoke space architects to think about all of the practical details of making architecture in alien environments from what we find there.

Even early uses of native material, such as extracting water from lunar polar ice or oxygen from lunar ilmenite for use as propellant, require quantitative site planning to accommodate extensive power installations, regolith mining operations, and repeated landings near high-value surface assets (Figure 23) [37].

Space settlement would also introduce societal issues and requirements far beyond those needed for small bases. Designing the infrastructure for viable off-world civilization would be the ultimate challenge for space architects, leading to forms of urbanism tailored for alien places, as terrestrial cities are adapted to their locations. Some basic principles likely to shape eventual lunar towns and cities can be understood now: they will be densely populated, hermetic, shielded and interior but kinesthetically expansive and visually lightweight, built and outfitted with indigenous materials, not biologically sterile or barren, and protective of lunar wilderness that, once touched, is changed forever [38].

4. Scenarios for Future Space Architecture

The actual course of space architecture throughout the 21st century will be determined by the value propositions that drive advancement of human space flight (HSF). HSF's value proposition has changed over the half cen-

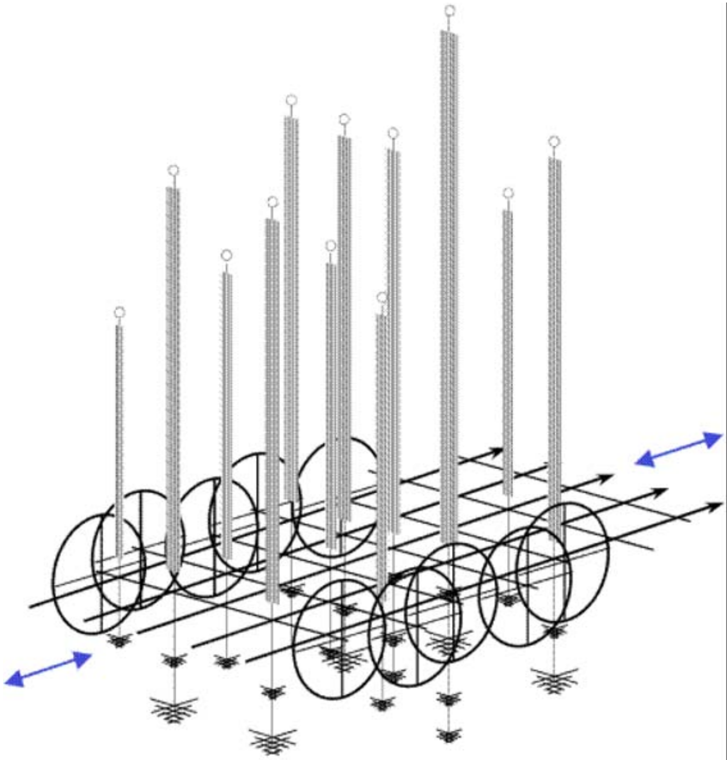

Figure 14. The form of eventual orbital cities will be driven by physics and economics: gravity-gradient orientation of a raft-like city structure with energy exchange above and tethered habitation below, maximization of high-value Earth views, transportation access forward and aft, and rotation vector of artificial-gravity segments normal to the orbit track. Credit [28].

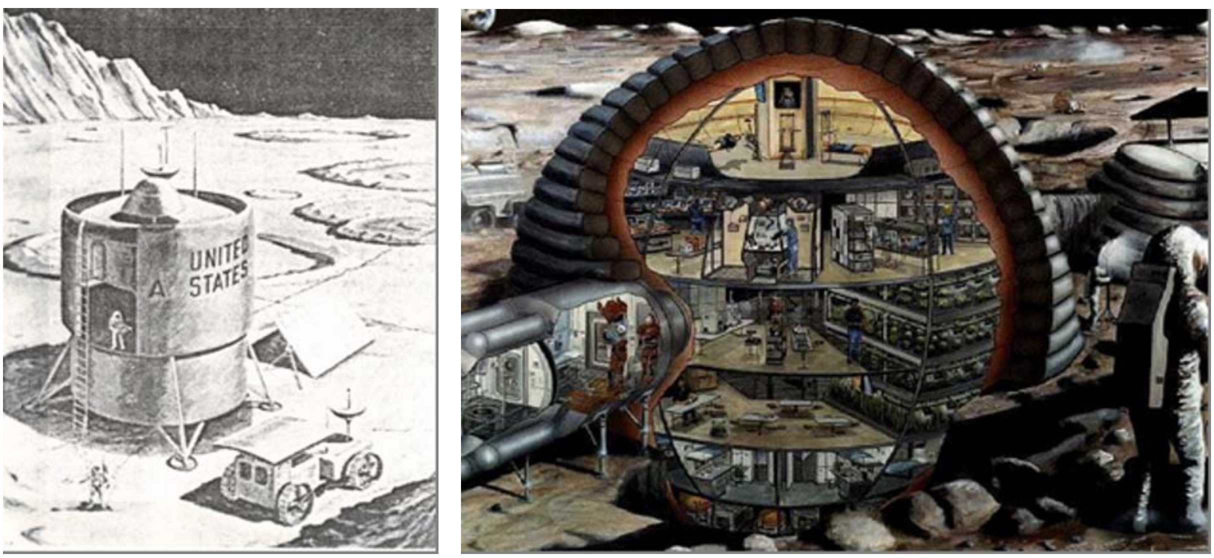

Figure 15. A great variety of concepts for planet-surface architecture have emerged over the years, from simple (left, Boeing concept from 1963, before Project Apollo, of adapted rocket stages on the lunar surface) to complex (right, Lacus Veris concept from 1989, with inflatable modules, regolith shielding, and farmed food). Credit [29].

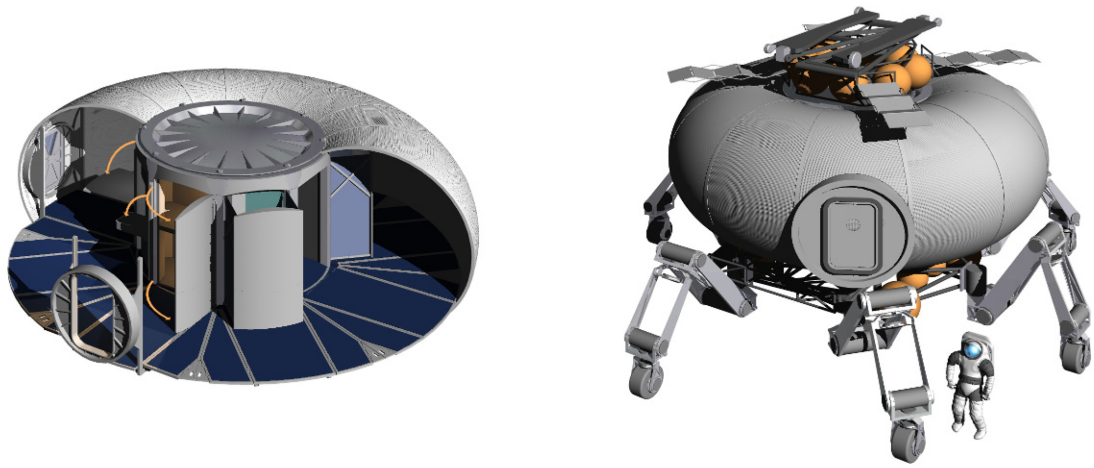

Figure 16. Contemporary NASA concept for Class II lunar outpost habitat can be relocated and integrated with other outpost systems. The adaptation of TransHab technology allows pre-integration and verification of core functional systems but also expanded living volume landed on the surface. Credit NASA.

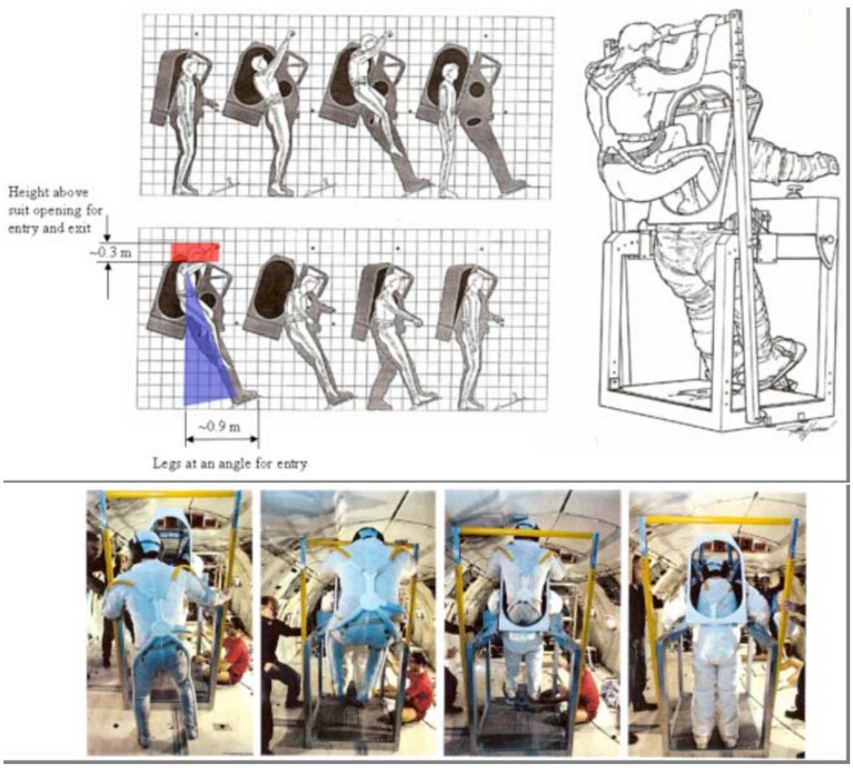

Figure 17. A suitlock may help manage the many system issues posed by planet-surface dust and frequent use. The suit is kept in a sheltered maintenance volume outside the habitat proper. The astronaut enters directly from the habitat through a port in the back, closes and verifies the seal, and detaches it from the pressure hull for egress. Zero-g flight tests validate the operation. Credit [31].

Figure 18. The Habot outpost concept divides inhabited functions into small, individually-mobilized modules that can be assembled in various combinations as needed throughout an itinerant mission. This prototype test investigated use of the ATHLETE mobility system to position representative modules. Credit NASA.

tury of its history [39]. Demonstrating global technological dominance propelled the first decade of government-funded HSF. Over the subsequent four decades HSF coasted on Apollo's momentum, gradually implementing the first two stages of a blueprint laid out by von Braun in the 1950s: reusable space shuttle, orbiting space station, humans to Mars.

Although the **Explore Mars** meme remained HSF's implicit value proposition in America, two fundamentals are now changing that. First, achieving human exploration of Mars would take significantly more time and money than the public appears willing to afford NASA, a mismatch that is becoming more widely recognized. Second, inchoate commercial human space flight is now ending NASA's monopoly on the "right stuff." However, until and unless the flow of private capital becomes much deeper and more diversified, government investment will continue to dominate; today NASA spends about $\$10^{10}$ per year on technologies, infrastructure, systems, and operations directly related to HSF.

Explore Mars is only one of four possible value propositions for such government investment; this traditional option, aimed at setting foot on the most distant place reachable by humans, would require at least $\$10^{11}$ over several decades. The second option would be to accelerate the growth of **Space Passenger Travel**, by investing that same sum over that same interval to solve the technical hurdles in creating a commercial industry that carries 10^5 ordinary people into space every year. The third option would be to enable **Space Solar Power for Earth**, by investing the same money and time instead to turn the U.S. into the world's largest energy exporter by creating a clean, terrestrial-scale commercial power industry in geosynchronous orbit. Among other advanced capabilities, hundreds of long-tour space workers would be needed. The fourth option would be to **Settle the Moon**, establishing humanity as a two-planet species with thousands of mixed-demographic families living there permanently. While many HSF activities have been envisioned and proposed, all of them are captured within these four diverse paths (Table 2).

We do not know yet whether the three non-traditional value proposition alternatives might be seriously considered by U.S. government policy. And even if they were, we cannot know today how they might be synthesized into a plan. But taken by themselves these paths diverge, with dramatically different implications for space architecture.

Explore Mars would need life support technologies and systems that are highly reliable in deep space without any supporting infrastructure, but only to accommodate a few missions of roughly half a dozen people each. Volumes would be few, small, and evolved directly from prior art. The closest applicable model is Apollo.

Space Passenger Travel would need flight and hotel accommodations for hundreds of ordinary people at a time for up to a couple weeks duration, and dormitories for hundreds of professional staff on extended duty tours. Volumes for social assembly would be required in addition to cabins. Resort amenities would be needed, as well as facilities for routine services like hospital, retail, and dining in addition to behind-the-scenes activities like food production, waste recycling, and maintenance. Life support infrastructure would be massive but robust through its size, redundancy, and modularity. Routine transportation would allow rich material interchange with Earth for fresh food, staff and entertainers, and equipment. Contemporary cruise ships provide an enlightening model.

Space Solar Power for Earth would need high-orbit dormitories and support services for professional space workers; construction and maintenance crews would live at GEO on extended duty tours. Accommodations could be more utilitarian than in the passenger travel case, but would require some of the same provisions: assembly, health care, entertainment. Resupply from Earth would be almost independent of mass given the huge quantity of power-station construction materiel being launched anyway. An applicable terrestrial model is frontier towns for oil drilling.

Settle the Moon would develop an architecture of permanence and growth based on in situ materials and equipment made from them. In addition to extensive facilities for experimentation and manufacture, provisions would increasingly be needed for the full array of human support,

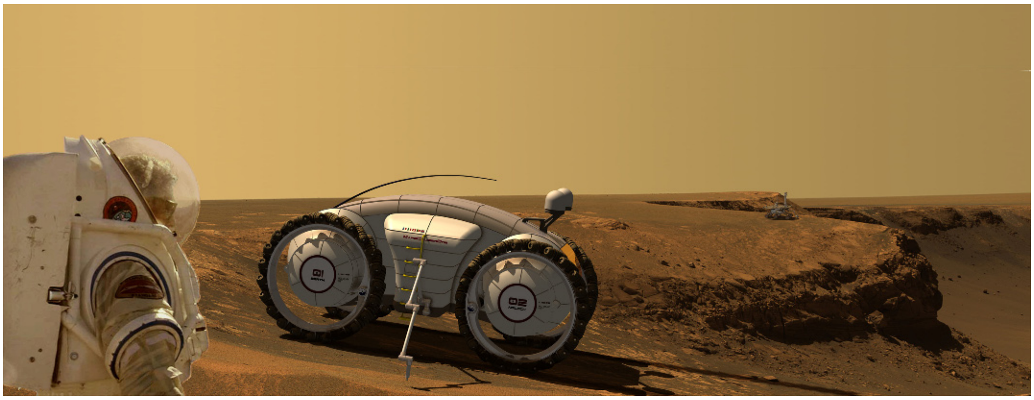

Figure 19. The Mars Cruiser One concept uses large-diameter, hubless wheels to integrate high-speed omni-directional mobility, suitport access, external robotics, and interior habitation and laboratory functions into a configuration compact enough to fit a 5-m diameter launch and landing envelope. Credit [33].

Figure 20. Mass-optimized pressure vessels "want to be" spheres, but asymmetrical and reinforced-gore geometries can be engineered to yield shapes more useful for planet surface applications. Credit [34].

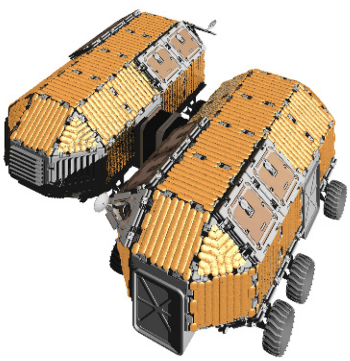

Figure 21. Self-assembling systems may prepare for human arrival, operate when unattended, and aid repair and reconfiguration. The TRIGON concept uses a kit-of-parts approach with standardized mechanical and electrical interfaces to "walk" panels over each other into a final assembly. Credit [35].

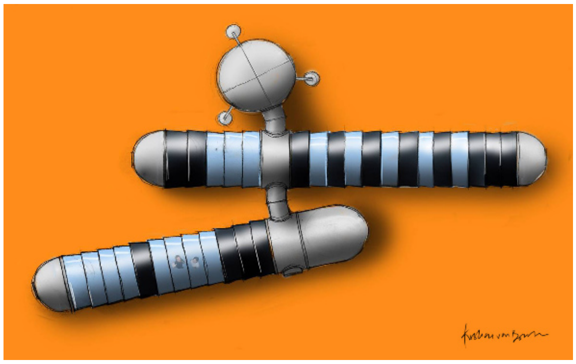

Figure 22. A hybrid habitat module architecture might combine pre-integrated elements brought from Earth (connectors, airlocks, and system equipment) with large, Class III glass pressure vessels cast and assembled onsite. This example concept stacks slightly conical segments with cemented, large-area lap joints. Credit [36].

including schools, recreation, and fulfillment. Supply from Earth would be routine but focused on high-tech components that exceed the local manufacturing capability, and bulk deliveries of useful alloying elements, reagents, and volatiles. The small town is an applicable model.

Table 3 shows the canvas on which the next century of space architecture is likely to be painted. Down the left are four layers of the design challenge. **Ergonomic** refers to the fundamental geometry that accommodates human activities. **Biological** refers to the technology that sustains life. **Psychological** refers to provisions that let human individuals function, be productive, remain healthy emotionally, and grow and thrive spiritually. **Sociological** refers to accommodation of the needs of human groups transcending the individual.

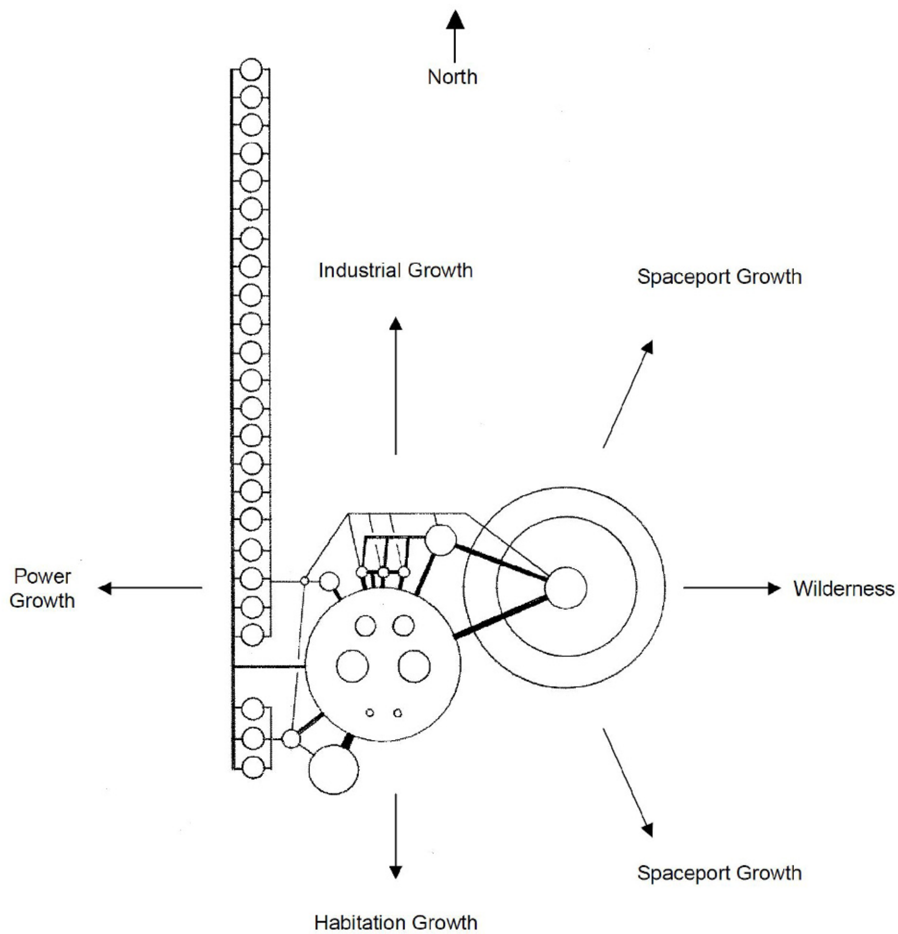

Figure 23. To-scale proximity diagram reconciles site planning considerations for a robotically constructed, oxygen-producing, habitable lunar base, including astrodynamic constraints, room to grow, and the number, size, and interrelationships of physical elements like solar arrays, landing pads, habitat shelters, and oxygen reactors. Credit [37].

Across the top are three types of spacefaring populations. **Mission crews**, whether explorers or professional staff, are trained for space conditions, hazards, and tasks using specialized equipment, and are paid to work and live in space. They operate in teams, from small crews up to hierarchical organizations comprising a few hundred specialists, and they live in space for the duration of their mission, which could mean tours of duty lasting many months. **Passengers**, whether leisure tourists or business travelers enroute to offworld workplaces, do not have deep training to operate or maintain space systems. Instead their support and safety are entrusted to mission crews. They live in space for very short durations, ranging from minutes to weeks. Typically they would be individuals, families, or small groups traveling together, differentiated by travel class rather than by rank or role. **Settlers** are committed to space for years, possibly life. They inevitably bring or develop specialized skills needed by the settlement, and function within a complex sociological web of interdependence, trust, and trade governed by persistent behavioral norms. Their efforts and value system are oriented toward collective safety, self-reliance, permanence, sustainment, and growth.

Checkmarks in the matrix indicate the state of current knowledge. Much is known about how mission crews can inhabit and do work in the microgravity of Earth orbit, and a little is known about how they can function in lunar gravity. A little is also known about technologies to keep small mission crews alive continuously, and about psychological characteristics of remote and hostile cis-lunar environments. Apart from these limited domains, nothing at all is known across the rest of the matrix. Paying visitors to Mir and ISS have been embedded in mission crews and undergone extensive training. As of early

Table 2. Four options for government-funded HSF lead to divergent alternative futures.

Option	Core Purpose	Core Myth	Legacy	Core Needs	Space Population Enabled by 2040
Explore Mars	• Extend direct human experience to the most remote destinations feasible • Understand past and future potential of Mars to support life	Hero (Lewis and Clark)	• Life elsewhere? • International interdependence • NEOs as stepping stones to Mars • Highly reliable space systems	• Advanced propulsion • Deep-space human systems • Public commitment sustained over decades • International co-investment	Six international government employees on a distant planet
Accelerate space passenger travel	• Open space to citizens • Create new travel-related industries • Extend LEO-experience perceptual shift to large population	Jet set (Branson)	• Highly reliable, reusable Earth-to-orbit systems • Space hotels and resort destinations • Routine in-space service industries (e.g., food, maintenance, medical) • 1-hr intercontinental travel	• "Four 9s" launch reliability • Reusable launch orbit • Public-private partnerships • Commercial crew corps	10^3 crew + 10^5 citizens per year visiting low Earth
Enable space solar power for Earth	• Prepare for post-petroleum age with minimal disruption • Create new energy-related industries • Become global exporter of unlimited clean energy	Green	• Heavy-lift launch • Routine in-space high-tech industries (e.g., construction, robotics) • Changed land-use patterns • Culture shift to use space resources	• Power beaming safety regime • Inter-Agency partnerships • Public-private partnerships • Commercial space worker corps	10^2 skilled workers on extended duty tours in high Earth orbit
Settle the Moon	• Establish humanity as a two-planet species	Pioneer (Heinlein)	• Permanent human presence offworld • Lunar industries (high-tech and service) • "Living off the land" in space • Offworld import/export • Lunar tourism	• Routine heavy traffic to lunar surface • Public-private partnerships • ISRU • Full suite of technical skills and social services	10^3 mixed-demographic citizens offworld, some permanent and raising families

2011, only mission crews have flown, and only twice, in only a single commercial suborbital vehicle. There are no precedents for designing and building inhabited environments that support large mission crews with both weightless and artificial-gravity conditions; for farms, factories, or workshops; for making and certifying livable space in planet surface environments; for processing a large weekly turnover of paying passengers; for orbital resort swimming pools; for open volumes large enough to accommodate a settler town hall assembly; or for ecological life support integration at urban scale. Despite the incredible achievements of human space flight to date, against the foreseeable range of space architecture we know next to nothing.

Today, we do not yet know that we will really need space architecture. But the diversity of possible human space flight futures indicates that we might. And most of the alternatives would catapult us into human space flight regimes without precedent, where architectural challenges dominate. Modern human societies may choose to invest a fraction of their gross productive economies in space-based industries for clean, inexhaustible energy; for transcontinental travel that takes less than an hour; for orbital vacations; for building on a new world; or for some combination or sequence of these. The job of space architects is to figure out how to make the human environments that will let these futures come to pass.

Table 3. Developmental opportunities for space architecture: challenge vs. population type. Unprecedented challenges make it a wide-open field.

	Mission Crews	Passengers	Settlers
Ergonomic	✓		
Biological	✓		
Psychological	✓		
Sociological			

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